A SOFTWARE FRAMEWORK FOR ADAPTIVE AND INTEROPERABLE INTERNET-DELIVERED PSYCHOLOGICAL TREATMENTS

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TO MY PARENTS, FAMILY, AND FRIENDS

for their love, support, advice, and encouragement. Especially, to my wife, `Anju Mukhiya`*, for being my loving and encouraging partner throughout our life's journey, and my beautiful little daughter,* `Yoshmi Mukhiya.`

PREFACE

The author of this thesis has been employed as a PhD research fellow in the software engineering research group at the *Department of Computer Science, Electrical Engineering and Mathematical Science* at Western Norway University of Applied Sciences. The author has been enrolled in the PhD programme in Computer Science: *Software Engineering, Sensor Networks and Engineering Computing, with a specialization on software engineering*.

The research presented in this thesis has been accomplished as a part of the INTROMAT project (`https://intromat.no/`). This thesis is organized into two parts. Part I is an overview of the work done during this thesis providing an introduction to the problem domain, primary motivation, a discussion of the research methodology used, a summary of the results obtained, and a discussion of this thesis's research contributions in the context of software engineering and health informatics. Part II consists of seven peer-reviewed research articles. Five of them are published (A-E); two articles are (F-G) submitted to journals and are under review:

Paper A S. K. Mukhiya, J. D. Wake, Y. Inal, K. I Pun, and Y. Lamo. *Adaptive Elements in Internet-Delivered Psychological Treatment Systems: Systematic Review*. J Med Internet Res. 2020 Nov 27;22(11):e21066. doi: 10.2196/21066. PMID: 33245285; PMCID: PMC7732710.

Paper B S. K. Mukhiya, F. Rabbi, K. I Pun and Y. Lamo, *An Architectural Design for Self-Reporting E-Health Systems*, 2019 IEEE/ACM 1st International Workshop on Software Engineering for Healthcare (SEH), Montreal, QC, Canada, 2019, pp. 1-8, doi: 10.1109/SEH.2019.00008.

Paper C S. K. Mukhiya, F. Rabbi, K. I Pun, A. Rutle, and Y. Lamo. *A GraphQL approach to healthcare information exchange with HL7 FHIR*. The 9th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH-2019), Coimbra, Portugal, November 4-7, 2019, volume 160, pages 338–345. Elsevier, 2019, doi: https://doi.org/10.1016/j.procs.2019.11.082

Paper D S. K. Mukhiya, J. D. Wake, Y. Inal and Y. Lamo, *Adaptive Systems for Internet-Delivered Psychological Treatments*, in IEEE Access, vol. 8, pp. 112220-112236, 2020, doi: 10.1109/ACCESS.2020.3002793.

Paper E S. K. Mukhiya, U. Ahmed, F. Rabbi, K. I Pun and Y. Lamo, *Adaptation of IDPT System Based on Patient-Authored Text Data using NLP*, 2020 IEEE 33rd International Symposium on Computer-Based Medical Systems (CBMS), Rochester, MN, USA, 2020, pp. 226-232,
doi: 10.1109/CBMS49503.2020.00050.

Paper F S. K. Mukhiya, Y. Lamo , F. Rabbi , *A Reference Architecture for data-driven adaptive Internet-Delivered Psychological Treatment Systems*, **submitted** to Journal of Medical Internet Research, 2021.

Paper G S. K. Mukhiya, Y. Lamo, *An HL7 FHIR and GraphQL approach for interoperability between heterogeneous Electronic Health Record systems*, Submitted to Health Informatics Journal, 2021.

Reading this thesis This thesis assumes the readers to be familiar with the fundamental software engineering terminologies. We also provided a background chapter 2 to provide theoretical knowledge and introduction of terminologies used in this thesis. The thesis contains three types of hyperlinks a) URL hyperlink (to external links), b) citations link (to bibliography sections), c) inter-document links (to a different section of thesis). We have attempted to make the thesis manuscript error-free to the best of our abilities. We will publish the reported and discovered errors as an errata list in the hard copy and digitally in the GitHub repository (`https://github.com/sureshHARDIYA/phd-resources/tree/master/thesis`), along with the following resources:

- Coloured and high-resolution images can be obtained for each chapter.
- We will update URL and the status of the research Papers F and G, currently under review, in the same Github repository.
- The study contains the development of OSS, which is changed, developed and updated continuously. Most recent versions of the software artefacts will be available from this repository.

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I want to express my sincere gratitude to my parents for all the love, support and encouragement during my life. I am incredibly obliged that they have always stood behind me, guided me in the right direction, and emboldened me to pursue my dreams. I also need to say thank you to my wife, *Anju Mukhiya*, and my beautiful little daughter, *Yoshmi Mukhiya*, who always supported, motivated and were beside me during my work. Thank you for your help, support, and love!

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Finally, thanks to all my friends from Nepal and other former and new PhD researchers in our PhD office at HVL for helping me survive all the stress during this period and not let me give up. I would also like to offer my gratitude to my elder brothers *Deo Narayan Mukhiya*, *Shiv Narayan Mukhiya*, and other family members for supporting me, motivating, and inspiring me to pursue a PhD. Thank you, *Monica Regmi*, for helping me proofread the thesis and always available for communication. Without support, as mentioned earlier, guidelines and love, this work would not have been possible.

August 2021
Suresh Kumar Mukhiya

ABSTRACT

BACKGROUND Statistics unveil the predominance of mental and neurological disorders globally. Handling these mental and neurological disorders is economically, physically and emotionally challenging. Proper healthcare treatments would have been an ideal solution for these people suffering from these disorders. However, provided limited healthcare resources, an alternative solution is to use the Internet to provide psychological treatments. The use of Internet-Delivered Psychological Treatments (IDPT) can accelerate treatments for people globally at a lower cost. While such IDPT systems have been practised at volume, user adherence is low with high dropout rates. Low adherence in treatments is primarily due to the IDPT system's inability to adapt treatments according to user needs, context and preferences.

OBJECTIVE This study is accomplished in collaboration with a large interdisciplinary project entitled as INTROMAT. INTROMAT brings together ICT researchers, ICT industries, health researchers, patients, clinicians, and patients next of kin to reach its vision. *The project's vision is to improve public mental health through innovative technologies.* The main objective of this thesis, inclined to fulfil this vision, is to design, develop and evaluate an adaptive IDPT framework.

METHODS Based on the INTROMAT project's problem domain and goals, we started with the study of *state-of-the-art* works, including *systematic literature review, evaluation of available systems, analysis of the previous studies on the problem domain*, and *evaluation of past case studies*. Based on these studies, we identified two primary gaps in the current IDPT systems, *lack of adaptiveness* and *limited interoperability*. Then, we used MDE and Domain-Driven Design (DDD) techniques to address these two gaps.

RESULTS We proposed a software framework for developing adaptive, reusable, and interoperable Internet-Delivered Psychological Treatments (IDPT), referred hereto as *OpenIDPT Framework*. The OpenIDPT Framework includes a) a Reference Model (RM), b) a Reference Architecture (RA), c) an Information Architecture (IA), and d) an open-source implementation of an adaptive IDPT system.The *reference model* reveals the adaptive elements (what to adapt), adaptive dimensions (on what basis to adapt), information architecture (how to structure content), and strategies (how to adapt) of an adaptive IDPT system. The *Reference Architecture* unveils the technical architecture of an adaptive IDPT system. The *information architecture* guides how to structure and organize the content for better discoverability and comprehensibility. To evaluate the proposed RA of adaptive IDPT systems, we implemented a prototype as an Open-Source Software. We refer to it as *Open-Source Adaptive IDPT System (OSAIS)*. We used Design Science Research (DSR) evaluation methods to assess the efficacy of the proposed artefacts and their ability to address identified research gaps. Our preliminary results demonstrate that the proposed artefacts exhibit capabilities to use comprehensive user profiling techniques to adapt interventions using different

rule-based engines, recommendation systems, and artificial intelligence (AI) based algorithms. As a Proof-of-Concept of AI-based algorithms, we present an adaptive strategy based on Natural Language Processing (NLP) techniques that analyze patient-authored text data and extract depression symptoms corresponding to a clinically established psychometric assessment questionnaire PHQ-9. The strategy utilizes the proposed novel Word Embedding (Depression2Vec) to extract depression symptoms from patient-authored text and adapts psychological treatments based on the absence or presence of depression symptoms. Furthermore, to obtain interoperability in the OpenIDPT Framework, we created an open-source Resource Server (RS) based on GraphQL. An RS is a web application that can read, write, update, and delete (CRUD) HL7 FHIR resources. HL7 FHIR is an open healthcare IT standard (analogous to data structure) for healthcare data exchange. GraphQL is a data query and manipulation language for Web-Service communications.

CONCLUSION This study demonstrates the feasibility of using an adaptive system to enhance user adherence. With the ubiquity of ambient intelligence and predictive algorithms, further study on how to combine these IoT technologies with the adaptive system is prudent and exciting.

SAMMENDRAG

BAKGRUNN Statistikk viser at mentale- og neurologiske-lidelser er et økende problem både nasjonalt og globalt. Å håndtere slike mentale- og neurologiskelidelser er krevende både økonomiskt, fysiskt og emosjonelt. Psykiske helsetjenester er av stor betydning for folk som sliter med slike lidelser, men siden det er begrensede resurser til behandling innen psykiatrien er en alternativ løsning å bruke Internett til å levere behandling. Ved å ta i bruk Internett leverte psykologiske intervensjoner (IDPT) (Internet-Delivered Psychological Treatments) kan en tilby kost effektiv behandling, også i en global skala. I dag er bruken av IDPT økende, men brukerenes oppfølging av behandlingen er lav, med mange drop-outs og lav gjennomføring. Dette er hovedsaklig knyttet til IDPT systemenes manglede evne til å tilpasse behandlingen i forhold til brukerens behov, kontekst og preferanser.

FORMÅL Denne studien er utført i tilknytning til det tverrfaglige forskningsprosjektet INTROMAT. I INTROMAT samarbeider IKT-forskere, IKT-industri, helseforskere, pasienter, klinikere og pårørende om å oppnå visjonen: *Å forbedre mentalfolkehelse ved å inføre inovative teknologier i behandlingen.* Hovedformålet med denne avhandlingen er å oppnå en del av denne visjonen, ved å designe, utvikle og evaluere et adaptivt IDPT rammeverk.

METODER Basert på problemorådet og målene til INTROMAT prosjektet startet vi med å studere *state-of-the-art* forskningsarbeider innen feltet, dette ble gjort i form av *en systematisk literatur studie, evaluering av tilgjengelige systemer, analyse av tidligere studier innenfor problemområdet* samnt *evaluering av tidligere case studies*. Som følge av disse studiene har vi identifisert to viktige mangler i dagens IDPT systemer: *mangel på tilpassningsmuligheter* og *mangel på samhandlingsmuligheter*. For å addresere disse manglene har vi anvendt Modell Basert (programvare) Utvikling, MDE og Domene-Drevet Design (DDD) teknikker.

RESULTATER Vi har foreslått et nytt programvare rammeverk for tilpassningsdyktige, gjenbrukbare og samhandlende Internett-Leverte Psykologiske-Intervensjoner (IDPT), som vi kaller *OpenIDPT Rammeverket*. OpenIDPT Rammeverket består av a) en ReferanseModell (RM), b) et ReferanseArkitektur (RA), c) et InformasjonsArkitektur (IA) og d) en åpen kildekode implementasjon av et tilpassningsdyktig IDPT system. *Referansemodellen* beskriver hvilke elementer som skal tilpasses (hva kan tilpasses), tipasningens dimensjoner (i hvilken sammenheng en skal tilpasse), informasjonsarkitekturen (hvordan skal inholdet struktureres), og strategier (hvordan skal en faktisk tilpasse) i et tilpassningsdyktig IDPT system. *Referansearkitekturen* beskriver den tekniske arkitekturen til et tilpassningsdyktig IDPT system. *Informasjonsarkitekturen* beskriver hvordan en kan strukturere og organisere behandlingsinnholdet for at brukerne bedre skal finne og forstå innholdet. For å evaluere den foreslåtte RA for tilpassningsdyktige IDPT systemer har vi implementert en prototype iform av en åpen kildekode programvare,

også kallt: *Open-Source Adaptive IDPT System (OSAIS)*. Vi anvendte evalueringsmetoder fra Design Science Forskning (DSR) for å evaluere de foreslåtte artefactene og deres evne til å svare på etablerte forskningsutfordringer. Våre foreløpige resultater viser at de foreslåtte artefaktene kan anvende avanserte brukerprofileringsteknikker til å tilpasse intervensjonene ved å anvende forskjellige regelbaserte beslutningssystemer, anbefalingssystemer, og kunstiginteligens (AI) baserte algoritmer. For å vise potensialet til AI-baserte algoritmer har vi presentert en tilpassningsstrategi basert på NaturligSpråkProsesserings (NLP) teknikker som analyserer data i form av tekster forfattet av pasienter, hvor vi undersøker om ekstraherte depresjonssymptomer fra tekstene sammenfaller med verdiene fra det etablerte kliniske spørreskjemaet PHQ-9. Strategien anvender den nylig foreslåtte Ord-Innebyggings tilnærmingen (Depression2Vec) for å ekstrahere depresjonssymptomer fra tekster som er skrevet av pasienter og tilpasser behandlingen basert på tilstedeværelse eller fravær av depresjonssymptomer. For å evaluere mulighet til samhandling i OpenIDPT rammeverket utviklet vi en åpen kildekode Resurs-Tjener (RS) basert på GraphQL. En RS er en webapplikasjon som kan lese, skrive, oppdatere og slette (CRUD) HL7 FHIR resurser. HL7 FHIR er en IT standard som anvendes innen helsetjenesten (på samme måte som en datastruktur) for å utveksle helsedata. GraphQL er et språk for å hente ut og manipulere data for Web-Tjeneste kommunikasjon.

KONKLUSJON Denne studien illustrerer mulighetene en får ved å anvende tilpassningsdyktige og samhandlende systemer for å øke gjennomføringsgraden til brukerne innen IDPT. Med stadig økende bruk av inteligens og prediktive algoritmer for å kontrollere omgivelsene vil det i fremtiden være spennende og tidsriktig å videre undersøke hvordan en kan kombinere slike IoT teknologier med tilpassningsdyktige IDPT systemer.

Contents

Part I

OVERVIEW

The only thing that interferes with my learning is my education.

— Albert Einstein

CHAPTER 1

INTRODUCTION

Mental and neurological disorders have been affecting people globally [135, 136, 144], and these statistics reveal that these disorders have significant growth over time. Furthermore, the prevailing COVID-19 pandemic has profoundly remodelled people's lives globally, as the virus spread almost every continent with over 168,509,636 confirmed cases and 3,505,534 deaths as of early June 2021 [144]. As a measure for this pandemic, several types of lockdown measures are taken globally. Consequently, the pandemic resulted in social isolation, creating intensified stress, depression, and anxiety level [116]. Handling such stress, depression, anxiety, and other mental or neurological disorders can be economically, physically and emotionally challenging. Hence, there is a crucial need to investigate a possible solution for these mental health problems. One of the possible solutions to these challenges is to use the Internet to provide psychological treatments. The use of the Internet to deliver such psychological treatments is referred to as Internet-Delivered Psychological Treatments (IDPT) [4]. IDPT can accelerate mental healthcare treatments for people globally at a lower cost [32, 83]. This solution is justified as:

1. It relies on the globally available Internet and prevalent digital devices such as smart wearables, smartphones, tablets and computers;
2. There is evidence of increased user acceptance and adoption of Internet-delivered healthcare services [47];
3. It is an affordable, easily accessible and available form of treatments; and
4. It can be as effective as face-to-face treatments [9, 31, 97].

IDPT is built on evidence-based psychological treatment models, such as Cognitive Behavioral Therapy (CBT) [22], and are adjusted for online delivery through the Internet. Research statistics reveals IDPT as an effective therapeutic tools [107] with increase potential to provide evidence-based mental health interventions [32, 83]. However, the actual user adherence to such interventions is low [7, 18, 29, 34]. One of the main reasons for such low adherence is the treatment system's inability to adapt treatments according to the users need and preferences [18, 29, 34]. This inability means that current software systems are inadequate for creating reliable treatments for increasing user engagement and adherence. Lack of proper user adherence results in low treatment outcomes. Thus, there is an urgent need for better approaches to create adaptive IDPT systems that can enhance user engagements and user adherence. Hence, in this thesis, because of the advantages of model-driven engineering (MDE), our research idea is to apply MDE [121] to design and develop a data-driven adaptive system for psychological treatments. Model-driven engineering (MDE) techniques are an intriguing technique to create innovative adaptive treatment systems since it helps fulfil the gap between software requirement specifications and software implementation [39]. Moreover, the MDE approach assures to offer several benefits in improving quality by enforcing re-usability, portability by separation of application knowledge from implementation technology, productivity by automation of mapping, and maintainability by separation of concerns and consistency [24, 30]. Furthermore, adaptive interventions are motivating because people with different mental health problems require various screening, continuous monitoring, and treatment. So, it is crucial for the technological solution or adaptive technology to provide personalized screening methodologies and procedures. However, the uniqueness of mental health problems makes it difficult to successfully make technology that collaborates with human behaviour and creates positive outcomes.

OBJECTIVE: The study envisions improving public mental health with innovative technologies. The main objective of this thesis, to fulfil this vision, is to design, develop and evaluate an adaptive IDPT system that can adapt psychological interventions according to the users need, context, and preferences.

With the objectives mentioned above in mind, we used MDE, and Domain-Driven Design (DDD) [33] techniques to create a software framework for developing adaptive, interoperable and reusable IDPT systems. We refer to it as the *OpenIDPT Framework* (see Section 1.5.1). The framework facilitates designing and developing adaptive, interoperable and reusable IDPT systems. Such a framework is essential because it increases interoperability among healthcare systems. There is a lack the mutually understandable language to assess and articulate healthcare services [104]. The main reason is the availability of several healthcare systems and diverse digital health communities, including government stakeholders, technologists, clinicians, implementers, researchers, donors, health network operators, healthcare providers, and other associated stakeholders. Diverse healthcare communities differ in their opinion causing a variation in the software architecture of the healthcare systems, choice of technology, healthcare IT standards, communication protocols, and information architecture. Consequently, these healthcare systems form silos, making interoperability challenging to obtain. Therefore, a shared and standardized vocabulary is necessary to identify gaps and duplication, evaluate the effectiveness, and facilitate alignment across various digital health implementations. We aim to fulfil this gap by the software framework proposed in this thesis. The OpenIDPT Framework intends to provide a common understanding of the underlying models, reference architecture [76], and Open-source implementation by following a well-established software development process, DDD.

This chapter outlines the thesis's problem domain (Section 1.1), the main motivations (Section 1.2), research questions driving this study (Section 1.3), research approach (Section 1.4), results and contributions (Section 1.5), the thesis structure (Section 1.6), and definitions of the most frequently used terms in this thesis (Section 1.8).

1.1 Problem statements

According to WHO (World Health Organization), one out of four people in the world will be affected by mental or neurological disorders at some point in their lives. Around 450 million people currently suffer from such conditions [144]. Moreover, based on EU Green Papers [135, 136], one out of every four citizens is affected by mental health problems at some point during their lives and has often led to suicide. Also, about half of the Norwegian population may have experienced mental health problems during their life, and about one-third during one-year [126]. These statistics indicate the significant growth in mental health disorders. In addition, mental health disorders like depression are highly prevalent, and more than 300 million people of all ages suffer from depression [144]. Furthermore, according to a study by Mathers et al., depression is expected to run as the leading cause of disease burden both at an individual and at a societal level in high-income countries by 2030 [86].

While the prevalence of mental or neurological disorders is widespread over time, there is a lack of available resources to provide effective treatments to the people suffering from such morbidities. For instance, according to WHO [144], *although there are known, effective depression treatments, less than half of those affected in the world (fewer than 10% in many countries) receive such procedures due to long waiting lists, high treatment costs and social stigma [132] associated with the mental disorders.* The same report reveals that depression can lead to suicide, and close to 800,000 people die due to suicide every year.

The higher prevalence of mental or neurological disorders is a massive problem as dealing with such illness can be economically [12, 100], physically, and emotionally challenging. Current status reveals the immense pervasiveness of mental or neurological disorders on the one hand, and the prediction that these conditions will increase over time worsens the challenge on the other. Moreover, there is a lack of available resources to offer effective treatments to those affected patients. Hence, there is a need for new approaches that focus on providing cost effective and accessible services for far reaching patients.

The rising development seen in the use of Information and Communications Technology (ICT) and the adoption of Internet facilities among middle and low-income countries has allowed availing the healthcare facilities by paying lesser cost [47]. The Internet enables individuals to receive support and treatment for various health illnesses and disorders from multiple means. Technology provides a variety of promising approaches to mental health interventions. For example, training and supervision in several ways, including using emails, chat, and instant messaging to conduct therapeutic relationship [131]; using mobile phone communication for therapeutic intervention [46]; using forums to enhance client peer support [46]; using websites, blogs and Wikipedia for gaining mental health knowledge [46]; using the computer in Cognitive Behavioral therapy [46]; and using Virtual Reality (VR) in impression therapeutic use [46]. Despite this high prevalence of ICT systems and significant growth of mental health issues, clinical practice for standardized screening, assessment, and treatment of mental health problems remains deeply rooted almost exclusively on the opinion of individual clinicians [23].

The usage of IDPT systems is one of the methods that is becoming popular to provide online treatments. IDPT is built on evidence-based psychological treatment models, such as Cognitive Behavioral Therapy (CBT), and is adjusted for online delivery through the Internet. Despite its effectiveness [107], the actual user adherence is very low [7, 18, 29, 34]. These results raise a critical question about an IDPT system: *how can these IDPT be useful if the user adherence is sub-optimal?* To answer this question, it is relevant to focus on the *factors associated with enhancing user adherence towards the IDPT systems.* This thesis, therefore, asks, "*how can we adapt the psychological treatments to improve user adherence and hence increase the treatment outcomes in IDPT systems?*".

1.2 Motivation

The following are the primary motivations for studying, designing, developing and evaluating an adaptive IDPT system in this thesis:

- *Literature review reveals lack of adaptiveness in current IDPT systems*: We conducted a systematic literature review [98] intending to identify adaptive elements of IDPT systems, examine how these elements contribute to the adaptation process, analyse how adaptations influence the efficacy of IDPT on mental health treatments, and identify underlying Information Architecture (IA) (see Section 2.2). As several other literature studies reveal, we found out that adaptive IDPT can enhance intervention outcomes and increase user adherence. However, there is a lack of studies reporting design elements, adaptive elements, and adaptive strategies in IDPT systems. Hence, focused research on adaptive IDPT systems and clinical trials to assess their effectiveness are needed. An adaptive system behaves differently for different users. It means the adaptive system attempts to find the most relevant information based on a user's interests and presents the information in a correct format. The adaptive system's main aim is to predict exciting and relevant information for a specific user such that the user comprehends the presented information. *The underlying hypothesis is that if the user finds the presented information exciting and relevant, the user will adhere to the system, thus increasing user adherence and treatment outcomes.* For an adaptive system to predict relevant information for a user, it requires the specification of:

  1. What information can be presented (adaptive elements)?
  2. What type of information does the current user prefer and need (user profile)?
  3. How can the system know which content can be presented to which user (adaptive dimensions)?
  4. How can such relevant information be extracted (adaptive strategies)?

  The answers to these questions facilitate an adaptive system to predict the most relevant information for a specific user. Hence, a healthcare system needs to outline all these components to create adaptive treatments. The reference model in *the OpenIDPT Framework* outlines these adaptive elements, user profiling techniques, adaptive dimensions, and adaptive strategies. In addition, we discuss these components in our study [94, 97] and explain its impact in Chapter 4.

- *Heterogeneity of healthcare information*: Healthcare ICT technologies have substantial contributions to uplifting the quality of life and reducing socioeconomic burdens. Technology provides a variety of promising approaches to mental health and neurological practices, training, and supervision in several ways, including therapeutic intervention [46], and cognitive behavioural therapy (CBT) [22, 131]. Despite this high prevalence of ICT system in healthcare, the inadequate provision of interventions for preventing and treating mental or neurological problems has become a global challenge. This challenge is mainly due to a lack of standardization in data collection and data preparation methodologies and heterogeneity of the data [63]. These problems limit the sharing of data among various healthcare providers. The limitation in sharing health data is detrimental to patient care, provider satisfaction, and healthcare cost [53]. Moreover, providing access to and sharing health data have been shown to benefit and empower the patients [145]. The complexity of heterogeneity in data and restriction in sharing patient data have hindered standardization and interoperability in the healthcare industry [85].

- *IDPT systems assure higher treatment availability*: The attention and acceptance of the movement from desktop applications towards web-based and mobile-based applications are massive and increasing over time. Such movements are noticed in healthcare applications as well. Hence, the development of web or mobile-based interventions, which can be flexibly and inexpensively presented to a large population, is justified. Face-to-face treatments are constrained to resources availability, accessibility and affordability. On the contrary, IDPT systems are only dependent on Internet accessibility.

- *IDPT systems help reducing stigma issues related to mental health:* A mobile or web application can provide a virtual therapist in everyone's pocket and help overcome stigma. Such stigma towards neurological or mental disorders is one of the leading causes why some ethnic minority groups do not seek and adhere to clinical treatments [42]. People with different mental or neurological health problems require various types of screening, monitoring, and treatment. Based on the patients monitoring condition, the intervention should be adapted. Nevertheless, the current Internet-based treatment programs are not flexible enough to support such a treatment plan and support customisation based on patients' needs.

- *Technical feasibility of personalizing intervention based on patient need*: Higher computational resources are prevalent. Moreover, Internet-of-Things (IoT) can capture various biological markers data (heart rate, blood pressure, voice, Electro Dermal Activity (EDA), body temperature, eye movements, and others). Consequently, it is possible to use these higher computational resources to build complex Artificial Intelligence (AI)-based models that can adapt intervention based on the users' current context. Integration of these analytical and predictive models with smartphones and web-based applications are feasible.

In alignment with the thesis's goal, to offer personalized treatments for patients suffering from mental or neurological disorders and based on the motivations presented in this section, we formulate several research questions in the next section.

1.3 Research questions

This research aims to develop adaptive technology that we can use in clinical and home-based setup for personalized assessment, monitoring and treatment of mental health problems. In this section, we outline the main research questions associated with the research. The main research question related to this research is summarized below:

> *How can we optimize the Reference Architecture of Internet Delivered Psychological Treatment (IDPT) systems to develop adaptive, interoperable, reusable and personalized treatments for mental health problems?*

The main research question has been further spliced into three research questions, each of which is further divided into sub-questions.

RQ1: *What are the state-of-the-art works done in creating adaptive IDPT systems? What are their capabilities and limitations?*

- **1.1:** What are the main choices of Information Architecture (IA) in IDPT systems? What are the main rationales behind choosing such IA? Does the choice of pervasive IA affect user adherence?
- **1.2:** What are the primary adaptive elements used in the architecture of the state-of-the-art IDPT systems? How do these adaptive elements contribute to enhancing user adherence and intervention outcomes?
- **1.3:** What are the primary adaptive strategies used in state-of-art IDPT systems? Can these adaptive strategies increase the outcome of mental health interventions? What are the main dimensions of adaptive strategies used in IDPT systems?

RQ2: *How can we utilize software engineering techniques to improve the architecture of current adaptive IDPT systems?*

- **2.1:** How can we utilize the MDSE [121] technique to build a reference architecture (RA) and conceptual framework for adaptive IDPT systems?
- **2.2:** Can we use AI-based predictive algorithms to perform automated adaption on IDPT systems? What type of AI-based adaptive strategies can be used for IDPT systems?

RQ3: *How can we evaluate architecture of IDPT systems?*

3.1: How can we use Design Science Research (DSR) [56] principles for evaluating the developed architecture with respect to ISO/IEC 25000:2014 software quality evaluation metrics [65]?

3.2: How can we use the adaptive IDPT systems in a clinical setup?

Chapter 6 revisits these research questions and describes how his thesis addresses these questions. In brief, Table 6.1 outlines the corresponding research methods and results that address each of the research questions mentioned above.

1.4 Research approach

We outline the PhD setting (Section 1.4.1) and research approach (Section 1.4.2) in this section.

1.4.1 PhD setting and INTROMAT project

The INTROMAT (INtroducing personalized TReatment Of Mental health problems using Adaptive Technology, `https://intromat.no/`) project, funded by The Norwegian Research Council, envisions to improve public mental health with adaptive Information Communication Technology (ICT). The project aims to bridge the gap between disease and unmet needs by integrating innovative technologies and psychological treatments. The background for INTROMAT is the knowledge that 20-25% of adults will experience depression in the course of a lifespan. As many as 8% of adolescents have anxiety and depression. INTROMAT brings together ICT researchers, the ICT industries, health researchers, patients, clinicians, and patients next of kin to reach its goals. Haukeland University Hospital (`https://helse-bergen.no/`) is the project owner. The project attempts to overcome the following barriers seen in the treatment of mental health: *a) lack of recognition of ICT as an approach to health assessment and treatment; b) lack of knowledge about its impact on health; c) lack of integration with existing ICT systems; d) lack of user-friendly and engaging interfaces*; and e) *lack of innovative procurement arrangements*. To overcome these barriers, we at the INTROMAT project envision developing interactive and adaptive technology to map patients' treatment needs. The research presented in this dissertation has been conducted at the Department of Computing, Mathematics, and Physics at Western Norway University of Applied Sciences (HVL) as a part of the INTROMAT project.

1.4.2 Research approach

Figure 1.1 shows the research method's overview and associated activities underlying our study. This project is part of the INTROMAT Project (see Section 1.4.1). The project is inclined towards creating personalized treatments (*research objectives*) for patients suffering from mental and neurological disorders (*problem domain*) using adaptive technologies. Based on the project's problem domain and goals, we commenced investigating *state-of-the-art* works along with previous *systematic literature review, available system, previous studies*, and *past case studies*. Based on these investigations, we identified two primary gaps in the current IDPT systems, *lack of adaptiveness* and *less interoperability*. To fulfil these two gaps, we used software engineering theoretical foundation approaches to propose a conceptual framework, referred to as *the OpenIDPT Framework*. The OpenIDPT Framework incorporates a reference model, RA, IA, and open-source implementation. We developed a prototype referred to as an open-source adaptive IDPT system (OSAIS) based on the proposed RA. We incrementally created these artefacts (*reference model, RA, open-source framework, prototypes, and documentation*) by evaluating them using case studies, randomized control trials (RCTs) [114], Domain-Driven Design (DDD) methodologies, and publications. The case studies, RCTs, DDD methodology, and research article publications were based on software engineering theoretical foundations.

1.5 Results and contributions

This section outlines the main results of this thesis (Section 1.5.1) and the main contributions (Section 1.5.2).

1.5.1 *The OpenIDPT Framework*

As aforementioned, we proposed a software framework for adaptive, interoperable, and reusable Internet-Delivered Psychological Treatments (IDPT), referred to as *OpenIDPT Framework* (see Figure 1.2). We present the framework as the main result of this thesis. The OpenIDPT Framework includes:

1. The *reference model* (see Section 2.1.1) reveals the adaptive elements (what to adapt), adaptive dimensions (on what basis to adapt), and adaptive strategies (how to adapt) of an adaptive IDPT system . The proposed reference model is outlined in Section 4.3.

2. The *Reference Architecture* (see Section 2.1.2) unveils the consumer architecture, technical architecture, and quality attributes requirement architecture of an adaptive IDPT system. RA is appealing because it provides a shared understanding across multiple systems and provides guidance, architectural principles and practices for future implementations. The proposed RA is outlined in Section 4.4.

3. The *information architecture* supervises how to structure and organize the content for better discoverability and comprehensibility (see Section 2.2).

4. *User Interfaces* (UI) refers to space where users interact with the digital system. Well-designed interfaces help increase user interaction, hence increasing user engagement. The *database* (DB) layer includes the selection of a proper database. The *technology stack* layer involves selecting the appropriate technology for developing the IDPT systems.

5. To evaluate the proposed RA of adaptive IDPT systems, we implemented a prototype as an Open-Source Software. We refer to it as *Open-Source Adaptive IDPT System (OSAIS)* (see Section 4.5).

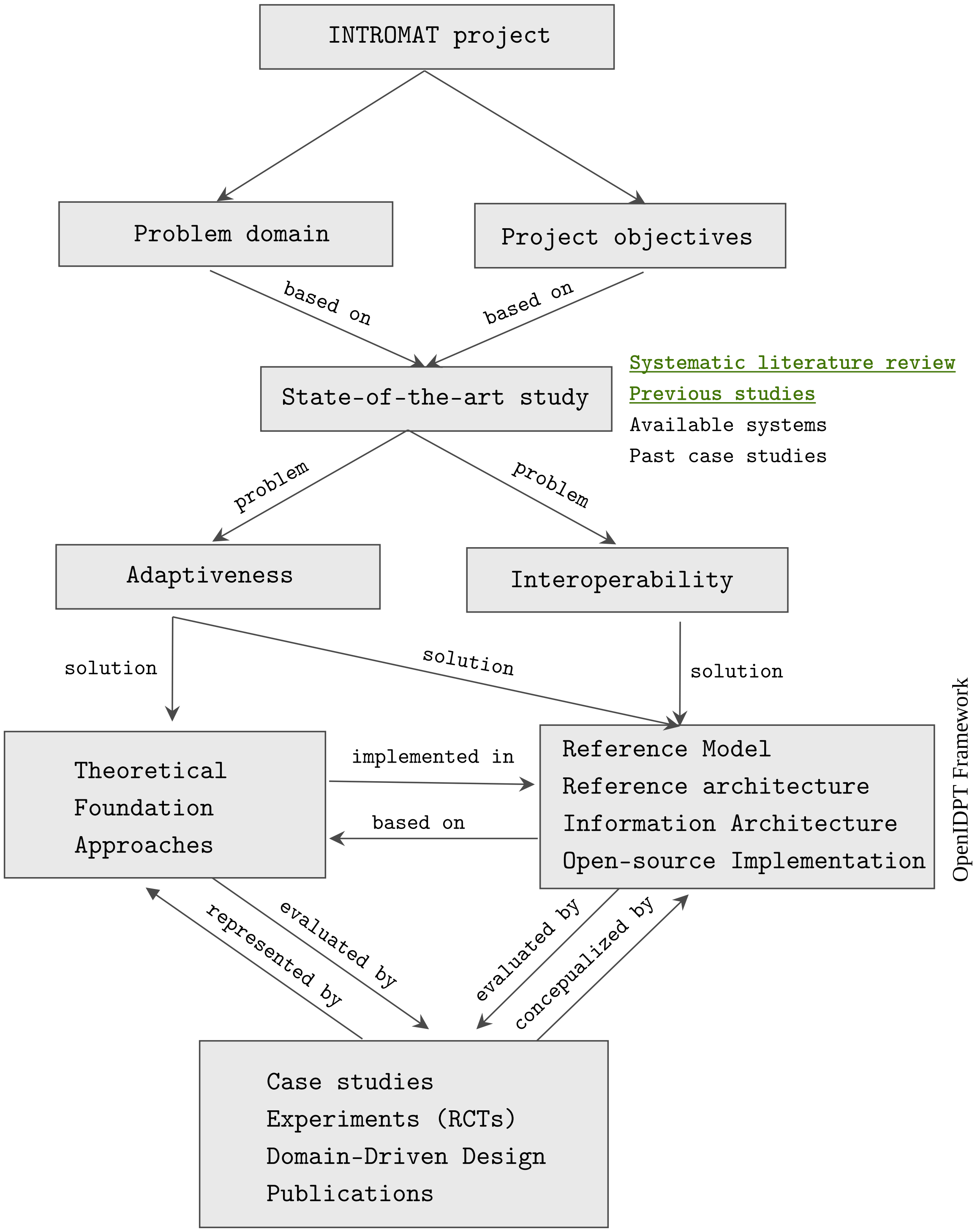

Fig. 1.1: Research method and activities

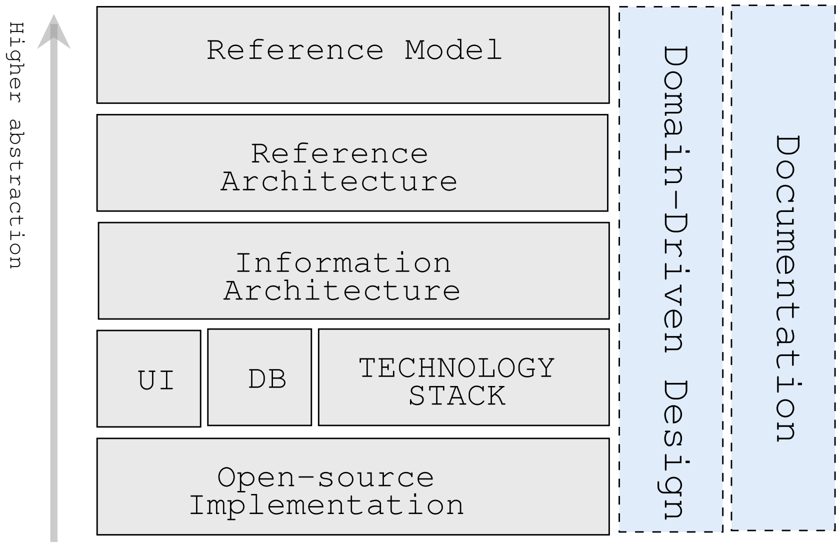

Fig. 1.2: The OpenIDPT Framework. The main contribution of the thesis is within the components of the OpenIDPT Framework (illustrated by the solid line).

6. The main contribution of the thesis is in the components of *the OpenIDPT Framework* (illustrated by the solid line). DDD is a software development process, and documentation is an essential secondary artefact produced during this study. Documentation refers to texts or illustrations (graphs, slides, videos, images) explaining how any software artefacts were produced, how to understand these artefacts, how to use them, and how we can extend these artefacts in future.

We used Design Science Research (DSR) evaluation methods to assess the efficacy of the proposed artefacts and their ability to address identified research gaps. The evaluation methods and their results are discussed in their corresponding sections. To evaluate interoperability, we created an open-source Resource Server (RS) based on GraphQL [38]. An RS is a web application that can read, write, update, and delete HL7 FHIR [49] resources. HL7 FHIR is standard (analogous to data structure) for healthcare data exchange. GraphQL is a data query (Data Query Language, DQL) and manipulation language (Data Manipulation Language, DML) for Web-Service (WS) communications. These prototypes are available for use and further development under the MIT license. All these artefacts are listed in Table 1.1.

Table 1.1: List of artefacts produced as the result of this research

Artefacts	Available at
Open-source IDPT	`https://github.com/sureshHARDIYA/idpt`
Depression2Vec	`https://github.com/sureshHARDIYA/phd-resources/`
Resource server	`https://github.com/sureshHARDIYA/intromat-fhir/`
Self-assessment app	`https://github.com/sureshHARDIYA/anxiety`
Authorization server	`https://github.com/sureshHARDIYA/authserver`
Web client	`https://github.com/sureshHARDIYA/fhir-client`
Documentation	`https://github.com/sureshHARDIYA/phd-resources`

1.5.2 Contributions

In Model-Driven Engineering, models are the primary engineering artefacts [124]. The proposed *the OpenIDPT Framework* incorporates several models, including reference model, reference architecture, information architecture. We present these models as the primary contribution of this thesis. Based on the proposed RA, we create a framework for building an adaptive IDPT system that defines primary adaptive elements, adaptive dimensions, information architecture and adaptive strategies. Moreover, to evaluate the RA and the proposed framework, we create an open-source implementation. Furthermore, we provide an architecture for obtaining interoperability among various healthcare providers. The architecture uses HL7 FHIR [49] and GraphQL [38] technologies that promote scalability, interoperability, and modifiability. All these contributions are documented and published in the form of research papers. In this section, we outline the list of research papers included in this thesis:

Paper A [98] This systematic literature review aimed to (1) inspect and identify the adaptive elements of IDPT systems, (2) examine how system adaptation influences the efficacy of IDPT on mental health treatments, and (3) identify the information architecture, adaptive dimensions, and strategies for implementing these interventions for mental illness. The result shows that the most common adaptive elements were *feedback messages* to patients from therapists and *intervention content*. However, how these elements contribute to the efficacy of IDPT in mental health were not reported. The most common information architecture used by studies was tunnel-based, although several studies did not report the choice of information architecture. Rule-based strategies were the most common adaptive strategies used by these studies.

Paper B [95] This paper presents a cloud-based interoperable architecture built on the top of Service-Oriented Architecture (SOA) for Internet-based treatment where patients can directly interact with underlying healthcare systems such as Electronic Health Records (EHRs). We also presented a prototype for screening and monitoring mental and neurological health morbidities based on this architecture. The proposed solution is based on the healthcare IT standards, HL7 FHIR, that enables healthcare providers to assess and monitor patients condition in a secure environment.

Paper C [96] In this paper, we exploit GraphQL and HL7 FHIR for Health Information Exchange (HIE), present an algorithm to map HL7 FHIR resources (see an example of HL7 FHIR resource in listing 2.1) to a GraphQL schema, and create a prototype implementation to compare it with a RESTful approach. Our experimental results indicate that Application Programming Interfaces (API) powered by GraphQL is cost-effective, scalable, and flexible for HIE. In addition, such APIs facilitate by enabling query capability (DQL) to both backend (data access layer, server) and frontend systems (presentation layer, client).

Paper D [97] This paper proposes a model that shows how adaptive systems are represented in classical control theory and discuss how the model can be used to specify adaptive IDPT systems. Concerning the reference model, we outline the core components of adaptive IDPT systems, the main adaptive elements, dimensions of adaptiveness, information architecture applied to adaptive systems, and strategies used in the adaptation process. We also provide comprehensive guidelines on developing an adaptive IDPT system based on the Person-Based Approach (PBA) [13]. The PBA is a development methodology explicitly designed to create digital mental health interventions. This method is based on user-centred design, particularly behavioural analysis and in-depth qualitative research.

Paper E [91] This study's primary objective is to present an adaptive strategy based on Natural Language Processing (NLP) techniques that analyze patient-authored text data and extract depression symptoms based on a clinically established assessment questionnaire, PHQ-9 [75]. Patient Health Questionnaire (PHQ-9) is a psychometric questionnaire made for diagnoses of depression and other mental disorders commonly used in primary care. To extract depression symptoms, we propose a novel word-embedding (Depression2Vec) to extract depression symptoms from patient-authored text data and compare it with three state-of-the-art NLP techniques. We also present an adaptive IDPT system that uses the proposed depression symptoms detection technique to adapt mental health interventions. Our results indicate that the performance of the proposed embedding Depression2Vec is comparable to WordNet. However, in some cases, the former outperforms the latter concerning extracting depression symptoms from the patient-authored text.

Paper F [94] This paper presents a *Reference Architecture* (RA) that supports flexible user modelling and adaptive delivery of treatments. To evaluate the proposed RA, we developed an open-source framework based on the proposed reference architecture. The open-source framework aims to a) improve the development productivity, b) facilitate communication with domain experts, and c) facilitate to obtain interoperability. We followed Domain-Driven Design (DDD) to implement a prototype of the open-source framework and evaluate it using empirical (case study) and non-empirical approaches (SAAM method [71], expert evaluation, and software quality attributes). This paper presents an initial study, and the preliminary results show that the developers and the researchers can implement and tailor the proposed RA for multiple healthcare interventions.

Paper G [93] This paper is an extended version of the ICTH Paper C and shows how the architecture is implemented to achieve interoperability between two running heterogeneous EHRs, based on HL7 FHIR and OpenMRS. Heterogeneity in data representation and care processes create interoperability complexity among Electronic Health Record systems (EHRs). We can resolve such data and process level heterogeneities by following consistent healthcare IT standards like Clinical Document Architecture (CDA) [58], and HL7 FHIR. However, these standards also differ at the structural and implementation level, making the interoperability complex. Hence, there is a need to resolve data level heterogeneity to achieve semantic data interoperability between heterogeneous systems. The presented approach establishes secure communication between heterogeneous EHRs and provides accurate mappings that enable timely health information exchange.

This section outlined an overview of the contributions made during this PhD studies. We discuss a detailed description of these contributions and how they impact the knowledge base of software engineering and health informatics in Chapter 6.

1.6 Structure of the thesis

This thesis consists of two parts. Part I contains a summary of literature review, research approaches, results and evaluations. This part finishes with conclusions and directions for future works. Part II contains the research papers A-G published during this study and are listed in Table 1.2. The published articles provide detailed descriptions of the activities and results summarized in the first part.

Table 1.2: List of publications included in Part II. (The ∗ marked publications has been submitted and are under review.)

Paper	Year	Venue	Main objective
Paper A	2020	JMIR [98]	Systematic literature review about adaptive elements
Paper B	2018	SEH [95]	Adaptive architecture and interoperability
Paper C	2018	ICTH [96]	Interoperability
Paper D	2019	IEEE Access [97]	Reference model and adaptive IDPT system
Paper E	2019	CBMS [91]	Adaptive strategy based on NLP
Paper F*	2021	JMIR [94]	Reference architecture for adaptive IDPT system
Paper G*	2021	SAGE [93]	Interoperability in heterogeneous system

Part I of the thesis consists of chapters that introduce the main research problem domain, background, literature review, essence of adaptiveness, interoperability, discussion, and conclusion. We outline the summary of each of these chapters below:

Chapter 1: Introduction This chapter outlines the thesis's problem statement, motivations behind selecting this problem domain, research questions aligned to solve the problem domain, the goals of the project, research approach, results, structure of the thesis, and a brief overview of terminologies used in this thesis.

Chapter 2: Background This chapter describes the theoretical backgrounds behind the adaptive system and interoperability. To provide background knowledge for reference architecture (RA), we also outline aspects of software architecture, including architectural quality attributes, architectural styles, architectural patterns, architectural principles, architecture design process and architecture documents.

Chapter 3: Literature review This chapter reflects on the process and results of the systematic literature review that we carried out to identify adaptive elements, IA, adaptive dimensions, and adaptive strategies in the current literature. The systematic literature review [98] establishes the basis for this chapter and can be found in Part II of this thesis.

Chapter 4: Adaptiveness This chapter summarises the concept of an adaptive system, its components, adaptive strategies, and the essence of user profiling in an adaptive system. Moreover, the chapter reflects on the work done on creating adaptive

IDPT system and how it fits in software architecture's context. The research papers B [95], D [97], E [91], F [94] establishes the basis for this chapter and can be found in Part II of this thesis.

Chapter 5: Interoperability This chapter summarises the interoperability concept in healthcare systems, its essence, and different approaches. Additionally, we discuss the interoperability work done during this study. The research papers B [95], C [96], and G [93] establishes the basis for this chapter and can be found in Part II of this thesis.

Chapter 6: Conclusion and future work This chapter re-visits our research questions and provides a summary of the main contributions. Furthermore, we also outline several implications and future research directions of the work undertaken for this thesis.

1.7 Supplementary materials

All the prototypes, tools, models, presentations, and documentations created during this thesis can be found on GitHub [90]. In addition to the articles listed in Table 1.2, two additional papers have been published that act as supplementary resources for the thesis:

[92] S.K. Mukhiya, A. Aminifar, F. Rabbi, K. I Pun, and Y. Lamo. Artificial Intelligence in Mental Health. Bentham Science Publishers LTD., pages 13–34, 2021.

This chapter provides an overview of recent AI applications for screening, detecting, and treating mental health problems; summarize the economic and social implications; present a systematic overview of which AI technologies are used for the various mental disorders and identify challenges for further development. We identify some future research questions that we can solve using AI in mental healthcare. The chapter concludes with an in-depth discussion of the critical challenges of applying AI in mental health interventions.

[2] U. Ahmed, S.K. Mukhiya, J. C. W. Lin, G. Srivastava, & Y. Lamo. (2021). Attention-based Deep Entropy Active Learning using Lexical Algorithm for Mental Health Treatment. Frontiers in Psychology, 12, 471. https://doi.org/10.3389/FPSYG.2021.642347.

This paper is an extension of Paper E [91]. This paper proposes attention-based deep entropy active learning using a lexical algorithm to detect depression symptoms from the patient-authored text. The objective of this research is to increase the trainable instances using a semantic clustering mechanism. Our method helps to reduce data annotation tasks and helps in the generalization of the learning system. The proposed framework achieved a better result indicating the synonym expansion semantic vectors help enhance training accuracy while not harming the results.

The papers [2, 92] are not formally part of this thesis and will not be discussed further.

1.8 Terminologies

This thesis uses the following software engineering terminologies in various chapters and papers. We assume the readers require to comprehend these terminologies to understand the thesis. We are aware that some of these terminologies definitions are opinionated based on the researchers, software developers, and other software practitioners' experience, knowledge, and background. To understand the findings and knowledge presented in this thesis, the following terms, if used in this document, should be interpreted as the definitions given below:

architecture : The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution [60].

reference architecture : According to RUP (Rational Unified Process) [76], a Reference Architecture is, in essence, a predefined architectural pattern, or set of patterns, possible partially or completely instantiated, designed, and proven for use, in particular, business and technical contexts, together with supporting artifacts to enable their use. Often, these artifacts are harvested from previous projects [21].

information architecture : In the context of a web application, information architecture describes the overall conceptual models and general designs used to plan, structure, and assemble a site. Every web application has an information architecture and primary aims are to a) organize the site content into taxonomies and hierarchies of information; b) communicate conceptual overviews and the overall site organization to the design team and clients; c) research and design core site navigation; d) set standards and specifications for the handling of HTML semantic markup[1] and the format and handling of text content, and e) design and implement search optimization standards and strategies.

adaptive system : An adaptive system behaves differently for different users based on different contexts.

IDPT : Internet-Delivered Psychological Treatments (IDPT) are based on evidence-based psychological treatments or therapies. It is also referred to as *digital therapy, online therapies, cognitive behavioural therapy, psychological treatments, treatments, interventions, digital interventions*, and others.

IDPT system : Internet-Delivered Psychological Treatment (IDPT) systems are software applications that offer psychological treatments through the Internet. Several terms are used in research to refer to IDPT systems, for example, *web-based treatments, web-based interventions, online treatments, computerized psychotherapy, e-therapy, Internet-based cognitive behavioural therapy (ICBT or iCBT), digital interventions, internet-based interventions, online interventions, web-application based psychotherapy treatments, therapeutic web-based interventions, eHealth interventions*, and *others*.

[1]https://developer.mozilla.org/en-US/docs/Glossary/Semantics

IDPT Framework : The IDPT Framework, referred to as the OpenIDPT Framework, is an abstraction that provides a standard way to build and deploy adaptive, interoperable, and reusable IDPT systems.

personalisation : It refers to instruction that is paced to the users' learning needs, preferences, and the specific interests.

customisation : Customisation is the action by a user of modifying something to suit a particular individual need or task. It puts control in the users' hand by explicitly allowing users to choose what kind of content or features they want to see. A customised system enables users to make changes to their experience by tweaking the content they see or work.

user profile : A user profile is associated with personal data related to a specific user. It is an accurate digital description of a person's characteristics. For example, a user profile may contain demographic data such as age, gender, occupation, nationality, income, residence, and family status.

user profiling : A user model refers to a data structure that captures the specific features of a particular user. The process of assembling and managing a user profile is referred to as user modelling or profiling.

Authorization server : It is an application server that performs both authentication (permits users to access resources) and authorisation (confirms the identity of a user).

Open Healthcare IT standards : These are a set of agreed-upon representations of data and methods for communication between Healthcare Information Systems (HIS). These standards incorporate agreement for security, data transportation, data format, and the used terminologies' meanings. Examples include HL7-FHIR and OpenEHR.

HL7 FHIR : HL7 FHIR is a Open Healthcare IT Standards for healthcare data exchange published by the HL7 organization (see an example of HL7 FHIR resource in listing 2.1). Besides HL7 FHIR, other interoperability standards exist, such as Clinical Document Architecture (CDA) [58], OpenEHR [103], SNOMED-CT and LOINC. Note that OpenEHR is a healthcare IT standard similar to HL7 FHIR, but OpenMRS [62] is an open-source Electronic Medical Record EMR systems.

Resource server : A resource server is a web application server built to CRUD (Create, Read, Update, Delete) HL7 FHIR resources.

frontend and backend Software engineering uses the term frontend and back end to indicate the separation of concerns (SoC) between the presentation layer (referred to as a front end) and the data access layer (referred to as a back end) in software. In the client-server architecture, the client is usually regarded as the front end. The server is usually regarded as the back end.

If builders built buildings the way programmers wrote programs, then the first woodpecker that came along would destroy civilization.

— Gerald Weinberg

CHAPTER 2

BACKGROUND

This chapter provides background information on Software Architecture (SA) and Information Architecture (IA) concepts. We present software models as the primary artefacts of this research study. To comprehend the ideology presented by these software models, we use terms related to software, software development processes, software architecture, information architecture, and its offshoots. Literature reveals contradictory definitions and interpretations of software architecture and information architecture. Hence, to provide the theoretical background required to comprehend these terms when reading this thesis, we have chosen to provide detailed discussions on software architecture and its associated topics.

Software architecture describes high-level concepts of software systems. For example, SA provides answers to questions like *How many tiers should this software system have? How should one split the system into interoperable components? How should these components be organized, structured and interact with each other? What are the functionalities of each of these components? Which web services should this software use to communicate?* And many more. We outline topics associated with SA in Section 2.1. Contrary to SA, **Information Architecture** pertains to the high-level software system concepts observed by a user. For example, in an IDPT system, the IA provides answers to questions like *how should we structure, organize, and divide content? How do we present this information? Where should we place the navigation system? Does end-users require search components? How can end-users navigate from one page to another,* and many more. We outline topics associated with IA in Section 2.2.

2.1 Software architecture

In programming, machine code comprises *machine instructions*. A *machine instruction* is a low-level programming language that can directly control the Central Processing Unit (CPU) of a computer. A *computer program* is a collection of such machine instructions. A collection of such computer programs, related data, rules and associated libraries is called *software*. Such software has an intended purpose (*functionality*), core structure (*architecture*), and exhibits other characteristics such as *efficiency*, *reliability*, *usability*, *maintainability*, and *portability* [65]. These characteristics are referred to as **software quality attributes** (see Section 2.1.5.1). A *software system* refers to a system of intercommunicating components based on software that forms a part of a computer system (both hardware and software). The core structures of such a software system and the discipline of generating such fundamental structures are referred to as *software architecture*. In general, software architecture defines the software elements, the relationships among these elements, and the properties of both elements and relations [20]. Such software development involves a process, often referred to as the Software Development Life Cycle (SDLC) [118] that requires planning, analysis, design, implementation, and maintenance (see Section 2.1.4). Besides, the software is referred to in terms of its architecture, reference architecture, patterns, anti-patterns, smells, and style. The next section establishes the relationship between these terms and how they are associated with the software. Figure 2.1 is adapted from [6, 115] and depicts the relationship between reference architecture, software architecture, architectural pattern, architectural style, and reference model.

2.1.1 Reference model

A reference model contains components grouped by their functional requirements and data flow between these components. For example, models of an interpreter, compiler or database management systems (DBMS) are reference models. The reference model helps in domain modelling, where we outline entities and the relationship between these entities. Reference models are independent of implementations, technologies, protocols, and other specific details [81]. These models facilitate the formation of RA, as we can use the entities in the reference models and map them into RA components [6]. An example reference model of an adaptive IDPT system is presented in Section 4.3.

2.1.2 Reference architecture

Several definitions of reference architecture exist. We use the term RA, according to RUP (Rational Unified Process)'s definition. *It outlines, a RA is a predefined architectural pattern or set of patterns, possible partially or fully instantiated, designed, and validated for use, in particular, business and technical contexts, mutually with supporting artefacts to enable their use.* Often, these artefacts are harvested from previous projects [21]. Several researchers supported this concept [21, 109]. The primary objective of RA is to guide future developments and implementations. As depicted in Figure 2.1, a RA is a reference model mapped onto software components and the data flow within these components. An example RA of an adaptive IDPT system is presented in Section 4.4.

Why RA is essential? RA aims to facilitate a shared understanding across multiple systems, enterprises, and disciplines about the current architecture and future directions. Proven reference models and architectures of past and exiting systems are transformed into RA with a common objective of providing guidelines for future implementations. Furthermore, RA is essential in psychological treatments context as:

- RA provides a common lexicon, taxonomy, architectural vision, modularization, and the complementary context around a domain. Such a common lexicon, taxonomy, and architectural visions form the basis for realizing interoperability among healthcare systems.

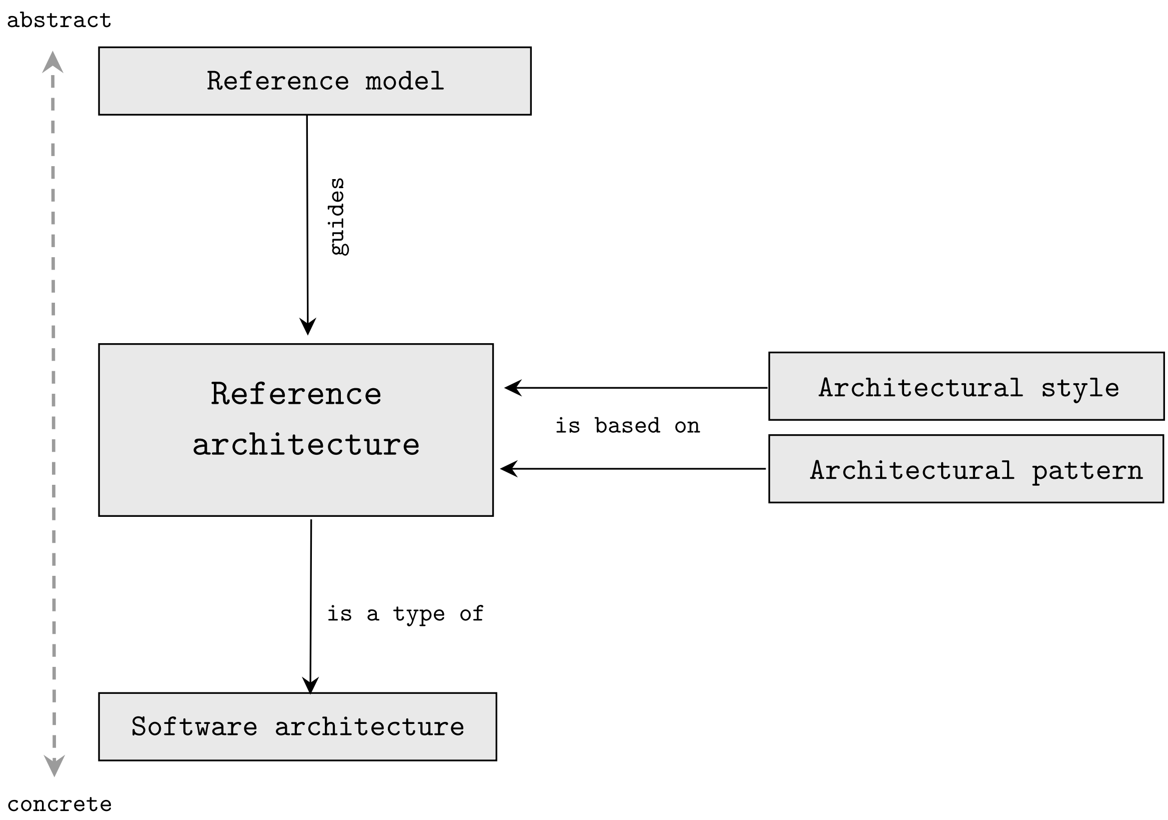

Fig. 2.1: The diagram depicts the relationship between reference architecture, software architecture, architectural pattern, architectural style, and reference model. The figure is adapted from [6] (Figure 2.2 in Second Edition) and from [115].

- As aforementioned, RA provides guidance, architectural principles and practices that forms the baseline for future implementations. Moreover, as depicted in Figure 2.1, RA is a way to document architectural patterns and architectural styles. These patterns and styles are closely related to creating software design. RA is an abstract representation of the entire system, and several instantiation steps of RA transforms into a tangible system.

- RA provides modularization and complementary contexts. These contexts help discover reusable components in the system, thus facilitating the separation of concerns (SoC software architecture principles).

- RA provides synergy from a business context, consumer context and a technical context. These contexts form the basis for the managerial decision-making process, software planning, and future development analysis.

2.1.3 *Architecture patterns and architectural style*

There are contradictory definitions and interpretations of architecture style and architecture patterns [35]. Several literature studies mention that architecture style and architectural patterns are synonym [89]. However, some studies take architecture pattern as a mechanism to implement architectural style. That is to indicate that the architectural style is on a higher abstraction level than the architecture patterns. Bass et al. [6] define architecture style as a *"specialisation of elements and relation types, together with a collection of constraints on how we can use these elements"*. Like this, Clements et al. [20] define an architecture style that outlines the architecture design based on a particular style that may or may not be helpful. An *architectural pattern* outlines a system's components, the relationship between them, and constraints specifying their usage. An architectural pattern is associated with the software quality attributes. Architectural pattern outlines a design of an architecture based on the problem and the context. Architectural patterns are one of the methods to document reference architectures. That being said, our aim is not to critically review the difference between architecture style and pattern. Hence, this section presents a list of both architecture patterns and style used in this study.

Several kinds of architectural patterns and architectural style exist [113]. However, we only mention those relevant to this thesis (see Figure 2.2), including *n-tier architecture, REST, layered architecture, Service-Oriented Architecture (SOA), microservice architecture*, and *monolithic architecture*. As depicted in Figure 2.2, architectural styles and patterns can be grouped into four distinct classes a) for communication purpose (microservice architecture, SOA architecture, REST), b) for deployment (client-server, n-tier architecture), c) for domain definitions or modelling (monolithic architecture, domain modelling), and d) for structuring system (layered architecture, component-based, object-oriented, plugins, and MVC pattern). Below we briefly define the architectural styles and patterns relevant for this thesis:

1. **Client-server architecture**: It is a software architecture that facilitates the separation of application functions into client and server [102]. We use the term client-server architecture in the context of the World Wide Web (WWW). A client is a system that can request resources or services from another system, referred to as a server. For example, in a World Wide Web (WWW)[1], a client requests a resource using Hypertext Transfer Protocol (HTTP), and the server replies with an HTTP response.

2. **REST pattern**: Representation state transfer (REST) [37] is the most commonly used web service (WS). A web service (WS) refers to:

   - a service provided by devices to interact with each other using WWW, or
   - service offered by a server running on a computer system, listening for requests at a particular port over a network.

   Web technology such as HyperText Transfer Protocol (HTTP) is used in Web services to send responses using file formats such as Extensible Markup Language (XML) and JavaScript Object Notation (JSON). Traditionally, there are two WS-protocols: Simple Object Access Protocol (*SOAP*) [141] and *REST* [37]. The SOAP protocol requires specification of all available methods, including input and out data structures in a schema. In contrast, the REST uses information encoded in the Uniform Resource Locator (`URL`) and `HTTP` method to describe the service

[1] https://www.w3.org/

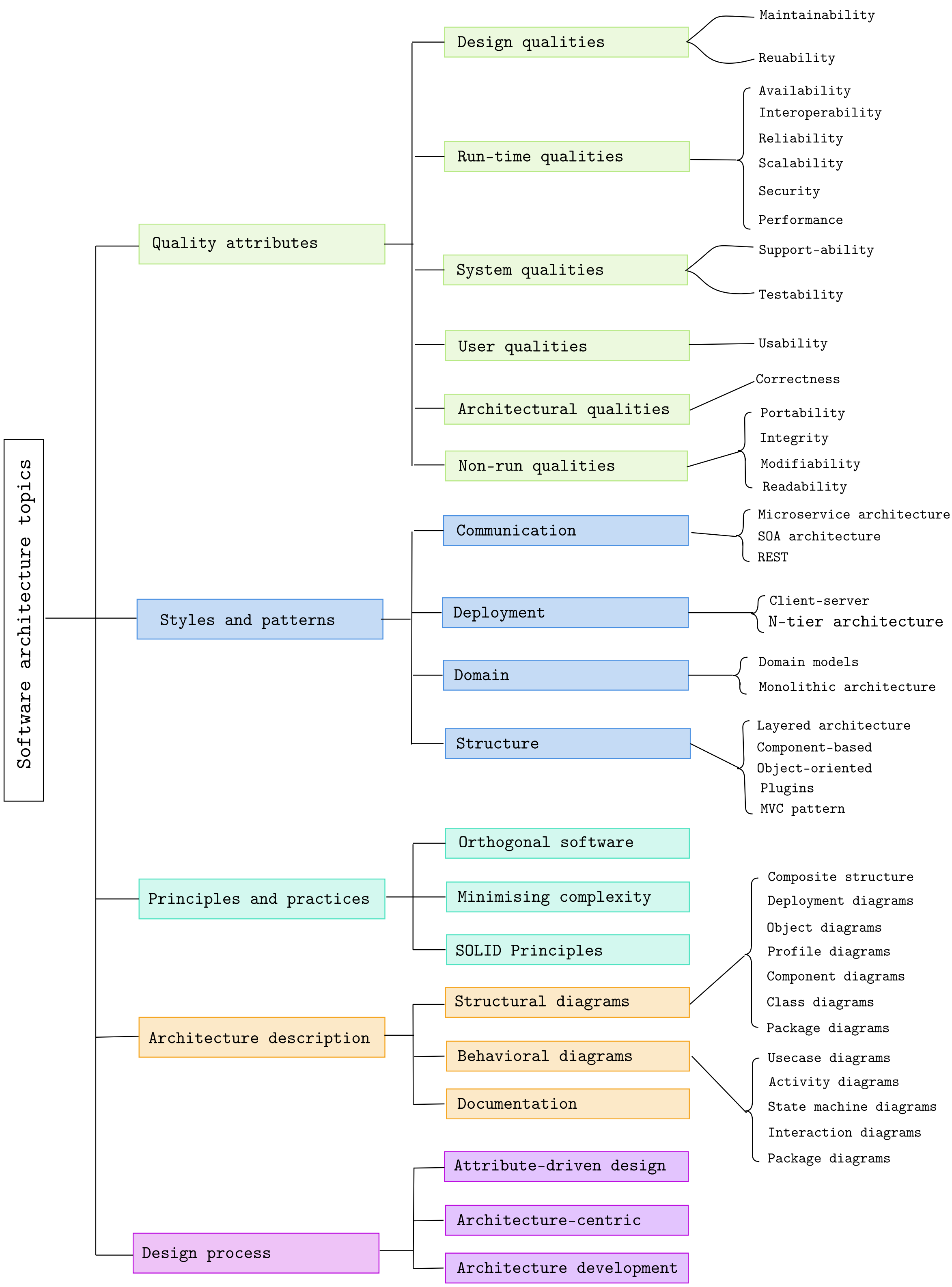

Fig. 2.2: The figure outlines the main topics associated with software architecture. We only outline the topics that are relevant to this study.

interface. The main disadvantage of SOAP is seen in its complexity and the overhead imposed through the explicit schema [129]. REST, on the other hand, is more lightweight and relies on the developer discipline.

3. **Layered architecture**: As its name says, the layered architecture style in which components of a system are separated to form different layers. For example, in an Object-Oriented Design (OOD), a system is layered into a presentation layer, application layer, business layer and data-access layer. The primary objective of this architectural style is to enhance modifiability, portability, and reusability. Hence, we can use this architectural style if an application has layers that multiple other applications can share. The layered style is described in [6, 14, 20].

4. **SOA**: It is an architectural style. SOA facilitates communication between distributed services. The distributed services have their own technical and business context and are under the administration of diverse owners. Each service providers (building blocks) act as one of the following three roles [81]: a) service provider, b) service broker, service registry or service repository (facilitates by providing information regarding the web services available to consumer), and c) service requester/consumer. Standardized Service Contract (SSC) governs the service agreements between the providers and the consumers [28]. Next, we outline some of the core benefits and characteristics of SOA architecture:

   - SOA enhances interoperability between distributed information system [59, 95–97].
   - It offers reliable services as separate providers are responsible for services. Each provider releases service descriptions. We can acknowledge the performance and behaviour of the entire SOA solution by studying these service-level descriptions [137].
   - It reduces the consequence of modifications and failures as the components are loosely coupled. For example, in a healthcare system, modification in an authorization server does not impact on intervention CMS system.
   - It facilitates horizontal scalability. It means that newer systems can be appended to the architecture. Vertical scalability is achieved in the coordination of service agreements between service providers.
   - It enhances the reusability of resources [59]. This architectural style reduces development time by distributing services to other providers. Besides, reinvention of system or services is not always justified. We can use existing systems, codebase, libraries and solutions.
   - It improves data and service duplication issues [59]. Companies working in their silo structures lead to data and service duplication. SOA has characteristics to address this intricacy. The reason is partially its ability to distribute services among different providers.

5. **Microservice architecture**: Microservice architectural style built on the top of SOA and follows the same principles. However, unlike SOA, microservices incorporate smaller services [66]. These smaller services are modelled around a

business domain and are functionalized to support business goals. Microservice architecture is claimed to offer maintainability and scalability. Large services are split into two or more atomic services. Further, since each service operates independently, it offers flexibility.

Several developers and development communities outlines microservice as a re-branded version of SOA [59, 87, 129]. SOA failed to gain adoption a decade before due to several technological constraints. However, development is seen in technology ecosystems such as *container-based deployment and cloud computing* (AWS, Azure, Kubernetes, and others), *adoption of the agile solution* by several organizations, *DevOps with Continuous Integration/Continuous Deployment* (CI/CD), *async programming* (IO block, parallel, distributed call) support as first-class constructs in several languages (for example JavaScript, TypeScript, C# and others), the *popularity of n-tier architecture*, and other factors. Since technology ecosystems have advanced, the adoption of distributed services has been adopted. Consequently, a re-branded version of SOA referred to as microservice architecture, has evolved. This architectural style has been criticized for being an immature approach, lack of development approaches, and not being to date. Consequently, it results in higher development errors leading to higher development costs [16]. The Microservice community offers several measures to handle these complexities; however, there is no empirical evidence of one's superiority over another.

2.1.4 Software Development Process

As SDLC process, we followed the Domain-Driven Design (DDD) approach to plan, design, analyze and implement adaptive IDPT system. The DDD principle advocates that it is essential to comprehend any problem before creating a solution. An inadequate and distorted understanding of the problem results in a faulty and non-useful solution. Hence, the development team responsible for the development of the software must understand the problem domain. However, the obvious question is, *how can we ensure that the development team do understand the problem?* Traditional software development approaches attempts to address this problem by creating Software Requirement Specifications (SRS) documents (see Figure 2.3(a)) that outlines what the software will do and how it will be expected to perform. There are two significant issues associate with it: a) domain experts lack understanding of which part of the domain is significant for software development, b) it often creates distance between the people who understand the problem domain and the development team. When transcribing domain experts understanding of the problem in the SRS document, a minor mismatch between their understanding can create sophisticated complexity. An improvised solution is to eliminate the intermediaries and encourage domain experts to be involved directly with the development team (see Figure 2.3(b)). There is an iterative feedback loop between the development team and the domain experts in such an approach. The development team regularly delivers something to the domain expert and corrects any misunderstanding in the next iteration. Such a development approach forms the core of the agile development process. However, even in this approach, the developers translate the domain experts' mental model into code, and the translation process can result in distortion and loss of essential details. Such distortion is problematic, especially for future developers, as the code does not correspond to the concept in the domain. The third approach is involving the domain expert, development team, and other stakeholders to share the same mental model (see Figure 2.3(c)). This approach is the primary objective of Domain-Driven Design (DDD) [33]. The primary goal of DDD is to design software around a realistic domain model(s). However, DDD is not appropriate for all software development, of course. It is helpful for business and enterprise software applications where software development teams have to collaborate with non-technical teams.

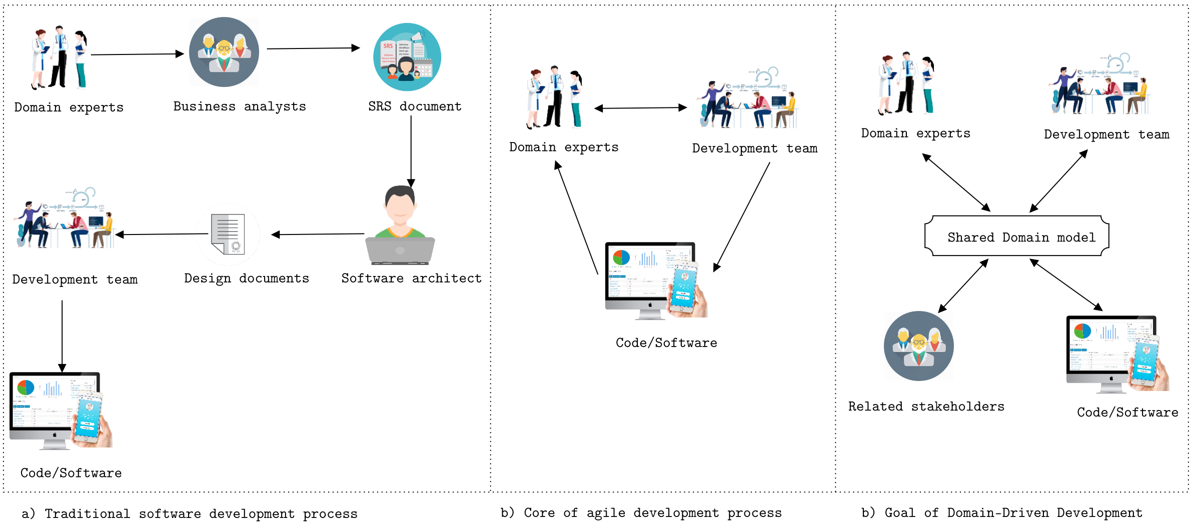

Fig. 2.3: Comparison between traditional software development approach, agile development approach and DDD approach

2.1.5 *Architecture topics*

This thesis uses several other terms (see Figure 2.2) related to software architecture, including software quality attributes (see Section 2.1.5.1), architectural principles and practices (see Section 2.1.5.2), architecture design process (see Section 2.1.5.3), and architecture documents (see Section 2.1.5.4). In this section, we outline these topics and discuss their significance.

2.1.5.1 *Quality attributes*

We have been using the term software quality attributes [65] in this thesis and in the included research papers. A quality attribute (QA) "*is a measurable or testable property of a system used to indicate how well the system satisfies its stakeholder's need*" [6]. When designing any system's architecture, we include functional requirements (must have functions), quality attribute requirements, and constraints. As depicted in Figure 2.2, these quality attributes can be grouped based on their capabilities: a) *design qualities* (maintainability, reusability), b) *run-time qualities* (availability, interoperability, reliability, scalability, security, performance), c) *system qualities* (support-ability, testability), d) *user qualities* (usability), e) *architectural qualities* (correctness, completeness), and f) *non-run-time* *qualities* (portability, integrity, modifiability, readability). As outlined in the research questions in Chapter 1, our primary software quality attributes requirements are adaptability and interoperability. Hence, we outline these two briefly here. Several studies [6, 14, 20, 89, 113] outlines other quality attributes and discuss how they can be measured in detail. Hence we do not discuss these here. We use these software quality attributes to evaluate and test our architecture, reference model and reference architecture.

Adaptability : Adaptability is the degree to which a software system changes its behaviour according to change in its environment [97]. Several studies impose its significance in software systems [97, 130]. Adaptability influences other software quality attributes such as performance, reliability, and maintainability. We discuss the reference model and RA of an adaptive system in our study [97], and outline the research approach, findings in Chapter 4.

Interoperability : The term *interoperability* has a subjective interpretation based on people context and experience [55]. We use the term in context to the definition provided by the IEEE 1990 as:

> *Interoperability is achieved when two or more systems or the systems' components can interchange data/information and utilise the data/information being interchanged. (IEEE 1990) [43].*

The definition incorporates both the *technical interoperability*, that is, the interchange of information and *semantic interoperability* which is the ability to utilise the information being interchanged. In addition to this technical and semantic interoperability, Tolk and Muguira proposed seven interoperability layers (see Table 2.1), including no interoperability, technical interoperability, syntactic interoperability, semantic interoperability, pragmatic interoperability, dynamic interoperability, and finally, conceptual interoperability [142]. Gibbons et al. introduced *clinical interoperability* [44], which refers to the actual usage of information in the clinical process workflow.

Table 2.1: The table outlines different levels of interoperability adopted from the study [142].

Levels	Name	Description
Level 0	No interoperability	No communication
Level 1	Technical	Create technical communication and exchange data between systems
Level 2	Syntatic	Successful communication with agreed protocol, without understanding the meaning of the data being exchanged
Level 3	Semantic	Communicate correctly and understand data being exchanged
Level 4	Pragmatic	Communicate being aware of context and meaning of information being exchanged
Level 5	Dynamic	Communicating systems can re-orient information, and dynamically consume the changes to the meaning as a change of context
Level 6	Conceptual	Systems are completely aware of each other, processes, context and assumptions

In this study, we mainly focus on achieving technical interoperability (by following HL7 FHIR (an example HL7 FHIR resource is provided in listing 2.1) and GraphQL) and semantic interoperability (by following `SNOMED CT`, and `LOINC`). We discuss our research approach, results on interoperability in Chapter 5.

```
{
  "resourceType" : "Patient",
  "identifier" : [{ Identifier }], // An identifier for this patient
  "active" : <boolean>, // Whether this patient's record is in active use
  "name" : [{ HumanName }], // A name associated with the patient
  "telecom" : [{ ContactPoint }], // A contact detail for the individual
  "gender" : "<code>", // male | female | other | unknown
  "birthDate" : "<date>",
  "deceasedBoolean" : <boolean>,
  "deceasedDateTime" : "<dateTime>",
  "address" : [{ Address }],
  "maritalStatus" : { CodeableConcept },
  "multipleBirthBoolean" : <boolean>,
  "multipleBirthInteger" : <integer>,
  "photo" : [{ Attachment }], // Image of the patient
  "contact" : [{
    "relationship" : [{ CodeableConcept }], // The kind of relationship
    "name" : { HumanName }, // A name associated with the contact person
    "telecom" : [{ ContactPoint }], // A contact detail for the person
    "address" : { Address }, // Address for the contact person
    "gender" : "<code>", // male | female | other | unknown
    "organization" : { Reference(Organization) },
    "period" : { Period }
  }],
  "communication" : [{
    "language" : { CodeableConcept },
    "preferred" : <boolean>
  }],
  "generalPractitioner" : [{ Reference(Organization|Practitioner|PractitionerRole)
    }],
  "managingOrganization" : { Reference(Organization) },
}
```

Listing 2.1: An example of an HL7 FHIR Resource in JSON format illustrating how to represent a **Patient**

2.1.5.2 *Architecture principles and practices*

The software development community has established several principles and practices to design software architecture and motivate the development teams to use them in their software design process. Such principles and practices are often opinionated as they are not validated or can be evaluated using rigorous scientific methods. These practices and principles are backed by several years of experience and practice in software designing. These principles and practices' primary aim is to improve software architecture such that the system captures functional requirements, fulfils intended software quality attributes, and make the software development process manageable. As our study aims to create an interoperable, reusable, and adaptive IDPT system framework, we attempt to abide by these principles and practices. To provide background information on these topics, we outline the relevant principles and practices we followed during this study.

- **Designing an orthogonal software system**: An orthogonal software system consists of modules that are independent of each other. It means that modification in one particular module should not enforce to change in another module. Software systems are characterized by higher modifiability. One of the reasons for such modifiability is its dependence on several other libraries. Designing orthogonal systems require a better architecture and hence higher upfront costs and time. *Orthogonality* makes modules loosely coupled and highly cohesive. *Coupling* is the degree to which a software module depends on another software module. Intuitively, tightly coupled software systems are complex and introduce a higher degree of challenges. Hence, we intend to enforce loose coupling to have minimal or no dependencies with other modules. Such an effort reduces complexity and decreases development time. The reason is that if systems are less dependent, developers take less time to modify changes, and testers take less time to test changes in a module.

  Furthermore, if a system is tightly coupled, it is harder to reuse a module. *Cohesion* is the degree to which the elements inside a module belong together. Highly cohesive modules have a single, well-defined objective and indicate better quality of design. The elements included in the module should be associated and commit to that purpose.

- **Minimizing complexity**: Software design and development is a complicated craft. The reasons for being complicated are a) dynamic nature, b) having several dependencies, c) influenced by its stakeholders, and d) has multiple ways of accomplishing it. To overcome these complexities, the software design and development community have recommended several principles. It is imperative to note that these principles are often opinionated based on the users' experience. Here, we outline the following principle that we followed by during our study:

  - *Keep it Simple, Straightforward (KISS)*: It conveys that systems work best if they are simple. Over-complications of solutions only cause frustrations to the end-users and the development team. Variations of the KISS acronym can be seen, such as Keep It Simple, Stupid; Keep It Short, Simple; Keep It Simple, Silly; and others. Kelly Johnson, who was an aeronautical and systems engineer, created KISS principle [112]. Several ways to implement the KISS principle include duplication removal, eliminating non-relevant features, information hiding and separation of concerns.
  - *Do not Repeat Yourself (DRY)*: As the title suggests, this principle aims to eliminate duplication as much as possible. Violation of the DRY principle is referred to as WET (Write Everything Twice). This principle suggests avoiding copy-paste programming, motivates the usage of magic strings (declaring most repeated constants, strings, and code in a single place), and supports abstraction. However, several developers support the idea that *no abstraction is better than a bad abstraction*.
  - *You are not going to need it (YAGNI)*: It suggests eliminating features that are not essential. This principle is borrowed from Extreme Programming (XP),

an agile method, and motivates removing unnecessary functionality and logic.

  - *Information hiding*: It is one of the oldest technique of minimising complexity. D.L. Parnas initiated the idea of information hiding [105] in 1972. This principle outlines the details of a module that do not need to be revealed should be made inaccessible. The main reason for such information hiding is that it reduces complexity and improves maintainability as one does not need to be concerned about them.
  - *Separation of Concerns (SoC)*: As the name suggests, this principle motivates to separate components of a software system such that each component has its single concern. An example of the SoC principle is a microservice architecture where each service are separated to perform separate functionality.

- SOLID principles: SOLID [84] design principle promotes comprehensibility, maintainability, reusability, and flexibility. It is an acronym that incorporates five different design principles.

  - *Single Responsibility Principle (SRP)*: Each class should have only one responsibility. By doing this, we follow the SoC principle on the one hand and improved manageability on the other. If a developer needs to change any responsibility, the developer can look into that particular class. Besides, it improves software code readability.
  - *Open/Closed Principle (OCP)*: This principle says that each class should be open for extension but closed for modification. Several researchers and the development community support this principle.
  - *Liskov Substitution Principle (LSP)*: It is an OOP principle that states subtype must be substitutable for their base types without changing the base type. Violation of the LSP principle reduces the readability of the software code.
  - *Interface Segregation Principle (ISP)*: It is also an OOP principle that promotes the usage of interfaces that define method and properties without actual implementation.
  - *Dependency Inversion Principle (DIP)*: This principle outlines how to handle dependencies to promote loose coupling in a software system.

2.1.5.3 *Architecture design process*

SA design process outlines different approaches for designing and developing the software architecture for software systems. As depicted in Figure 2.2, different types of architecture design processes exist, including Attribute-Driven Design (ADD), Architecture-centric Design Method (ACDM) and Architecture development Method (ADM). For interested readers, the book by Bass et al. outlines ADD approach in their book, Software Architecture in Practice [6]. The ADM approach is a part of The Open Group Architecture Framework (TOGAF) [50], a framework for enterprise architecture. Software Architect's Handbook [64], a book by Joseph Ingeno, outlines Microsoft's architecture and design technique. We followed the ACDM method for constructing

RA and the reference model for the adaptive IDPT system. The main reasons for choosing ACDM over others are a) it is an iterative process, b) it is a lightweight process ensuring a balance between business and technical concerns, c) its primary focus is on software architecture, and d) the process fits well for SOA architecture. Since we used the ACDM method in our study, we briefly outline the ACDM process to provide a brief background. As outlined in the study [67], the process involves eight steps:

1. **Discovering architectural drivers:** Determine architectural drivers, including design objectives, functional requirements, quality attribute scenarios, constraints, and architectural constraints.

2. **Establishing project scope:** Define the project scope by reviewing architectural drivers, removing unclear, missing or incomplete needs or architectural quality attributes.

3. **Creating notional architecture:** Create a notional architecture based on architectural drivers.

4. **Evaluating the architectural:** Review the notional architecture with internal and external stakeholders. It includes multiple review sessions, expert evaluation, and comparison with state-of-the-art artefacts.

5. **Production go/no-go decision:** Based on the architectural review, the team decides whether to accept the architecture of refining the architecture. This step involves several iterations until the team decides that the architecture is ready for production.

6. **Experiment planning:** Team design experiments to evaluate architecture. The primary goal of such experiments is to discover underlying risks and challenges.

7. **Experiment with refined architecture:** The team executes the experiment based on the plan. Results of the experiments are recorded and based on the result, and the architecture is updated.

8. **Production planning and production:** Once the architecture designing process is complete, it is ready to move into production. Hence, with proper planning, the architecture becomes ready to be used by the development team for the detail design of elements, coding, integration and testing.

Because of its lightweight nature, ACDM is preferred by both industry and researchers. As a result, several ACDM versions can be seen; for example, a tailored version of ACDM [26] with Rapid prototyping.

2.1.5.4 *Architecture descriptions*

A software architecture description is a method of explaining and communicating software architecture and the results with stakeholders. It is also referred to as software architecture documentation, architecture specifications or architecture representations. Such architecture documentations assist in a) communicating architecture with other stakeholders, b) helping the development team, c) information team members, d) providing input for software architecture review, e) promoting reuse of architecture by informing interested readers, and f) helping in planning, analysis, designing and development of software system.

Both industry and academic researchers tend to use information, semi-formal and formal notations for documenting software architecture. Architecture viewpoints, architecture description languages, and architecture frameworks are the most common mechanism for architecture descriptions.

1. **Informal notations:** Architecture viewpoints and natural languages (documentations) are the most common information notations used to document software architecture. Architecture is expressed in several views. Each view is a representation of a set of system elements and relations among them. Example views include functional viewpoint, logical viewpoint, module viewpoint, requirement viewpoint, security viewpoint, user action viewpoint, and many others. There is no definitive standard on which view should be created. It depends on the software quality requirements and other functional requirements. *Examples: rule-based adaptation diagram (Figure 5 in Paper D), AI-based adaptation diagram (Figure 6 in Paper D).*

2. **Semi-formal notations:** A semi-formal notation in views is a standardized notation that can be used in diagrams. It uses both views and semi-formal notations like UML for documenting architecture. *Examples: Workflow Model (Figure 1 in Paper A), Transformation model (Figure 1 in Paper C), Reference Model (Figure 1 in Paper D), Reference Architecture (Figure 2 in Paper F) and others.*

3. **Formal notations:** *Architecture Description Languages* (ADL) and *architecture frameworks* are formal notations for expressing architecture. An ADL uses formal notations for documenting software architecture. For example, Architecture Analysis and Design Language (AADL) and System Modeling Language (SysML). SysML is a subset of UML. It contains both structural and behavioural diagrams as depicted in Figure 2.2. We use SysML for documenting architecture in our study [95, 97, 98]. A framework provides standard conventions, principles and techniques for describing architecture. Example of architecture framework includes 4+1 architectural viewpoint [6], RM-ODP (Reference Model of Open Distributed Processing), and TOGAF (The Open Group Architecture Framework) [50]. *Examples: Flowchart (Figure 1 in Paper A), Sequence diagram (Figure 3 in Paper B), Diagram Predicate Framework (Figure 4 in Paper B), UML diagram (Figure 2 in Paper D), Use case diagram (Figure 3 in Paper D).*

We have outlined several topics about software architecture in Section 2.1. The term *software architecture* is often confused with *information architecture* (IA). Both of these terms are used in this thesis. Hence, to clarify the difference between these two terms, it is essential to outline a background about information architecture. We discuss IA in the next section.

2.2 Information architecture

Information Architecture (IA) is related to how people cognitively process information in any information systems. Furthermore, it helps the development team to structure the content such that the content is discoverable and comprehensible [117]. Content structuring deals with creating organizational and navigational schema such that the users of the system can move through the content efficiently and effectively.

2.2.1 *Components of IA*

IA contains three components - user, content and context [11, 117]. As an example of these components, we map these components with the INTROMAT project in Table 2.2.

1. **User**: Users need information. This information need is the primary reason why they use information systems. Hence, it is essential to comprehend who these users are and what are their needs. For example, a mental health patient with mild depression has different search preferences than a nurse using the same system. In the same way, a manager needs to get an executive summary of the systems. Hence, understanding the users, their preferences, behaviours, level of access, roles, and permission is essential in defining the structure of the system, search layout, content structure, and designing adaptive content and layout.

2. **Content**: Understanding user context helps to structure and organize information systems. According to Rosenfeld [117], all information systems have an organizational and a business context, whether implicit or explicit. These contexts align with the system's goal, mission, strategy, infrastructure, resources, constraints, and technology.

3. **Context**: Content is all the value the end users perceive from any information system. It can include documents, tables, metadata, figures, texts, audio, video, slides, animated characters, schema, and others. Such content exhibits different characteristics, including *ownership* (who owns the content?), *format* (text, audio, video, image, slide, animation, 3D animations), *structure*, *volume*, *metadata*, and *dynamics* (how much new information is given, and how often they are updated?).

2.2.2 *Why is IA essential?*

World Wide Web (WWW) contains a massive amount of data [88, 140] actively produced from smartphones, IoT, activity monitoring systems, real-time systems, other healthcare applications. Consequently, it is challenging to structure, store, access and understand the information in these data when required. IA is a design principle that is inclined to making such information discoverable and comprehensible. Hence, IA is crucial as:

- As the prevalence of data is high, the cost of finding information is higher.
- The cost of not finding information is higher, especially in the healthcare scenario.

Table 2.2: Mapping components of IA with respect to INTROMAT project

Components	Example
Users	• **Who are the end users?** Patients suffering from mental health illness, and therapists supporting the patients. • **How can users use the information system?** Our system will provide IDPT designed by the domain experts. End users can learn about their illness, self-care and take intervention through mobile and web applications. • **What information end users want from our system?** Information about what is happening to them, why and how can they manage their illness, and measures they can take to reduce them? • **What information therapists need to make informed decisions?** Information and visualizations therapists need to make decision.
Context	• **Mission**: Improve public mental health with innovative ICT. • **Strategy**: Through innovative ICT, web applications, mobile applications, VR applications and IoT. • **Procedure**: Through research, understand the need of users, understand how these needs can be fulfilled from domain experts, present the need to software engineers and create a usable prototype, evaluate the prototype with RCT techniques and disseminate the results to the world to get feedback. • **Infrastructure**: Internet/Smart Phones/ Smart Watches/ Computer • **Why**: Managing the prevalence of mental health issues is socially and economically challenging. Internet Delivered Interventions would be accessible to everyone at a reduced cost.
Content	• **Ownership**: INTROMAT project (https://www.intromat.no/) • **Format**: Text, audio, video, images, VR applications • **Structure**: Through web/mobile application in formatted HTML. • **Metadata**: The domain expert labels all the content of the IDPT system. • **Volume**: Based on the interventions created. • **Dynamics**: New content is available every week based on the completion of the users.

- The cost of maintenance and its impact on the patients can be economically higher.
- It takes time and effort to train users to use any system properly. Hence, it is essential to structure the content properly.

2.2.3 IA Designs

Information Architecture (IA) plays a vital role in web application development. Good architecture can enhance end users' ability to find information and decrease application maintenance cost [117]. Despite some recommendations for using Architecture Centric Development Method (ACDM) in behavioural and mental health interventions, there is still a lack of empirical evidence for the role of architecture in IDPT [108]. Current IDPT using ACDM primarily focus on navigation systems [25] and their architecture can be *hierarchical*, *matrix*, *hybrid* and *tunnel based* [41, 108]:

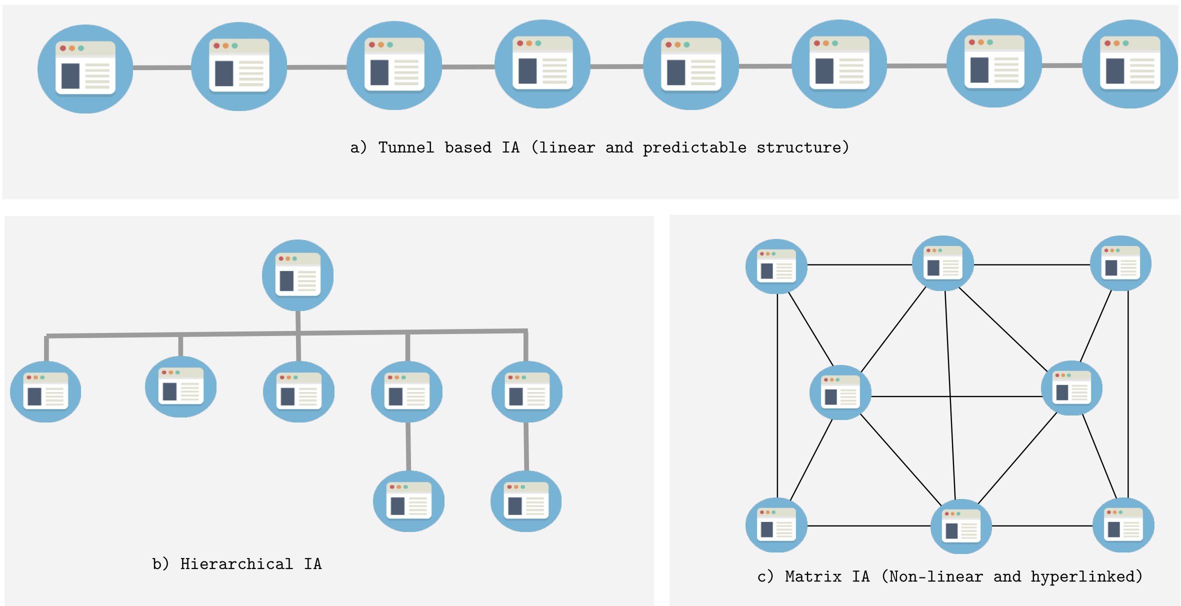

Fig. 2.4: The figure illustrates three different types of IA, including a) Tunnel-based IA where content is organized sequentially; b) Hierarchical IA, where content is structured in a hierarchy; c) Matrix IA, where content is interlinked, forming a non-linear structure.

1. *Tunnel design:* Tunnel based design (Figure 2.4 (a)) is analogous to watching TV, reading textbooks, attending academic classes, or attending multiple clinical sessions.
2. *Hierarchical design:* Information is organized in a top-down manner so that users can review specific content in a non-sequential way (Figure 2.4 (b)). The hierarchical design provides a simplified view of the content, making it easy to retrace steps.
3. *Matrix design:* Matrix IA is designed on the principle of hypertext HTML (Figure 2.4 (c)). In a matrix design, users can freely pursue their interests by using their path available through information.

4. *Hybrid design:* It is a combination of different IA designs that best fit content and purpose.

We have outlined software architecture and associated topics in this chapter. This chapter is intended to provide background information on how adaptability and interoperability, being the primary software quality attributes requirement, fit into a broader software context. In the next chapter, we outline the results of the literature review.

To survive you must tell stories.

— Umberto Eco

CHAPTER 3

LITERATURE REVIEW

One obvious method of finding a solution to any problem domain is correlating the problem domain with the previous studies and state-of-the-art works. This correlation can reveal what part of the targeted problem domain these previous studies and state-of-the-art works can solve and what it can not. Hence, we started the research by analyzing previous studies and state-of-the-art works that were inclined to the problem domain and project objectives (see Figure 1.1). Section 3.1.1 outlines the results from our previous studies. Section 3.1.2 outlines the findings from the investigation of existing systems. These previous studies and evaluations of existing systems hinted lack of adaptability and interoperability gaps in the current IDPT systems.

To verify these gaps, we conducted a systematic literature review on investigating the adaptiveness of the current IDPT systems. Section 3.2) outlines the review process and the results from the systematic literature review. Section 3.3 outlines the literature review done in the direction of interoperability.

3.1 Review process

The review process began with analysing and assessing the previous studies and evaluating the existing healthcare applications inclined to the problem domain. As the first step, we started studying previous studies.

3.1.1 *Previous studies*

Several studies have been conducted with an attempt to reduce user dropout rates and increase user adherence in IDPT. Some studies claimed to provide therapists contact for online guidance and support during interventions duration has been found to increase adherence and effect sizes [4, 18, 128]. Clarke et al. added telephone calls and postcard reminders from the therapist intending to increase user adherence [19]. The study concluded by discovering no significant difference between intervention groups with or without reminders. However, a similar study done by Farrer et al. [36] to evaluate the effectiveness of a six-week IDPT for depression with and without telephone interaction concludes that IDPT is effective both with and without tracking for reducing depression. This result indicates that the success of specific interventions are associated with the settings in which they are performed. Klein et al. [72] conducted a study to examine if therapists' frequency (from one e-mail per week to three e-mails per week) make a difference in user adherence. The study concluded that the effectiveness of IDPT might be independent of the frequency of therapist support. Hilvert-Bruce et al. [57] conducted a study to inspect if dropouts of users in IDPT because of lack of efficacy; can change in adding a choice of treatments, reminders and financial cost improve adherence; and finally, if the addition of clinical contact improves user adherence. The results obtained in this study claims to add reminders; the choice of treatments, cost and timing; contact of clinicians improves the user adherence.

A systematic review by Christensen et al. [18] discovered that *disease diversity*, *treatment length* and *chronicity* predicted are important factors contributing to user adherence in IDPT. Similarly, *clinical severity* has also been indicated as one of the important factors contributing to user adherence in web-based interventions targeting problematic drinking [10]. Similar factors have been identified as the most prominent factors in user adherence towards IDPT. However, only a few studies discuss why the target group choose not to adhere to. The most common reasons cited for nonadherence in state-of-art studies were:

- users believe they have made sufficient progress,
- users reported there was too much content without much flexibility,
- users reported that treatments were too complicated,
- treatments did not match users' expectations,
- there was a lack of therapist contact, and
- there was a lack of personalization.

A meta-analysis by Vandereycken et al. [138] elaborates the target groups choose not to adhere to the eating disorder treatment because they believed they achieved sufficient progress. However, the lack of progress is not related to nonadherence according to several other studies [18, 72]. According to a survey done by Johansson et al. [68], participants chose not to adhere as they could not perceive a compatible correlation between the length of weekly text modules and the conditions in their personal life.

Moreover, the participants found the content to be a tiresome burden because of the length of the text modules and time consumed to go through it. Furthermore, the fixed format of the content sent to the participants each week was perceived as inflexible for some participants. Content complexity was perceived as challenging to comprehend and process by individuals participating in interventions [68, 73] especially when these individuals consider themselves as having attention problem or limited reading and writing skills. Participants' knowledge and expectations about the treatment process have known to influence user trust and hence adherence [125]. Johansson et al. [68] outlined in their study that participants mentioned they were grateful for being offered the treatment. However, not all of them appeared to be fully aware of the treatment and its significance. A similar conclusion has been drawn in the study by Alaoui et al. [3] indicating higher treatment credibility as the most potent prognostic factor for user adherence. Feedback has thought to increase user adherence [10] for sixty-five per cent of intervention participants.

Contrary to this, no face-to-face therapist during the interventions was perceived as the therapist not caring about their issues [68]. In addition to this, some participants outlined they never prioritized on their personal development as they were aware that face-to-face meeting was not required. A recent study on mental health indicates that compliance failure can result from a lack of personalization [73]. A study done by Doherty claims to have improved user compliance with the IDPT system by focussing on user personalization [27]. Most of the researches examining the causes of declining user adherence towards IDPT discovered the patients personal reasons [18]. More than about the diagnosis and problem severity, it is about personal and interpersonal competencies and resources. Moreover, it is about the patient's intrinsic motivation to change, self-relatedness, and receptivity to change. Levey et al. [79] characterizes this reason as *patient variable*. Considering this reason for premature termination of interventions indicates the need to investigate the reasons and circumstances for non-adherence further. Specifically, this indicates a gap in the literature concerning the in-depth exploration of the subjective reasons for non-adherence in online psychological interventions. In general, the factors affecting premature termination of participants from IDPT, as outlined by Johansson et al. [68], be characterized by the interaction between the *participant perception of the treatment* (Content complexity, therapists feedback, information about significance) and the *participants' situations* (awareness about the treatment, availability, daily routines, treatment expectations, perceived language skills). Analogously, a report by WHO [146] distinguishes five interacting dimensions affecting adherence to medication, therapies and healthcare in general: *socio-economic factors, therapy-related factors, patient-related factors, condition-related factors,* and *health system/healthcare team-factors*. The same report justifies relatively limited research has been done on the effects of the healthcare team and system-related factors on adherence.

In addition to the reviews mentioned earlier, we evaluated a list of previous reviews about the IDPT system and its efficacy in treatment outcomes. The list of reviews is outlined in Table 2 in the study [97]. As summarised in the Table, previous studies report a lack of adaptability in the current IDPT systems and motivate to comprehend variables like disease diversity, treatment length, treatment complexity, personalizing treatment contents and others. While several studies mention flexibility in treatment content, none of the studies reports what these contents are and how can these contents be personalized to the patients. Nonetheless, none of the studies reported a reference model of an adaptive IDPT system with its significant components nor provided comprehensive guidelines on developing an adaptive IDPT system. These previous studies hinted lack of adaptability in the current IDPT system without much detail:

- *What can be adapted in an IDPT system?*
- *How can the IDPT system be adapted?*
- *When should the adaptation be triggered?*
- *What type of strategies and dimensions can be used to adapt intervention?*
- *How should we exchange these interventions from one healthcare system to another?*

To answer these questions, we started conducting a systematic literature reviews. We outline the systematic literature review in Section 3.2.

3.1.2 *Evaluating existing systems*

As a part of INTROMAT project, Yogarajaha et al. [147] conducted a usability evaluation of current IDPT systems. The study proposes a set of evaluation criteria for inspecting the usability and responsive design of IDPT systems. The study [147] results indicate that despite the excellent treatment results and proven clinical effects, the systems, in general, have several issues regarding usability, universal design and outdated technology. Finally, the same study proposes that there should be established guidelines for testing IDPT systems' usability and technology.

3.1.3 *Systematic reviews and meta analysis*

We conducted several reviews as a part of the INTROMAT Project. A meta-analysis by [31] suggested that face-to-face treatment were as effective as a digital intervention in reducing Fear of Public Speaking (FoPS). Inal et al. [61] conducted a systematic literature review to analyse literature on how usability is being addressed and measured in mHealth intervention for mental health problems. This study provides a detailed account of how evidence of usability of mHealth apps is gathered. The study outlined that most studies described their methods as trials, gathered data from a small sample size, and carried out a summative evaluation using a single questionnaire, which indicates that usability evaluation was not the main focus. As many studies described using an adapted version of a standard usability questionnaire, there may be a need for developing a standardised mHealth usability questionnaire. To continue finding answers to the questions mentioned in Section 3.1, we conducted a systematic literature review. The review process and methodology is outlined in the next section.

3.2 Adaptive Elements in IDPT Systems: Systematic Review

We discuss the details of the systematic literature review in Paper A [98]. In this section, we outline the overview and discuss the main findings from the review.

Background: Internet-delivered psychological treatments (IDPT) are built on evidence-based psychological treatment models, such as cognitive behavioural therapy, and are adjusted for Internet use. The use of Internet technologies can increase access to evidence-based mental health services for a more significant population proportion using fewer resources. However, despite extensive evidence that Internet interventions can effectively treat mental health disorders, user adherence to such internet intervention is sub-optimal.

Objective: This review aimed to (1) inspect and identify the adaptive elements of IDPT for mental health disorders, (2) examine how system adaptation influences the efficacy of IDPT on mental health treatments, (3) identify the information architecture, adaptive dimensions, and strategies for implementing these interventions for mental illness, and (4) use the findings to create a conceptual framework that provides better user adherence and adaptiveness in IDPT for mental health issues.

Methods: The review followed the Preferred Reporting Items guidelines for Systematic Reviews and Meta-Analyses (PRISMA). The research databases Medline (PubMed)[1], ACM Digital Library[2], PsycINFO[3], CINAHL[4], and Cochrane[5], were searched for studies dating from January 2000 to January 2020. Based on predetermined selection criteria, data from eligible studies were analyzed. The selection criteria yielded studies between 2000 to 2020 that aimed to adapt intervention using a web or mobile-based technology for mental or neurological disorders.

Results: A total of 3341 studies were initially identified based on the inclusion criteria. Following a review of the title, abstract, and full text, 31 studies that fulfilled the inclusion criteria were selected, most of which described attempts to tailor interventions for mental health disorders.

- The most common adaptive elements were *feedback messages* to patients from therapists (11/31, 35%) and *intervention content* (9/31, 29%). However, how these elements contribute to the efficacy of IDPT in mental illness was not reported.
- The most common IA used was *tunnel-based IA* (4/31, 13%), while many studies (20/31, 65%) did not report the IA used.
- The rule-based technique was the most common adaptive strategy used in these studies (20/31, 65%).
- All the studies were broadly grouped into two adaptive dimensions based on *user preferences* or *performance measures* such as psychometric tests.

Findings: The study resulted in following two primary conclusion:

1. Several studies suggest that adaptive IDPT can enhance intervention outcomes and increase user adherence. However, there is a lack of studies reporting design elements, adaptive elements, and adaptive strategies in IDPT systems. Hence, focused research on adaptive IDPT systems and clinical trials to assess their effectiveness are needed. To overcome this gap, we proposed a reference model [97] and reference architecture [94] of an adaptive system and its associated components.
2. There is a lack of standardized definitions for the healthcare information systems and associated taxonomies that could facilitate the grouping of similar interventions. As mentioned in the introduction, using nonstandard terms to refer to the same system causes inconsistencies and makes it hard to conclude. Based on this

[1]https://pubmed.ncbi.nlm.nih.gov/
[2]https://dl.acm.org/
[3]https://www.apa.org/pubs/databases/psycinfo/coverage
[4]https://www.ebsco.com/products/research-databases/cinahl-complete
[5]https://www.cochranelibrary.com/?cookiesEnabled

challenge, several researchers have made an effort to formalize the healthcare information systems to support interoperability, such as the HL7 FHIR created by the Health Level Seven International (HL7) organization. Assuming researchers and healthcare providers follow these healthcare standards, in that case, systems can communicate with each other, hence, obtaining interoperability. In addition, the findings and results from any research become highly discoverable, thus providing opportunities to extend in the future directions. We proposed the GraphQL and HL7 FHIR approach for Health Information Exchange (HIE) to overcome this gap [93, 96]. We discuss our methods and findings in the next section.

3.3 Literature review on interoperability

Achieving interoperability among healthcare applications is one of the hottest topics in healthcare [77, 96, 129]. *It is associated with delivering the correct information at the precise time and to the correct place.* Assuming interoperability is achieved, the healthcare system's stakeholder can benefit from safer care, less resource waste, error-free information, timely care, and less duplication. These benefits motivate both researchers and industry partners to achieve a higher degree of interoperability among healthcare applications. To attain interoperability, researchers and industry partners have developed several standards. These standards are referred to as healthcare IT standards. These standards facilitate linking healthcare systems to share information, maintaining a higher degree of security and privacy. Several works have been done to achieve interoperability in the field of healthcare systems. However, due to the complexity of healthcare systems (see Section 5.2) and lack of open-standards, there is still a need for a common definition of healthcare data and data interchange standards. Clinical Document Architecture (CDA) [58], OpenEHR [69], and HL7 FHIR [49] are some common standards for Health Information Exchange (HIE) [96]. As shown by the literature study [51, 96, 111, 120, 129], HL7 FHIR has received interests from both industry and academia. Hence, we chose to use HL7 FHIR in our system.

HL7 FHIR supports Representational State Transfer (REST) architecture and Service-oriented Architecture (SOA) for information exchange. However, it inherits the RESTful approach's inflexibility and complexity, such as over-fetching and under fetching [96]. In over-fetching, a REST endpoint provides more data than required. The latter, under-fetching, does not return all the data necessary. In these situations, an application has to make an additional request to fetch all the required data. This addition request is referred to as `n+1` request. To reduce the problems mentioned above, Facebook proposed GraphQL query language in 2012. After GraphQL's public release in 2015, companies from diverse areas, including technology (GitHub, GitLab), entertainment (Netflix), marketplace (Airbnb), travel (KLM), finance (PayPal), and others added GraphQL to their development stack. Consequently, there is a rise of architectures, design patterns, development paradigm, experimentation and frameworks to leverage the benefits of GraphQL and support interoperability.

There are several emerging solutions in the GraphQL echo-system including

`PostGraphile`[6] that generates a GraphQL schema from a `PostgreSQL` database, and `Prisma`[7] that allows generating queries and mutations. In addition to this, various other transformation, the community is developing libraries to support various database systems. There is research on the syntax and semantic representation of GraphQL. A recent study by Ulrich et al. [134] introduces QL^{4}MDR, an ISO 11179-3 compatible GraphQL query language, which promotes interoperability by defining a uniform interface between different metadata repository (MDR), allowing querying over a distributed network. However, their study does not explicitly answer how HL7 FHIR can be used for HIE and how HL7 FHIR resources can be transformed into the GraphQL schema. Our work helps bridge this gap and is different from the work in [134] as we focus on experimental evaluation to demonstrate the applicability of HL7 FHIR and GraphQL based API in a healthcare setup. Another study was presented in [54] which formalizes the semantics of GraphQL queries based on the labelled-graph data model and analyzes the language to demonstrate that it admits efficient evaluation methods.

It is imperative to point out that there are publicly available Resource Servers that work with HL7 FHIR. Moreover, we have not benchmarked their properties with the Resource Server proposed in this study. However, all of these servers follows REST communication, inheriting its discrepancies. This section outlines some of these publicly available HL7 FHIR servers:

- **Hapi FHIR** (`https://hapifhir.io/`): It is an Open-source server based on REST communication and SQL databases. It is programmed using Java that defines a model for all HL7 FHIR resources and data types defined by FHIR specifications.

- **Firely Server** (`https://server.fire.ly/`): It is an FHIR Reference server based on REST communicaiton for .NET[8]. It is built for educational purpose only.

One of the future work would be to benchmark the performance of the proposed Resource server with these publicly available HL7 FHIR reference servers. We will outline the result of our study, other aspects of interoperability and address them in Chapter 5.

[6] https://www.graphile.org/postgraphile/
[7] https://www.prisma.io/
[8] https://dotnet.microsoft.com/

It is not the strongest of the species that survives, nor the most intelligent. It is the one that is most adaptable to change.

— Charles Darwin

CHAPTER 4

ADAPTIVENESS

We recognized the inability to adapt interventions as one of the significant gaps in the current IDPT systems. This chapter describes the proposed solution and explains how we venture to address the adaptiveness intricacies in the IDPT systems.

This chapter explains the components of *the OpenIDPT Framework* proposed in this study. We describe an IDPT and its components in Section 4.1 and IDPT System and its components in Section 4.2. Then we present the reference model of an IDPT system along with its associated components (Section 4.3). We discuss the proposed reference architecture of the IDPT system and outline its significant components (Section 4.4). Section 4.5 outlines the Open-Source implementation of the Adaptive IDPT system (OSAIS). Finally, we outline user profiling which forms the fundamental basis for adaptation in Section 4.6.

4.1 IDPT and its components

Internet-Delivered Psychological Treatments are digital therapies provided for mental and neurological disorders. Figure 4.2 depicts the conceptual model of any intervention. An intervention generally consists of cases, modules, tasks, and taxonomies. This section explains these components:

- **Cases**: Typically, IDPT targets one or more cases such as Depression, Social Anxiety, Bipolar Disorder, ADHD, or other health issues. An example of an ADHD case is presented in listing 4.1.

```
{
   "name":"RCT ADHD",
   "description":"Attention Deficit/Hyperactivity Disorder therapy.",
   "status":"ACTIVE",
   "availableFrom":"2019-12-19T00:00:00",
   "id":"CASE-1",
   "taxonomy": "SNOMEDCT:406506008",
}
```

Listing 4.1: An example of a case

- **Modules**: Each case contains one or more modules that focus on any particular treatment dimension of the case. For example, for the depression case, there can be modules for understanding and monitoring emotions, behavioural activation, identifying automatic thoughts, and others. One specific module can be part of one or many cases. The modules can have dependencies that specify the ordering of the modules. An example of a module from the ADHD case is presented in listing 4.2.

```
{
   "owner":"CASE-1",
   "name":"Week 2: Breathing",
   "description":"The breath is a useful tool to use when we work with
attention. Breathing can help you slow down and be more present here and
now.",
   "status":"ACTIVE",
   "tasks": [{"..."}],
   "prerequisite":[null],
   "taxonomy": "SNOMEDCT:306506009",
}
```

Listing 4.2: An example of a module

- **Tasks**: Each module, in turn, can include one or more tasks. A task can be in form of learning materials (informative task) or exercise (interactive task). *Informative tasks* provide learning materials about mental health issues (cases), symptoms, use cases, and several ways to manage them. The main objective of such informative tasks is to provide psycho-education so that:

  – patients and their families can learn about symptoms, causes, and treatment concepts

  – patients can comprehend the self-help program and steps required to manage their illness

  – patients can correlate their situations with others with similar issues, which helps to ventilate their frustrations.

  Such informative tasks are in the form of reading (text), listening (audio), graphics, presentations, and watching (video). In contrast to informative tasks, *interactive tasks* involve user interactions and often in the form of exercises and psychometric tests. The exercises can be *physical activities* or *computerized tasks*. Examples of physical activities include physical workouts and mindfulness exercises such as breathing exercises, walking certain distances, stretching, or physically performing any other activities. Examples of the computerized exercises involve filling in the blanks, answering (Q/A), multiple-choice questions (MCQ), and feedback. The feedback forms consist of using free text, rating systems, or multiple-choice questions.

  Figure 4.3 depicts an example of tasks belonging to a module named *breathing*. The example is taken from the ADHD case from the INTROMAT project. The proposed open-source adaptive IDPT system (OSAIS) uses the data structure outlined in Figure 4.1 to represent any task. This representation is unique and interesting because it empowers the IDPT system to adapt in several dimensions. For example,

- `prerequisite` array holds the identifiers and score of the tasks that the user needs to finish before the task become active for the user. It provides a mechanism to create task dependency (see Figure 8 in Paper F [94]).
- Each task has `points` that the user is rewarded after completing the task. It provides a way to gamify interventions (see Section 6.1.3 in Paper F). Furthermore, each task has `completionRequired` to force a task to be completed by the user. A combination of these two fields can enforce user to complete necessary tasks before moving to other tasks.
- Each task has `complexityLevel`. This field can be combined with user profiles to adapt intervention. For example, if we know the educational background of a patient, we can recommend tasks accordingly. A person with higher education can be recommended scientific literature, whereas a patient with primary education can be recommended with more animations, illustrations and videos.
- Each task has one or more evaluation criteria in the form of `key:value` which determines if a patient completed a task or not. For example, see Figure 8 and Table 3 in Paper F [94].
- Each task has a `taxonomy` and `tags` attached to it. These provide a useful mechanism to label each task. Since an IDPT system logs user interactions with these tasks, these labelled data becomes handy for using several supervised Machine Learning algorithms.

• **Taxonomy/Labels**: Each case, module, and tasks are associated with a label or taxonomy. Since the case, module and tasks form a hierarchical structure, and these taxonomies provide ontological structure for adaptation.

4.2 IDPT system and its components

IDPT systems refer to software applications that facilitate interaction with psychological therapy (intervention) through the Internet. These systems mainly include web applications, mobile applications, augmented reality, and virtual reality applications. This section outlines an IDPT system as an adaptive system (see Section 4.2.1) and the significant components of an IDPT system (see Section 4.2.2).

4.2.1 IDPT systems as an adaptive system

An *adaptive system* is a set of interacting or interdependent entities, real or abstract, forming an integrated system that changes its behaviour according to its environmental changes. The changes that occur in its behaviour are relevant and directed towards fulfilling the system's objectives. As depicted in the reference model of an adaptive IDPT system in Figure 4.4, an IDPT system changes its behaviour with changes in the

```
TASK_DATA_STRUCTURE
├── ID: Integer
├── prerequisite: [{ID, score}] ................................ ARRAY OF IDs
├── description: String
├── tags: [String]
├── points: Integer
├── completionRequired: Boolean
├── complexityLevel: Integer
├── nextTask: ID
├── type: String == TEXT
│   ├── isRead: Boolean
│   ├── totalReadTime: Integer
│   └── content: String
├── type: String == AUDIO
│   ├── isPlayed: Boolean
│   ├── audioLength: Integer
│   ├── playedLength: Integer
│   └── file: File
├── type: String == VIDEO
│   ├── isPlayed: Boolean
│   ├── videoLength: Integer
│   ├── watchedLength: Integer
│   └── file: File
├── type: String == EXERCISE
│   ├── type: [QUIZ,FEEDBACK,RATING]
│   ├── passingScore: Integer
│   └── owner: [ID] .................................... BELONGS TO MODULE/TASK
├── taxonomy: [{key: value}]
└── evaluation: [{key: value}]
```

Fig. 4.1: Data structure of a task

environment. In an IDPT system context, the behaviours are influenced by adaptive dimensions such as user performance measure or user preferences. Based on these dimensions, the IDPT system changes its behaviour to increase user engagement and increase user adherence.

4.2.2 *Components of an IDPT system*

An IDPT system provides several services, including Content Management System (CMS) services, core services and interfaces to therapists, patients and administrators. Figure 4.5 outlines the components of an adaptive IDPT system.

- **CMS services:** It provides user interfaces to build intervention, creates reminders/alerts and stores intervention content.
- **Interfaces for therapists and patients:** It provides user interfaces (UI) for both

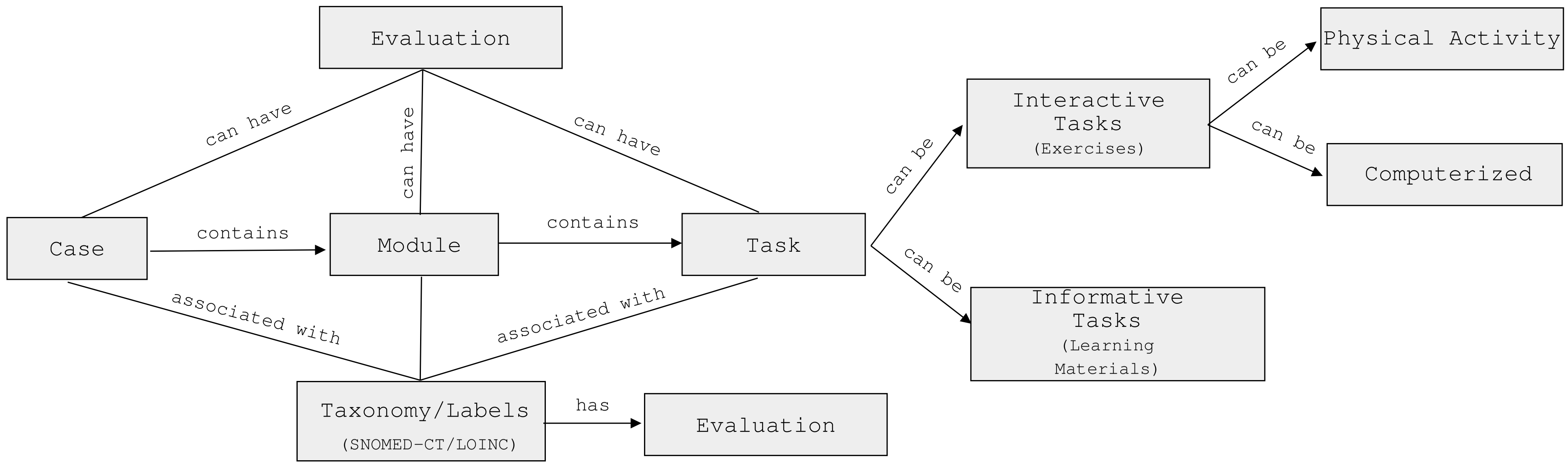

Fig. 4.2: The figure depicts the conceptual model of any intervention that is always associated with a case. A case contains one or more modules. Each module has one or more tasks that can be learning materials or exercises. An exercise can be physical activities or computerized.

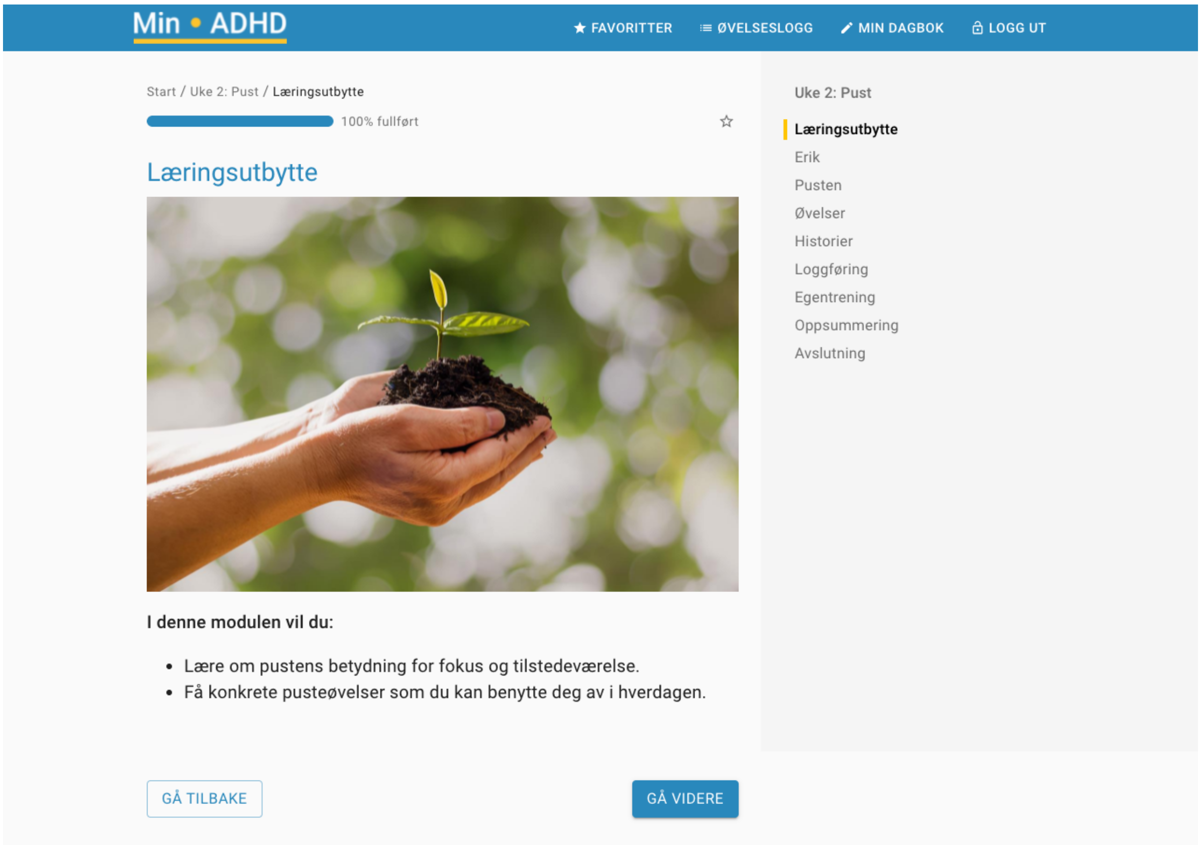

Fig. 4.3: Example of tasks inside **breathing module** from the ADHD case.

therapists and patients. The *patient's UI* includes dashboard, progress viewer, communication channel, history viewer, and current tasks or modules. The *therapists' UI* includes dashboard, progress viewer, communication channel, history of patients, and user profiles.

- **Core services:** The core services include adaptation services, user profiling services, communication services, and utility services. *Adaptation services* provide a rule-based engine to build adaptation rules based on the user profile. *User profiling services* maintain such a user profile. Similarly, *communication services* create a communication channel between patients and therapists. Finally, *Network and utility* services handle Internet connectivity logic and other utility-oriented tasks.

4.3 Reference model

We chose to define an adaptive system abstractly using classical control theory, as illustrated in Figure 4.4. The formal representation of the adaptive IDPT system constitutes the following components:

- a set of environments **E** in which IDPT is working as a complex process
- a set of controlled inputs **I** consumed by IDPT systems for changing the behaviour of the process. We refer to these inputs as **adaptive elements.**

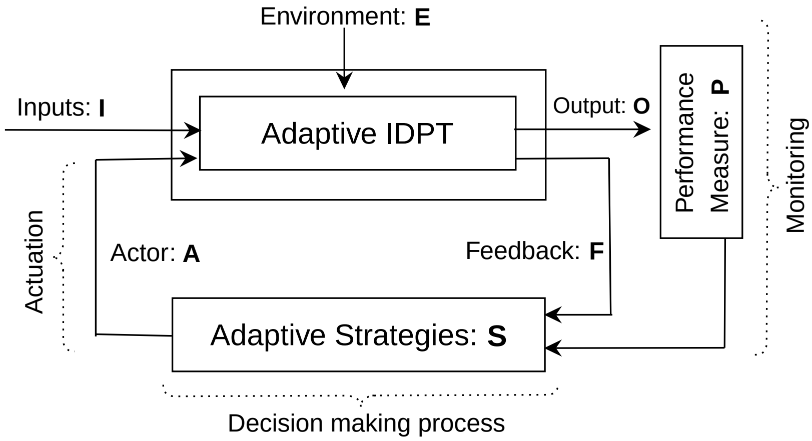

Fig. 4.4: We propose an Adaptive IDPT model based on classical control theory [97]. It illustrates IDPT systems as a complex function that works in an environment (E), consumes controlled inputs (I), generates outputs (O). The system measures the performance of the outputs using some measures (P) and uses some feedback function (F) to create adaptive strategies (S). Actors (A) trigger the adaptation. These strategies control how the IDPT system should adapt.

- a process to measure the performance of the system **P** indicating performance of the IDPT in environment **E** when consuming **I** as input. Psychometric tests are the principal performance measures for IDPT systems.
- a feedback function **F**, which generates an adaptive strategy with dynamic information about the process being controlled.
- a set of **adaptive strategies S**, which use the knowledge learned from information and performance of the system
- a set of actors **A** who trigger adaptation.

We provide details of these components in our study [97]. For the thesis readability, below, we briefly outline the reference model's main components with a summary of each:

Adaptive elements vs Design elements: Adaptive elements refer to the content part that is created to provide psycho-education about mental health. These elements include *content, content presentation, information architecture, content complexity, content recommendation, user interface, feedback, notifications*, and *reports*.

It is imperative to note that adaptive elements differ from design elements. Design elements incorporate objects (text, line, form, shape, and others) used to create a design of software applications. The main design elements include:

- *Colour*: It describes a particular colour of an object. Several colour theories, interaction design study, usability study highlights the significance of suitable colour, as it forms a mechanism of visual communication with end-users [82].

- *Line:* A line is a series of points and is an essential design element for software applications.
- *Shape:* It represents a two-dimensional area and forms an essential basis for design. In software applications, shapes interact with one another [82].
- *Space:* Space is used to connect or separate design elements. We can control how design elements interact and create rhythm, direction, and motion by controlling space.
- *Texture:* Web applications and mobile applications rely on the texture of the screen. The right texture creates a more dimensional object. For example, box-shadow and proper gradient can make a square shape look like textile.
- *Typography:* It is an essential component of applications and has different properties, including colour, size, weight, types [82].
- *Size (Scale):* The size and scale of any software application's design objects add emphasise and interests. For example, we use a header with a larger font size to emphasise its importance.

Design elements contribute to the usability, readability, and graphical layout of software applications. While usability, readability and design are an essential part of an application, these are kept as the secondary quality attributes. Adaptability and interoperability being the primary software quality attributes. Hence, we mainly focus on adaptive elements.

Adaptive dimensions The way an adaptive system changes its behaviour depends on a multitude of factors: a) users' preferences, b) goals of the interventions, c) measures, d) adaptation actors, and e) adaptation strategies. We refer to these aspects as the dimensions of adaptive IDPT. These dimensions answer an essential question, *"on what basis does an IDPT system adapt intervention?"* We outlined these adaptive dimensions in detail in Paper D and is summarised here briefly:

1. **User preferences:** It indicates user interests and choices about interventions. Such preferences can be extracted from user profile such as interests, knowledge, background, goal, individual traits and user context (see user profiling Paper F [94]).
2. **Goals of the interventions:** Goals are the primary objective of the entities under consideration. We outlined patient goals and the therapist goals along with different characteristics of these goals in Paper D.
3. **Measures:** We outlined two different measures in an adaptive IDPT system, psychometric tests and user behaviour analysis. Psychologists have developed an effort to quantify people's preferences, behaviour, and intelligence through self-assessment questionnaires referred to as psychometric tests, for example, PHQ-9. The user behaviour analysis includes analysing the interaction data to gather user preferences and learn what a user likes the most.

4. **Adaptation actors** are involved in triggering adaptation. We outlined different actors involved in an IDPT system (see Figure 3 in Paper D [97]).

5. **Adaptive strategies:** In the last decade, several strategies for adaptation has been practised to improve the effectiveness of IDPT, and a multitude of endeavours to generalise these strategies into discrete classes has been carried out. We grouped these adaptive strategies into four types: *adaptation through rule-based engines*, *adaptation through a feedback loop*, *goal-driven adaptation*, and *adaptation through predictive algorithms*. Adaptive strategies unveil the answer to the question, *"how does an IDPT system adapt intervention?"*

4.4 Reference architecture

Based on the guidelines provided by the proposed reference model in Paper D [97], we proposed a reference architecture of adaptive IDPT system intending to improve adaptiveness and interoperability (Paper F [94]). Figure 4.5 depicts the RA of adaptive IDPT system. We use the term RA concerning the context and definitions provided by Cloutier et al. [21]. Our RA contains the *consumer layer* (customer context), *requirement layer* (business architecture) and *technical architecture*. The technical architecture provides guidelines and solutions in terms of technology. The requirement layer provides business requirements required by the RA to solve. Furthermore, finally, the consumer layer provides consumer context and the problem domain RA is intended to solve.

The RA comprises four major components: authorization server, mobile client, intervention system and analytics server:

- The **authorisation server** is an OpenID connect [119] compliant web server that can authenticate patients and grant authorisation access tokens. The server creates OpenID connect or Oauth 2.0 [80] tokens to handle such authentication and authorisation process.

  - The **OAuth 2.0 protocol** authorises a user to temporarily access a third-party software's protected resources without disclosing their identity. For example, suppose we want to share a file from Dropbox[1] with an email group in Google Mail[2]. Dropbox allows importing our contacts from Google Mail. We have to authorise Dropbox to access contact lists from Google Mail by logging in to it. In this scenario, Google provides access to the email list to Dropbox without giving our password. This process is referred to as *authorisation*.
  - **OpenID Connect**, an identity layer residing on the top of OAuth 2.0, facilitates client identification verification and obtains profile information about the user logged in. This process is referred to as *authentication*. For example, we want to create an account in Dropbox; we can sign up using Google Mail. In the sign up process, Google Mail shares profile information to Dropbox in order to create our account.

[1]https://www.dropbox.com/
[2]https://www.google.com/gmail/

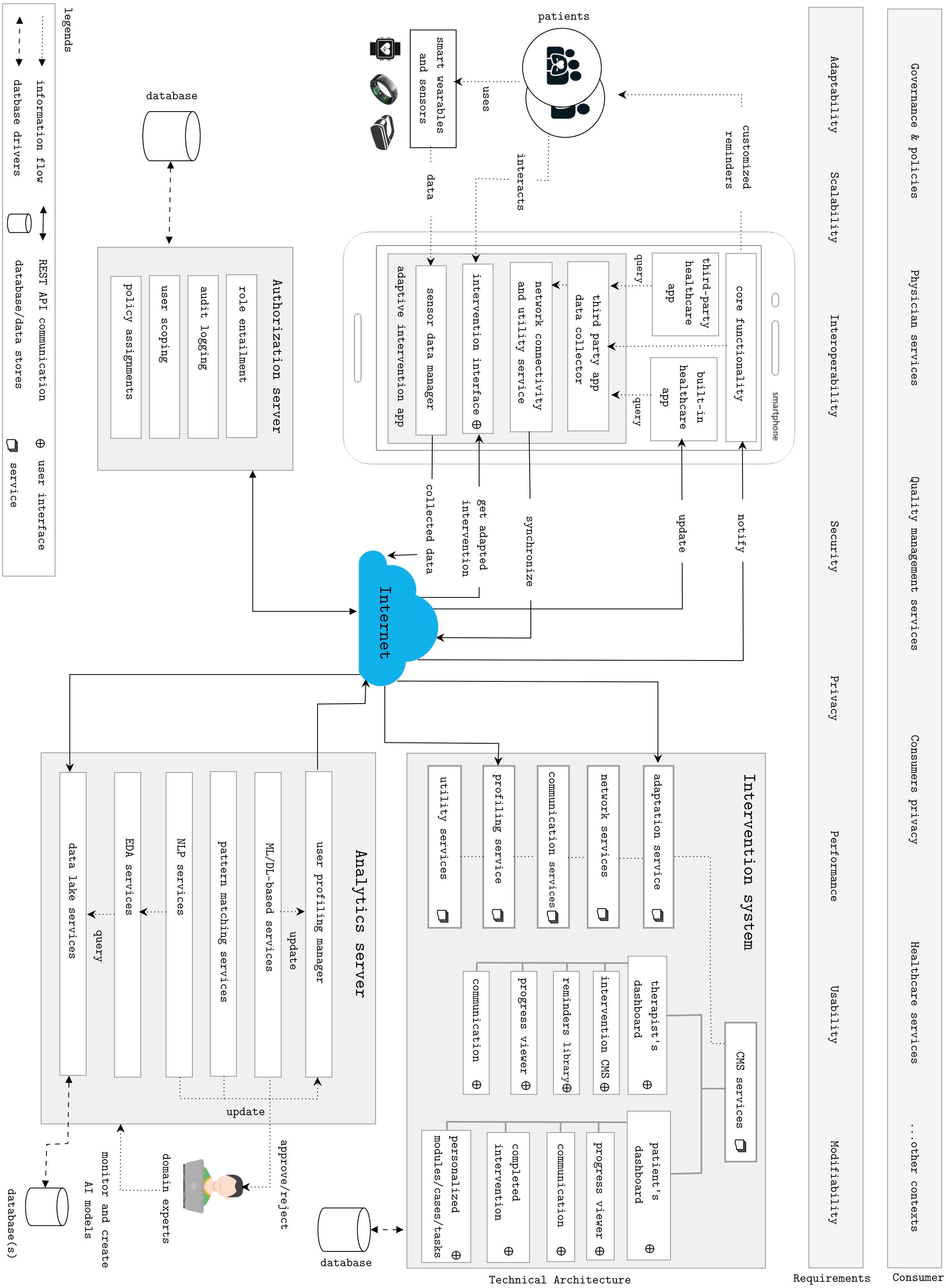

Fig. 4.5: Reference architecture of data-driven adaptive IDPT system

- The **mobile client** is the host, where an adaptive intervention app (mHealth app) is installed. Furthermore, the mobile client accumulates sensor data and forwards it to the intervention system.
- The **analytics server** has two parts: a) structural part of building a user profile and b)analytics method to feed information to profile.
- The **intervention system** provides different CMS services for intervention creation and user interfaces for therapists and patients.

We outlined these components and how these components communicate with one another to adapt intervention in Paper F. Moreover, we provided different example scenarios of adaptation that the proposed RA can achieve.

4.5 Open-source Adaptive IDPT System (OSAIS)

To evaluate the proposed RA, we developed an open-source IDPT system based on the proposed RA. The open-source framework aims to a) improve the development productivity, b) facilitate communication with domain experts, and c) facilitate interoperability. Besides, OSS can facilitate the successful realization of security and interoperability in healthcare systems. The following section discusses the motivations behind using the OSS paradigm to develop an adaptive IDPT system:

Why open-source software (OSS) in the healthcare systems? OSS refers to computer software that provides the copyright to edit, modify, use, and redistribute the software free of charge [17, 40, 48, 123]. Free software implies freedom to a) run the program for any purpose; b) study how the program works and change it to make it do what we wish; c) redistribute copies; and d) improve the program and release the improvements so that the whole community benefits [15, 17]. Open-source and closed-source choice impacts the software's security, interoperability, and effectiveness because software design methods are seldom peer-reviewed. Gropper [48] compares OSS with a textbook or patent available for all to see and improve. Closed-source software is like a secret, a black box not subject to peer review or independent improvement. Healthcare software has become mission-critical. Consequently, *doctors are becoming increasingly sceptical of software secrecy and the inability to peer-review closed software [48]*. On the other hand, OSS provides all the source code, and users can analyze it to know what is being stored, what type of information is being used by the system. Such openness provides trust in the system. Furthermore, the following are the fundamental reasons why OSS can work in healthcare systems:

- **Standardization, integration and interoperability:** Interoperability depends on the ability to communicate with one or more system. Such communication can happen if systems follow the same standards. Providing OSS in healthcare is an effective way to enforce people to use the same open Healthcare IT standard. Using different or custom healthcare IT standards make it difficult for other healthcare systems to communicate. This difficulty arises as the communication protocols (such as HTTP, TCP) define rules, syntax and semantics for communication.

The communicating parties must abide by these rules, syntax, and semantics to exchange information.

- **Transparency with privacy:** Every bit of information used by OSS is open to the public. This openness provides **solid ethical advantages**. Healthcare software offers decision support, risk management, performance rating, analytical features, treatment care plans and other sensitive information. Healthcare software involvement in data directly associated with people's privacy is the sufficiently agreeable reason people should not accept black boxes with closed-source software. Since there is openness in what data is being stored and how they are used in OSS, it provides transparency with data privacy.

- **Cost-effective:** OSS is a promising approach that healthcare organizations can reduce IT infrastructure costs while remaining agile enough to adopt new IT solutions. OSS does not require licensing fees, which frees up funds for other IT initiatives. It is not surprising if interoperability and integration cost in the closed-source software and proprietary software is extremely high. The cost is high because using closed-source software involves: a) the cost for developing software according to custom specification; b) charge for upgrading the software; and c) the charge for developing a middleware translator, if the user of closed-software intends to communicate with other healthcare providers.

- **Collaboration:** OSS advocates collaboration among vendors, providers, developers, and academicians to develop ever-changing and upgrading infrastructure technology by sharing source code. Doctors collaborate with other doctors and specialists to find a quicker solution. The same collaboration is seen in OSS. Multiple people work on a similar problem domain. It is a natural way of working and is comprehensible by the domain expert.

- **Potential to bring innovation:** OSS can bring innovation into the healthcare industry than independent development. The open-source nature of OSS makes its components, process, algorithm, and approach publicly available. Such openness allows both researchers to compare, benchmark and innovate. One of the dynamic characteristics of technology is, it is constantly updated and upgraded. Consequently, such upgrading and updating are seen in software too. This feature provides a strong position for innovating updated, state-of-the-art solutions. For example, Firefox and WebKit (Apple Safari and Google Chrome) browsers are OSS. Because of its one-source nature, developers can study its protocols, working processes and build their extensions on top of it.

- **Control over IT infrastructure:** OSS allows control over IT infrastructure compared to proprietary software. Healthcare providers benefit from such control as they can build flexible IT infrastructure around what is currently available. Reynolds and Wyatt's similar conclusion states that healthcare providers using OSS in healthcare are in a stronger position to inspect the code, documentation, community and try before implementing it in their care flow [110]. With OSS, healthcare providers can inspect code maintainability, data storage format, user interfaces, and extendability. In short, OSS users are on the safe side when they use OSS than proprietary software.

- **Improved patient experience:** Doctors can share reports easily, irrespective of systems being used by the patients. Such experience improves patient care. Moreover, it saves time for migrating patients information from one system to another.

- **Support, bug fixing and upgrading:** Upgrading, bug fixing and maintenance are inevitable tasks in software. Furthermore, these tasks are critical in the case of healthcare software. However, proprietary software and closed-source software send invoices for these supports. Moreover, it is subject to their availability since proprietary software owners spend more time acquiring new customers than locked-in customers [110]. OSS excels at bug fixing and upgrading [48]. OSS community publicises known bugs, patches, and upgrades to fix the bugs themselves and wait for a new release. Even more critically, OSS is not forced to reinvent the code that others have already developed. The quality of proprietary software suffers significantly from the secrecy of its internal workings. On the other hand, OSS mirrors typical medical research practice by reusing proven code and promoting transparency with equivalent patient safety benefits.

- **Knowledge sharing and learning**: OSS provides an opportunity for new developers and researchers to learn knowledge.

What can the open-source adaptive IDPT system do? Why is it interesting? As mentioned earlier, the Open-Source Adaptive IDPT System (OSAIS) is a technical implementation of the proposed RA. The OSAIS is interesting because of its underlying features given below:

- *Functional requirements:* The framework is built by following the DDD techniques meaning that, it is backed up by decision from healthcare domain experts. Hence, it addresses the challenges and scenarios required to build psychological interventions.

- *Technological stacks:* It is built with the updated JavaScript framework, ReactJS [3]. It uses GraphQL [38] in both the backend and frontend systems. Hence, it has benefits over the RESTful approach we addressed in Paper C [96]. MongoDB [4], a NoSQL database, powers the framework.

- *Extendability:* The framework consists of orthogonal modules that are independent of each other. Each module can be easily extended to build custom requirements. For example, the module responsible for assignment creation (therapist creation part) and rendering (patient interface part) can be easily extended by healthcare providers to match their design and user interfaces.

[3] https://reactjs.org/
[4] https://www.mongodb.com/

- The framework follows principles and practices (especially KISS, DRY, YAGNI, SoC, and information hiding) mentioned in Chapter 2 to minimize complexity (see Section 2.1.5.2). There is a lack of rigorous scientific methods to evaluate these principles. However, it can be noticed during static code analysis (manual code verification). Master students at HVL extended some framework modules (see Section 6.3), hence, verifying adherence to these principles and extendability.

4.6 User profiling as the basis for adaptation

Previous sections outlined what an adaptive system is; advocated IDPT system as an adaptive system (Section 4.2.1); presented a reference model (Section 4.3) and reference architecture of the adaptive system (Section 4.4); and discussed motivations behind using OSS in the healthcare domain. The primary goal of an adaptive system is to facilitate and provide infrastructure for adapting treatments. An essential question to unveil is, *"how does an adaptive system attempt to adapt intervention?"* The answer to this question is by comprehensive user profiling mechanism. While we have discussed what user profiling is, several approaches for user profiling, and different user profiling components in our Paper F [94], in this section, we outline how user profiling techniques can be used for adapting intervention.

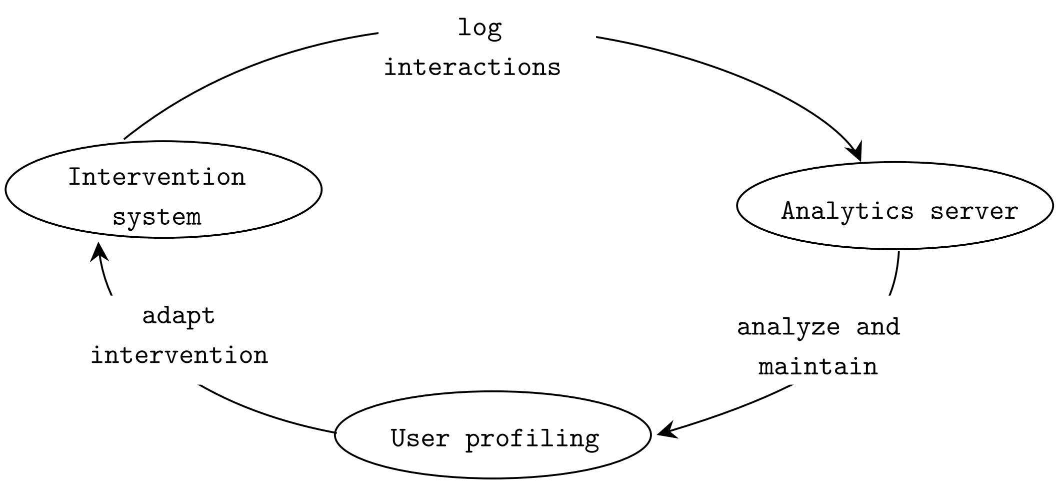

Fig. 4.6: The figure depicts our proposed model of a data-driven adaptive IDPT system. The patients interact with the intervention, and an analytics server captures those interactions. Based on the logged data analysis, a process referred to here as user profiling maintains an up-to-dated the user model to provide the adaptive effect.

Figure 4.6 describes the interaction model of the data-driven adaptive IDPT system. The patients interact with the *intervention system*, and a *analytics server* stores those interactions. Analytics server refers to third parties that contain data stores to collect a large amount of data and provides data analytics services such as pattern matching, NLP service, Exploratory Data Analysis (EDA) service, ML/DL services and others. Based on the logged data analysis, a process referred to here as *user profiling* maintains an up-to-date user model. The user model is used to provide an adaptive effect. An adaptive system behaves differently for different users. The decision on how the system should behave for any particular user is based on a user model. The user model is a detailed representation of an individual user's information associated with an adaptive system. The user preferences and needs are dynamic. Hence, it is essential to create, maintain, and update the user model. An adaptive system accumulates data in two distinct approaches to create and maintain an up-to-date user model: a) implicitly by observing user interactions and b) explicitly by requesting direct input from the user. This process is referred to as user *profiling*. The essence of the adaptation effect that a system can deliver depends on the user model's information.

How does user profiling help? Figure 4.7 depicts why user profiling is essential for creating adaptive content. Users interact with the intervention system generating a large number of interaction logs. These interaction logs are stored, analyzed and processed by the analytics server to create a comprehensive user profile. Major user profile components include interests, knowledge, background, goals, individual traits, user context, user history and other demographic data. These user profiles serve as an input for recommendation engines, AI-based predictive algorithms, and rule-based engines to create adapted content. Once a user profile is maintained, we can adapt content using several predictive algorithms, recommendation engines, or rule-based engines. We discuss these adaption scenarios in the following section.

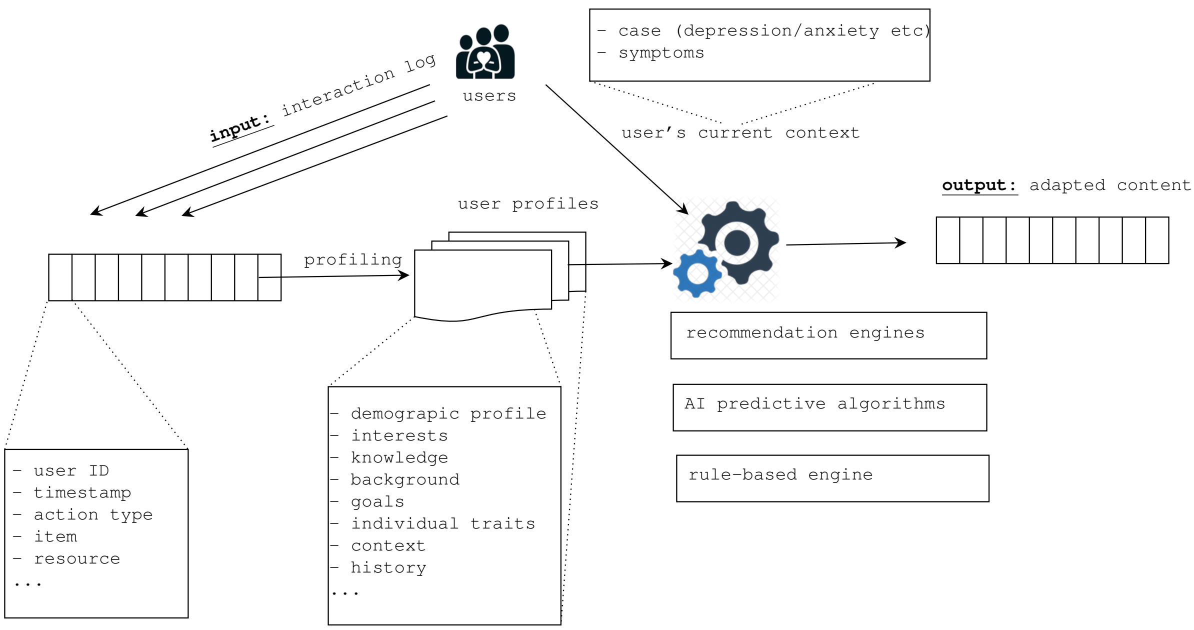

Fig. 4.7: The figure depicts why user profiling is essential for creating adaptive content. Users interact with the intervention system generating a large number of interaction logs. These logs are stored, analyzed and processed to create a comprehensive user profile. These user profiles serve as input for recommendation engines, AI-based predictive algorithms, and rule-based engines to create adapted content.

4.6.1 *Adaptation based on AI-based algorithms and user profiling*

Paper E [91] outlines a study where we proposed a novel word embedding (Depression2Vec) to extract depression symptoms from patient-authored text data and compare it with three state-of-the-art NLP techniques. Based on the proposed extracted depression symptoms, we present a technique for how an adaptive IDPT system can personalize contents. In addition to this technique, we propose attention-based deep entropy active learning using a lexical algorithm to detect depression symptoms from the patient-authored text in the study [2]. This method helps to reduce data annotation tasks and helps in the generalization of the learning system. The proposed framework achieved a better result that shows the synonym expansion semantic vectors help enhance training accuracy while not harming the results.

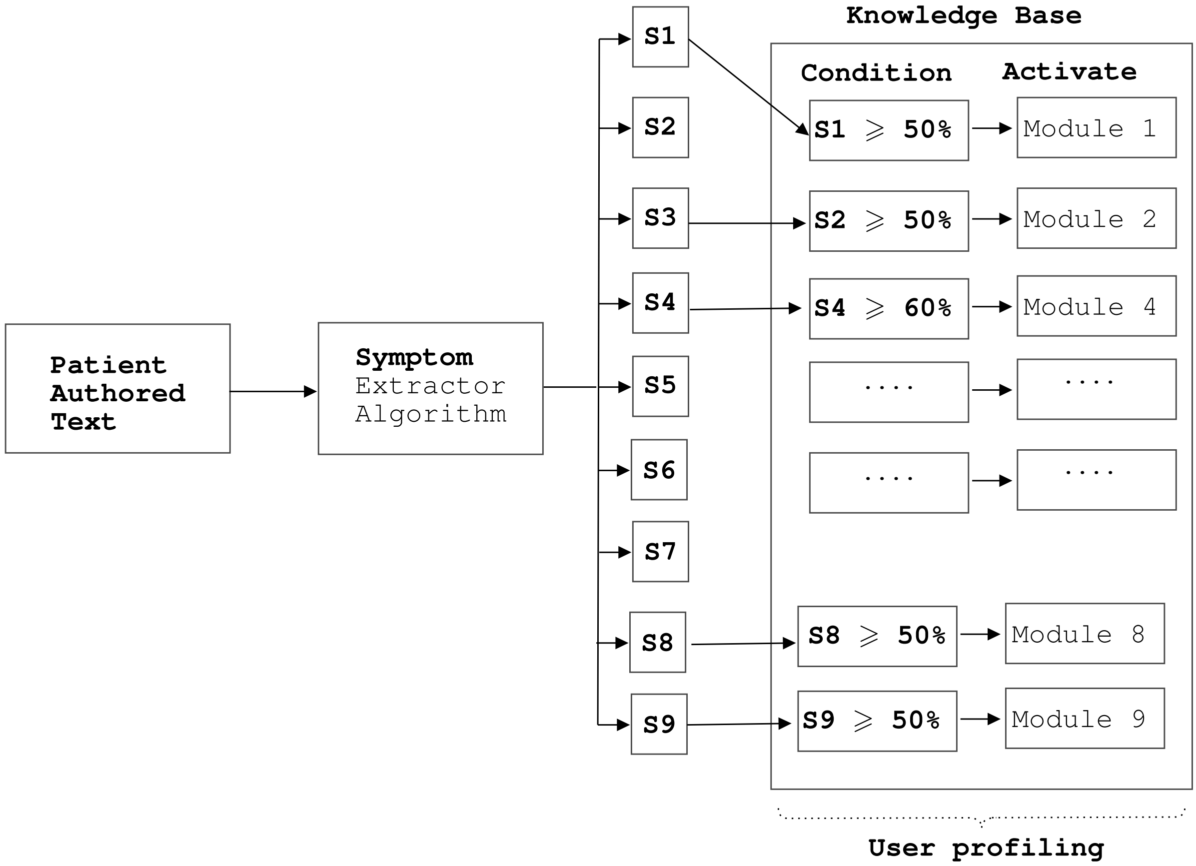

Fig. 4.8: The figure is adopted from paper E [91]. Symptom extractor algorithm takes patient-authored text as input and gives the nine similarity scores as output. Based on the user profiling, domain experts maintain a knowledge base to adapt intervention based on the symptoms detected from the patient-authored texts.

As depicted in Figure 4.8, the proposed depression symptom extractor algorithm takes patient-authored text as input and gives the nine similarity symptoms scores as output. Several possibilities of adapting intervention can be seen once the symptoms are extracted from patient-authored text. These possibilities are based on user profiling. For example, in this section, we present three use cases where `Depression2Vec` symptoms extractors can be used to adapt intervention:

- **Adapting modules based on symptoms**: As shown in Figure 4.8, if the detected symptom score is greater than 50%, we recommend a particular module to a patient.

- **Adapting tasks based on symptoms and user profile**: As mentioned in Section 4.1, an intervention contains cases that comprise several modules and tasks. A task can have several levels and modalities (audio, video, texts, slides). Suppose a profile is created for a particular user who likes watching videos and has a higher education background. Our depression symptoms extractor detects the presence of sleeping disorder symptoms. In such a case, the IDPT system can adapt tasks such that the user is presented with videos containing scientific backgrounds on the sleeping disorder.

- **Adaptive conversational agent**: As aforementioned, comprehensive user profiling is the fundamental basis for adaptation. An example of such a precise user profiling technique and depression symptom extractor is creating an adaptive conversational agent. Figure 4.9 depicts a flowchart using both the user profiling technique and depression symptom extractor. We can see the following sequence of events in the chatbot:

- Bot initiates with customary greetings and presents users with a menu to select between an existing user or a new user.

- If the user is new, the user is asked to create a profile by presenting questions about hobbies, background, goals, knowledge, and other demographics.

- If the user exists in the system, the bot asks for their unique ID to load the user's profile. If the entered user ID is correct, the bot initiates the content or modules where the user previously left.

- Once the user profile is created for the new user and the existing user profile is loaded, the bot asks the user's current context by initiating questions like how they feel today? Or how was their day?

- The user enters their current context by typing some texts. We referred to these text as patient-authored text. Once the bot has sufficient text, it runs a depression symptom extractor on the text.

- If no depression symptoms are extracted, the bot asks other follow up questions. Here, an assumption is that domain experts create a set of follow-up questions that they use in clinics to understand the patient's current context.

- If the symptom extractor algorithm detects depression symptoms, the bot loads the user profile and finds the most appropriate content and recommends it. An underlying assumption here is, we have a comprehensive profile. It means the bot knows the type of content the user prefers and engages in primarily; the bot knows the user's current depression symptoms; the bot knows the user's background.

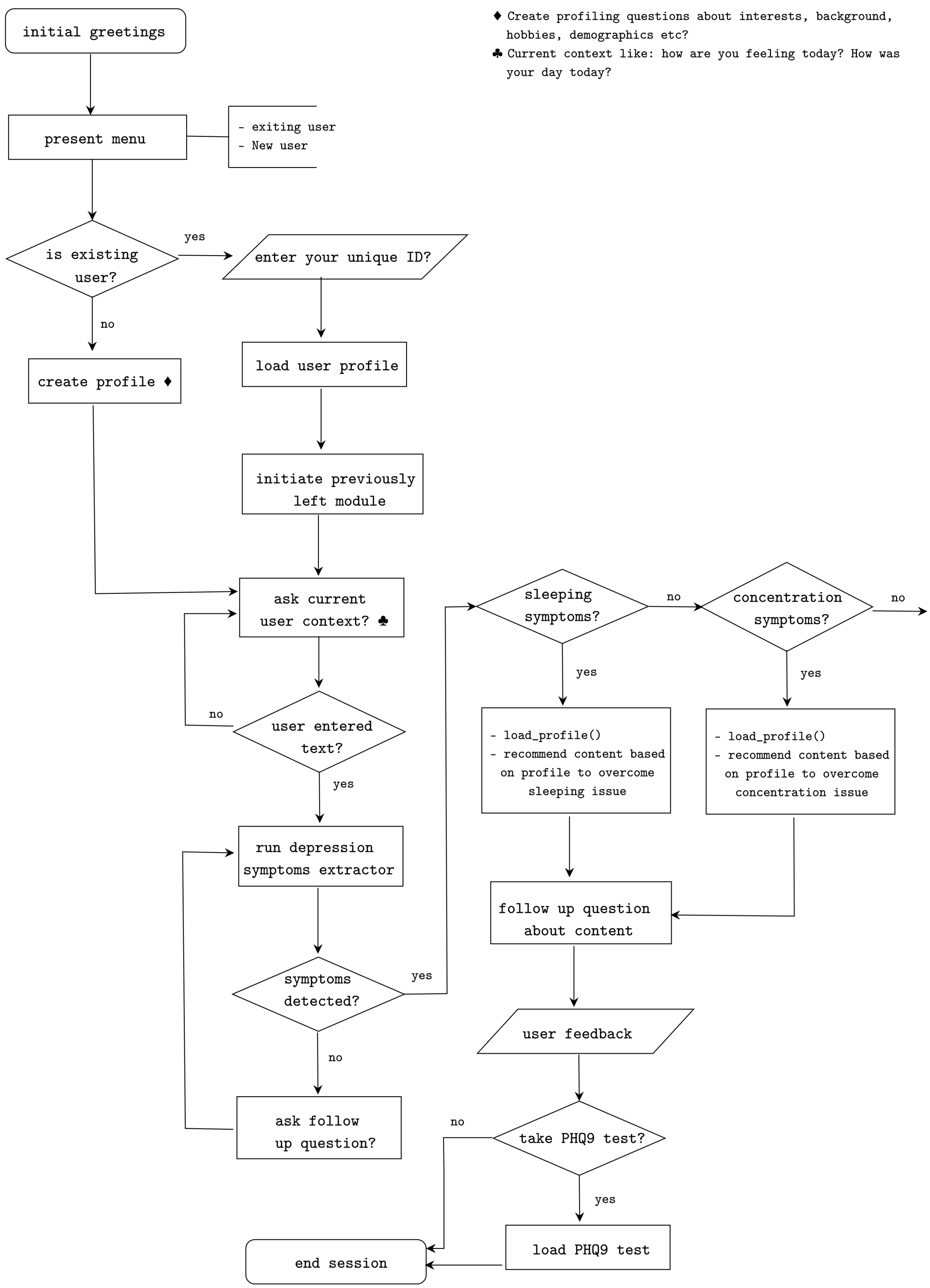

Fig. 4.9: A use case example of building an adaptive chatbot based on depression symptom extractor and user profiling

- The bot creates a follow-up question regarding the recommend content to comprehend if the user finds it interesting or helpful. All user's input is recorded and stored as interaction logs used to update the user profile.
- The bot prompts the user to take PHQ9 tests based on the settings of the bot. For example, we can configure the bot to encourage users to take the PHQ9 questionnaire twice a week.

It is imperative to mention that the adaptive conversational workflow mentioned above is an example scenario showing how user profiling and `Depression2Vec` symptoms extractors can be used. Several possible implementations can be done based on design and development preferences.

4.6.2 Adaptation based on recommendation engine and user profiling

While we have used user profiling to build a recommendation engine, this section illustrates that we can build several recommendation engines if we have comprehensive user profiles. The application of recommendation engines is prevalent in various fields, including education, news, healthcare systems, blogs, and other information systems. Such applications of recommendation engines are not surprising, as these information systems benefit from these recommendations engines, which helps to predict the most exciting content for the users, thus increasing user engagements. However, an efficient recommendation engine needs to understand the users' preferences, interests, backgrounds and other individual traits [52]. In other words, an efficient recommendation needs comprehensive user profiling. Recommended systems take the following approaches:

- **Collaborative filtering:** It is based on the assumption that people who agreed in the past will agree on the future. Recommendations are based on rating profiles for different users [1].
- **Content-based filtering (personality-based approach)**: These methods are based on a description of the item and a user profile stating his/her preferences and interests [1].
- **Hybrid recommender approach:** These approaches combine both collaborative and content-based filtering [1].

Explaining the working mechanism and other variations of the recommendation engines are beyond the scope of the thesis. As aforementioned, we aim to show that we can personalize treatments using recommendation engines once we have user profiling.

4.6.3 Adaptation based on rule-based engine and user profiling

Rule-based engines and user profiling can be combined to achieve several forms for adaption on IDPT systems. The rule-based adapting systems change their behaviour based on pre-defined rules. The psychiatrists manage these rules based on their domain expertise. These rules are in the form `IF <logical conditions> THEN <action>` as follows:

$$C_i \rightarrow A_i \tag{4.1}$$

where:

1. logical conditions C_i combine one or more basic conditions to produce a Boolean result and are connected by using the logical operators `NOT, AND, OR` (listed in descending precedence order).

   - Each basic condition is of the form `«adaptive_dimension» «operator» «value»`.
   - A *dimension* can be any adaptive dimension (psychometric questionnaire, user activity, goals).
   - An *operator* is one of the rational operators, including equal to (==), not equals to (!=), greater than (>), less than (<), greater than equal to ($\geqslant$), less than equal to ($\leqslant$).
   - A *value* can be a string or a number.

2. an action A_i represents events that will be triggered when the corresponding condition is evaluated to be `true`.

An example of the rule-based adaptation illustrated in Figure 4.10, where an adaptive system sends a reminder (based on predefined email template) to a therapist if the following conditions are `True`. There are three basic conditions (BC_1, BC_2, and BC_3) and they are composed to form the condition C as:

$$C = BC_1 \text{ AND } (BC_2 \text{ OR } BC_3)$$

The condition mentioned above is evaluated as:

1. (BC_1) is `true`, if the Psychometric score is GAD-7 (Generalized Anxiety Disorder) and its value is greater than 21 and,

2. (BC_2 OR BC_3) evaluates to `false` only if both basic conditions BC_2 and BC_3 are `false`. The expression (BC_2 OR BC_3) evaluates to `true` if any of the following two conditions are `true`:

   - BC_2: the user has not logged in to the system for more than 72 hours, or
   - BC_3: the user's goal is to decrease anxiety.

Similar to the example above, Paper D [97] outlines several such scenarios where domain experts can build rule-engines based on user profiling to achieve adaptation effect. Furthermore, we outlined example use cases for content adaptation (content materials, content presentation), reminders/alerts adaptations and user-level adaptation in Paper F [94].

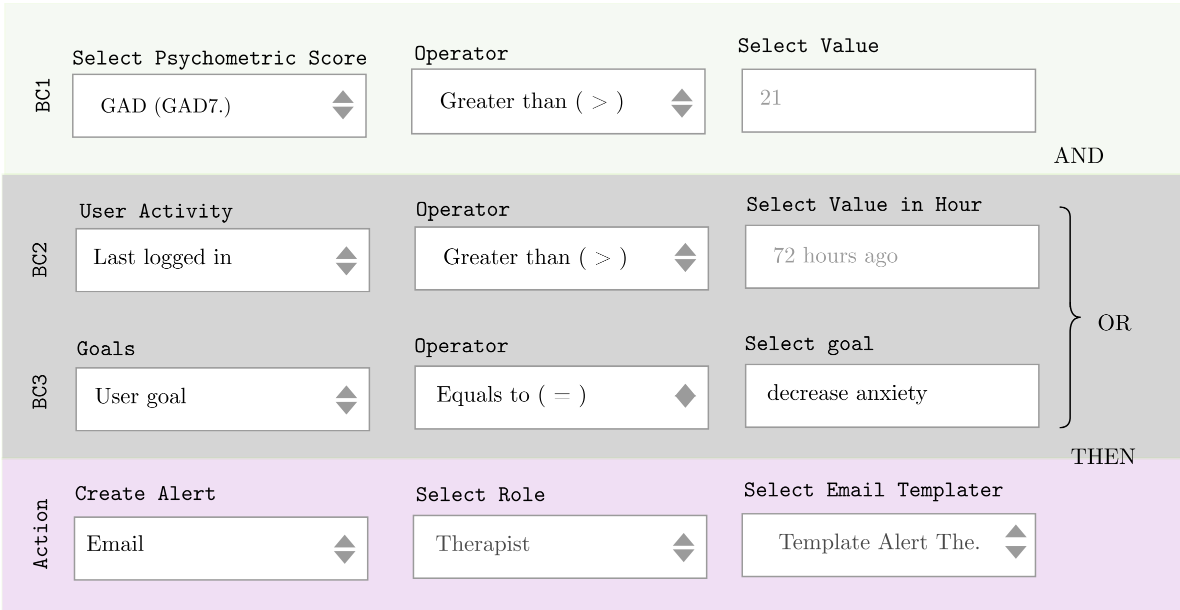

Fig. 4.10: An example illustrating *rule based adaptation* where a therapist could create several alerts based on *psychometric tests score, user activity, goals and other* appropriate variables. The middle grey coloured layer indicates the grouping of the two basic conditions (BC_2 and BC_3).

4.7 Limitations of the proposed solution

The proposed open-source framework is a preliminary prototype and can be extended in several directions. Being constrained by time, several works have been marked as the immediate future work.

- *Code coverage:* Code coverage measures the total lines of the code are executed while running the automated tests. Such code coverage measurement requires specialized tools. The framework has initiated Test-Driven Development approach, which advocates testing the codebase using unit testing, functional testing and integration testing mechanism. While a few components of the OSAIS has been unit-tested, we have not been able to make 100% test coverage. Tested code increases trust in the system. Hence, it is kept as an immediate future work.

- *The system's privacy:* We assume that patients consent to store their interaction data and other demographics data. However, in the future, we can use different anonymization techniques to store data in a format not to store and reveal sensitive information.

- *Functionality extension:* We have open-sourced the user profiling library. However, it is not integrated into the open-source framework yet. As a next step, integration of the library into the OS framework is required.

- *Testing and evaluation of the framework:* Although we have used some empirical and non-empirical evaluation techniques, as mentioned in the corresponding research articles, further testing and evaluation of the framework are required.

Such testing involves participation from both domain expert and researchers in the actual clinical context.

This chapter outlined details on the adaptive IDPT system, its reference model, reference architecture, and how user profiling can provide several adaptive effects. Furthermore, we mentioned the open-source framework developed to evaluate the proposed reference architecture. In this next Chapter 5, we will discuss how we aim to achieve interoperability in healthcare systems.

If Big Data is the new oil in healthcare, clinical & business intelligence is the refinery.

— Brendan Fitzgerald

CHAPTER 5

INTEROPERABILITY

Our literature review (see Chapter 3) uncovered two essential issues in the current IDPT system, lack of adaptiveness (addressed in Chapter 4) and interoperability. We address interoperability problems and how they are associated with the IDPT system in this chapter.

This chapter discusses interoperability and how we proposed to solve this issue in our proposed framework. First, we outline why interoperability is essential in the current healthcare context (Section 5.1). Next, we outline why it is challenging to achieve interoperability in the current healthcare context (Section 5.2). Next, section 5.3 outlines how we propose to achieve interoperability in the Healthcare Information Systems (HIS). Finally, in Section 5.4, we outline how the proposed solution addresses interoperability challenges.

5.1 Essence of interoperability

Several studies state interoperability as an essential requirement for the successful realization of healthcare systems [77, 96]. A similar conclusion is sketched by the 21st-century Cures Act [45] by the ONC (National Coordinator for Health IT in the US), which states that there are stringent measures to be taken to conquer the lack of proper electronic data management in the future. Furthermore, numerous studies outline different levels of interoperability [8, 77] and their significance in the healthcare system. With the prevalence of edge computing and IoT devices, ambient intelligence is seen everywhere in healthcare. These IoT devices rely on secured and reliable communication. Consequently, interoperability is more crucial now than ever. Following are the primary reasons why interoperability is essential:

1. **Connected technologies:** As aforementioned, ambient intelligence is prevalent. As a result, several IoT devices are used to monitor the health of patients. For example, sleep trackers in a wearable wellness device, such as Oura ring [74], are used to reveal how people sleep from duration, consistency, and timing. Sleep is one of the main contributors to our life and well-being. Sleep disorders are known to have adverse health effects, but studies have shown that too little or too much sleep is correlated with a greater risk of death. With trackers like Oura ring, physicians can not only track sleep but monitor patients health [74]; such as physical activity, monitor heart rates, track body temperature.

2. **Need for data exchange with physicians:** Data sharing is the crucial factor for physicians to diagnose, interpret, and monitor patients health. Physicians require access to patients' medical record, including hospital admission information, discharges, laboratory tests, medication lists, results of diagnosis and care plans. Having access to these data makes it possible for physicians to interpret, diagnose, and develop further care plans.

3. **Need for technological advancement in healthcare:** Digital healthcare data are expected to transform the healthcare industry. Such modifications are predominately visible in the current context, such as the application of Artificial Intelligence (AI) and big data in self-assessment, assessment, diagnosis, decision making, and monitoring of patients health. Furthermore, interoperable data are essential in a) AI and big data, b) medical communication, c) research, and d) international cooperation [78]. Big data, AI, and other analytical algorithms are fundamentally based on historical data consumption, analyzing it and providing meaningful interpretation. Failure to share data, creating data silos, and incompatible software hinders applying AI and other big data techniques to improve healthcare systems in terms of efficacy and efficiency.

4. **Patient mobility:** Mobility is one of the fundamental characteristics of people. People travel and migrate from one geographic area to another. Consequently, there is a need for sharing data from one software system to another. One of the vital issues healthcare providers face is determining where a patient has been treated previously [143]. Furthermore, previous healthcare providers' quality and quantity of data are either overwhelming or in an incomprehensible format.

It is imperative to point out that the successful realization of interoperability is a complex problem. Several challenges cause this complexity. The main reason is the lack of regulators to enforce interoperability, availability of several proprietary healthcare systems, massive data, and others. OSS is one of the potential solutions to overcome these challenges. OSS provides free source code that several developers inspect, test and maintain. More importantly, it provides transparency in how data is stored and used by the software. Nevertheless, *it is imperative to point out that OSS paves a pathway to accelerate interoperability but is not a sufficient condition. The necessary condition[1] for obtaining interoperability in healthcare systems is by following the same open healthcare IT standards.*

Open Healthcare IT Standards: Healthcare IT Standards are a set of agreed-upon representations of data and methods for communication between Healthcare Information Systems (HIS). These standards incorporate agreement for communication among HIS. Such agreement includes:

- A mechanism for enforcing secured communication
- Structure of format of data structure
- Definitions of common terminologies

[1] https://philosophy.hku.hk/think/meaning/nsc.php

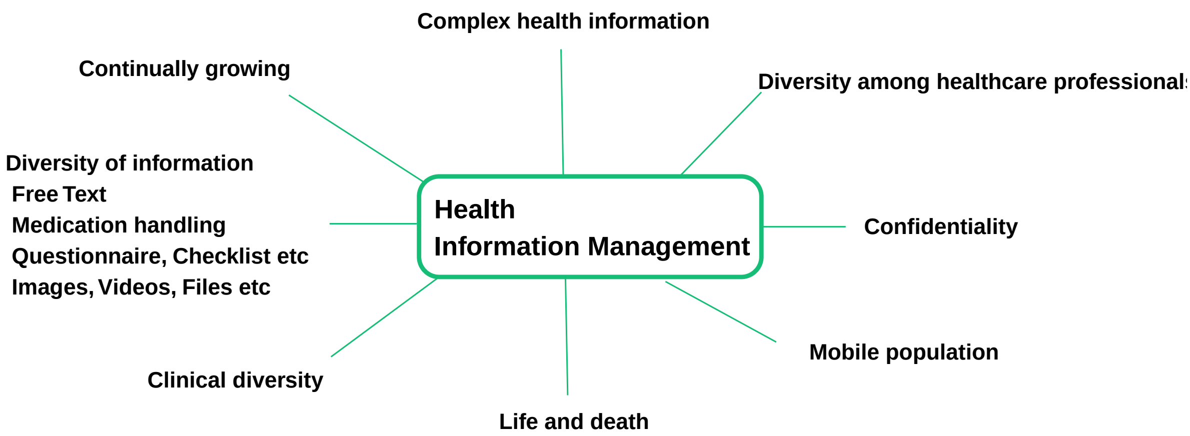

Fig. 5.1: The figure illustrates the main reasons why health data management is very complex.

- Description and architecture of the communication protocols
- A comprehensive documentations

Examples of such Healthcare IT standards include HL7 FHIR and OpenEHR. By *Open* Healthcare IT Standards, we refer to those standards which are open-sourced. In Open Healthcare IT Standards, the agreements for security mechanisms, what data is represented, how information is stored, and how they communicate is disclosed, unlike black-box proprietary HIS. Such openness enhances user trusts. Such trusts act as a motivation for them to use these standards in their HIS, promoting interoperability. We again point out that following Open Healthcare IT standards is necessary for obtaining interoperability in HIS.

5.2 Challenges in realization of interoperability

Networked computerized systems connect people making the world smaller and smaller. These enhanced connectivities accelerate reaction times as people can communicate easily. However, several challenges arise since various software and computer system, IoT devices communicate with each other for automated data sharing. With different complex systems and IoT devices networked together, several interoperability challenges arise. We outline the following primary interoperability challenges in the healthcare system and argue why they are difficult to realize:

1. **Existence of several healthcare systems:** Several EHR software systems exist, each with its interfaces and technical specifications. Consequently, it is challenging to exchange information in a friction-less way. The essential question is, *why do people reinvent the wheel and create their Healthcare Information Systems (HIS)?* Following are the main reasons why people attempt to reinvent the wheel:

    - There is lack of publicly available healthcare system.
    - Lack of trusts in the available closed-systems.

- Hunger for innovation and novelty
- Technology requires update and upgrading.
- Lack of trust in the privacy and security of the system.

2. **Lack of regulators:** There is no one to regulate with power to ensure healthcare deployment happen systematically in the global scenario. Consequently, a custom version of EHR systems and healthcare standards are followed. The obstacle with these custom standards is not that there are so diverse to pick from, but we have failed to adopt the currently available ones [8].

3. **Data explosion:** There are massive events in the healthcare ecosystem, including patient admission, prognosis, pre-assessment, diagnosis, monitoring, follow-up and others. These events show the characteristics of big data. Hence, it requires proper attention to be processed, stored and accessed. Furthermore, as depicted in Figure 5.1 health data is very complex. Complexity is due to several reasons, including clinical diversity, data related to life and death, mobile population, need for confidentiality, diversity among healthcare professionals, complex health information, continuous data growth, and diversity of information (free text, medical imaging, questionnaires, checklists, images, files, videos, presentations and audio files).

4. **Translation is complex:** Interoperability at the root level transfers data from system A (sender) to B (receiver). If both sender and receiver adhere to the same Healthcare IT standard, no translation is required. However, EHR systems have been used before these standards came into existence. Many of these EHR systems are enclosed in protected firewall and follow traditional or proprietary Healthcare IT standards. In such a case, the sender data has to translate to the format understood by the receiver and vice versa to communicate. Such translation adds extra operation. Following Open Healthcare IT standards such as HL7 FHIR removes the need for such translation.

5.3 Approaches to achieve interoperability

We believe there are two significant approaches to achieve interoperability in the healthcare system:

1. **By following the same Open Healthcare IT Standards:** Open Healthcare IT Standards provides a set of agreements on how to structure and communicate with other HIS. When these healthcare standards are used consistently and correctly, there can be high interoperability among healthcare systems. For example, if a medication is not prescribed using an appropriate medication code (using RxNorm standard[2]), another health IT system may misinterpret it. Several international organizations, referred to as Standard Development Organizations (SDOs), are involved in developing and maintaining these healthcare IT standards. SDOs constitute healthcare providers, insurers, health IT software developers,

[2]https://www.nlm.nih.gov/research/umls/rxnorm/index.html

SDO Abbr.	SDO Name	Link
HL7	Health Level 7 International	https://www.hl7.org/
ASC X12	Accredited Standards Committee X12	https://www.x12.org/
NCPDP	National Council for Prescription Drug Programs	https://www.ncpdp.org/
IHE	Integrating the Healthcare Enterprise	https://www.ihe.net/
ISO	International Organization for Standardization	https://www.iso.org/
LOINC Codes	Regenstrief Institute	https://loinc.org/
CMS (ICD-10)	Centers for Medicare & Medicaid Services	https://www.cms.gov
CDISC	Clinical Data Interchange Standards Consortium	https://www.cdisc.org/
SNOMED-CT	International Health Terminology SDO	https://www.snomed.org/

Table 5.1: Most common Standard Development Organizations

patients, caregivers, and others. Table 5.1 outlines the most common SDOs that provide Open Healthcare IT standards.

The SDOs creates, maintains and documents the healthcare IT standards. These standards are available for everyone to read, comprehend and follow. Hence, the healthcare community can abide by these standards when creating any healthcare software. By consistently and correctly following these standards, we can increase interoperability. According to [103], the two most commonly used healthcare IT standards are OpenEHR [103] and HL7 FHIR [49]. During our literature review, HL7 FHIR appeared to most predominantly used standard. Hence, we chose to use HL7 FHIR in our application.

2. **By embracing Open-Source Software (OSS) in the healthcare system:** Although several healthcare IT standards' exist, the successful realisation of interoperability in the healthcare system is still challenging (see Section 5.2). Furthermore, cutting-edge technologies such as the Internet of Things (IoT), cloud, big data, and AI have made their way into the healthcare industry. Consequently, there is a data explosion and a rapid scope of information sharing in an accessible, affordable and cost-effective mechanism. One plausible alternative to overcome these challenges is accepting the Open-Source Software (OSS) paradigm for healthcare systems. OSS appears to be a promising avenue for quickly and cheaply introducing health information systems appropriate for developing nations. Section 4.3 outlined several reasons why OSS can help in achieving interoperability. OSS helps achieve interoperability by providing free and open-access software. If such healthcare software follows open healthcare IT standards, is well tested, documented; people trust the system and use them. However, we would like to emphasise that OSS is not a sufficient condition to achieve interoperability. It means that if the software is open-sourced, it does not mean interoperability is guaranteed.

5.4 Proposed solution

Interoperability involves the ability of the systems to exchange information and comprehend the information being exchanged. Consider two EHR systems attempting to communicate with one another. The communication pattern falls mainly in one of the following scenarios:

1. *Scenario 1:* A single EHR system follows a client-server architecture and has several end-users (for example, an independent clinical EHR system).
2. *Scenario 2:* Both EHR systems follow the same open healthcare IT standard (for example, organization A follows `HL7 FHIR` version R4, and organization B follows `HL7 FHIR` version R4).
3. *Scenario 3:* EHR systems follow the same standards but different versions. (Example, organization A follows `HL7 FHIR` V3, and organization B follows HL7 version R4).
4. *Scenario 4:* EHR systems follow different health standards. (Example, organization A follows `OpenMRS`, and organization B follows `HL7 FHIR`).

Table 5.2: The table presents different healthcare systems communication scenarios and how our proposed solution addresses these communications.

Scenarios	Implementation of the scenario	Publication
Scenario 1	Uses Authorization server, Resource server for client-server communication.	Paper C [96]
Scenario 2	Uses Authorization server, Resource server, and a web client for client-server communication.	Paper C [96]
Scenario 3	Uses Authorization server, a web client and two different Resource servers following two distinct version of HL7 FHIR	Paper G [93]
Scenario 4	Uses Authorization server, Resource server, OpenMRS server, and mUzima for Health Providers using SOA architecture	Paper G [93]

Table 5.2 outlines how these scenarios can be addressed by our different studies. Most of the existing studies concentrate on the problem associated with scenario 1 and 2 from different perspectives. Interoperability can be achieved when one or more EHR systems follow the same healthcare standard (as in scenario 1 and 2). However, it becomes challenging when EHR systems [120] uses different healthcare IT standards (scenario 3 and 4). As a solution to scenario 3 and 4 problems, we propose exploiting GraphQL-based architecture to achieve interoperability among heterogeneous systems. Paper G presents a GraphQL based architecture for interoperability among several EHR systems following different healthcare standards. To justify our approach, we developed a prototype where we communicate between OpenMRS [62] and HL7 FHIR server and is outlined in Paper G. In addition to this, we present a non-empirical evaluation based on software quality metrics ISO/IEC 25000 [65], of the proposed architecture. We discuss these two papers in the next section.

Paper C: GraphQL approach to Healthcare Information Exchange: In this paper, we exploit the use of GraphQL and HL7 FHIR for HIE, present an algorithm to map HL7 FHIR resources to a GraphQL schema, outlines a prototype implementation of the approach and compare it with RESTful techniques. Our experimental results indicate that the combination of GraphQL and HL7 FHIR-based web APIs for HIE has a better performance than the RESTful approach, is cost-effective, scalable and flexible to meet web and mobile clients requirements.

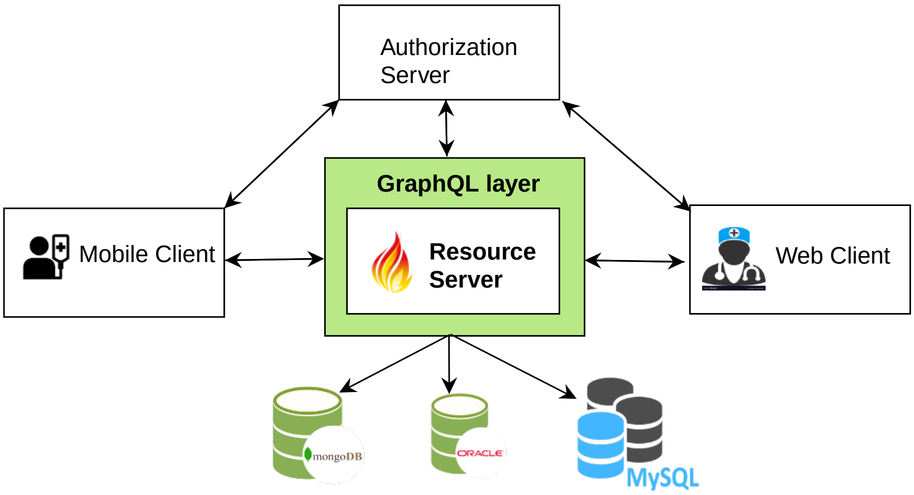

Fig. 5.2: The prototype from Paper C [96] contains five major components: a) mobile client for self-assessment, b) resource server based on `HL7 FHIR`, c) authorization server for authentication and authorization, d) web client: to provide web interface for therapist and e) mongoDB to store data.

Figure 5.2 depicts the prototype implemented in Paper C. It represents a scenario taken from the INTROMAT Project (see Section 1.4.1) and addresses above mentioned scenarios 1 and 2. As illustrated in Figure 5.2, the architecture contains the following main components communicating over SOA standards:

- **Authorization Server** is an OpenID connect compliant web server with the ability to authenticate users and grant authorization access tokens. It is the same Authorization Server as mentioned in the RA of an adaptive IDPT system (see RA 4.4).

- **Resource Server** is an HL7 FHIR [49] compliant web server with an ability to respond to `HTTP` requests consuming access tokens granted by the Authorization Server.

- **Web Client** provides an interface for therapist and administrators to login and view the list of patients, questionnaires and other resources.

- **Mobile Client** is a self-assessment mobile application that consumes *Questionnaire* HL7 FHIR resources and sends response by using *QuestionnaireResponse* resource. The main aim of developing the self-assessment application is to provide a possible way for people suffering from mental health morbidity to self-evaluate and manage their illness. Also, the application showcases the exchange of information based on `HL7 FHIR` standard to support interoperability. The application utilizes the `REST API` standard to exchange information between *mobile client* and *resource server*.

The workflow, communication details, evaluations are outlined in Paper C [96]. Our results show that the combination of GraphQL and HL7 FHIR-based web APIs for HIE has better performance than the RESTful approach, is cost-effective, scalable and flexible to meet web and mobile clients requirements. An essential point here is, the architecture and the artefacts produced in this study can address interoperability scenarios 1 and 2 as mentioned in Table 5.2.

Paper G: HL7 FHIR and GraphQL approach for interoperability between heterogeneous EHR systems: Paper G presents a GraphQL based architecture for interoperability among several EHR systems following different healthcare standards. To justify our approach, we developed a prototype where we communicate between OpenMRS [62] and HL7 FHIR server. Figure 5.3 depicts the main component of the prototype presented in the Paper.

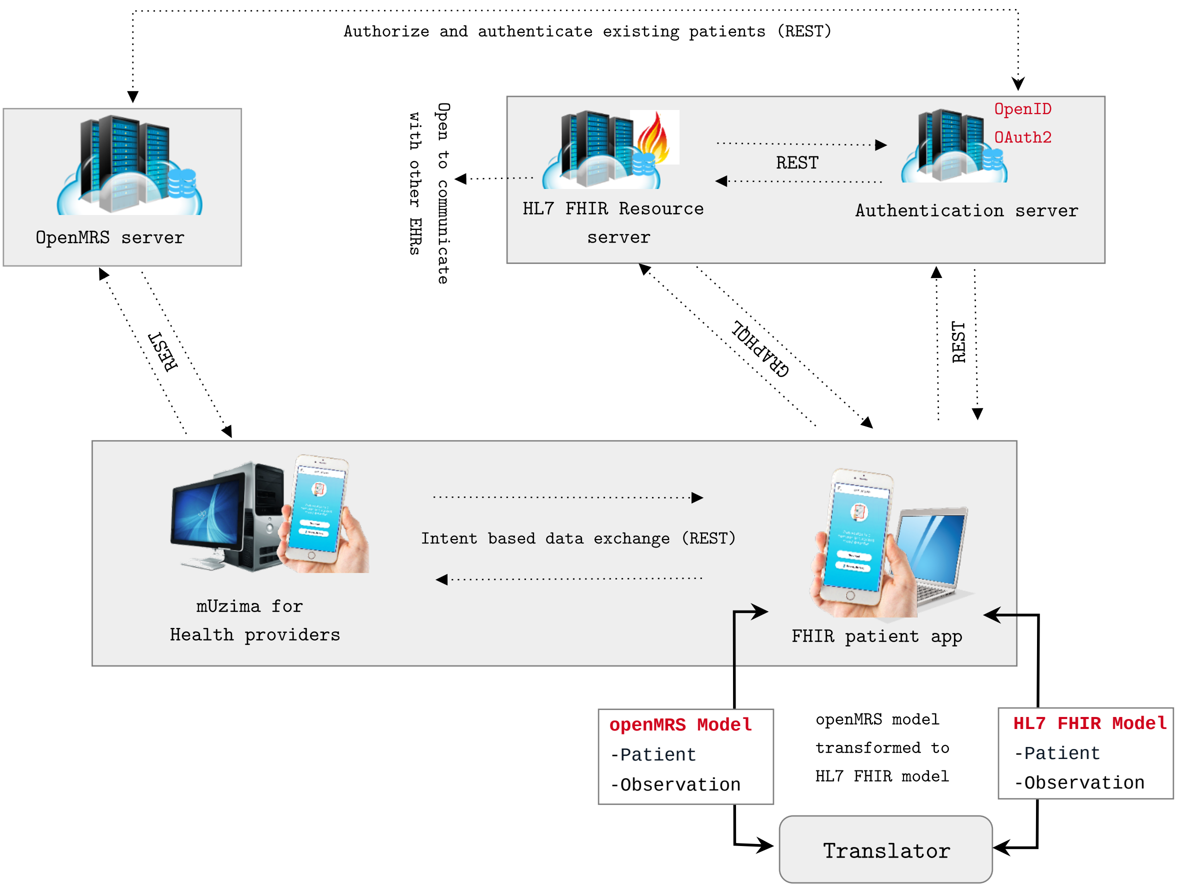

Fig. 5.3: The figure depicts our experimental setup for establishing communication between OpenMRS and resource server based on HL7 FHIR and GraphQL.

1. *OpenMRS server*: OpenMRS[62] is an open-source, configurable EHR system programmed in Java, JavaScript and several open-source components including MySQL, Apache Tomcat, Hibernate and others. It represents data in XML and XML Forms format and uses a relational database with Structured Query Language (SQL).

2. *Resource Server:* We used the same HL7 FHIR Resource server that was developed for Paper C.

3. *Authorization Server:* We used the same authorization server that was developed for Paper C.

4. *FHIR patient app:* FHIR patient app can be a mobile application or web application that assist in data interchange between wearable sensors and resource server. Moreover, we can utilize such a patient app to create a user interface for the patient to provide information or accumulate information. In SOA, both mobile and web application corresponds to the service requester/consumer components [95]. In our implementation, the FHIR patient application uses a middleman service to translate OpenMRS entities to HL7 FHIR entities and vice versa. We can delegate such translation to a separate service similar to the broker-architecture pattern[122]. However, we chose to implement a middleman service for translation inside the FHIR patient mobile application for the initial prototype.

5. *mUzima for health providers:* mUzima for health providers [133] is a client that presents interfaces authentication and authorization to the healthcare provider. The muZima health provider application provides abilities to create resources such as patients, observations, clinical process, and others for their users and present them in a dashboard, associated with their progress and activities [70].

The study's primary aim is to: a) establish technical interoperability between two different EHR systems following different healthcare standards, HL7 FHIR and OpenMRS, b) outline an architecture for exploiting `GraphQL` for achieving communication between distinct EHR systems. We outline the architecture for exploiting `GraphQL` to achieve interoperability between EHR systems following different healthcare standards. The workflow, communication details, and evaluations are outlined in Paper C [93]. Our results indicate that the proposed architecture can communicate with different EHR systems. An essential point here is, the architecture and the artefacts produced in this study can address interoperability scenarios 3 and 4 as mentioned in Table 5.2.

This chapter outlined our work in interoperability and the solution we proposed to address several communication scenarios. An essential point to remember is, we identified interoperability as a significant gap in current healthcare systems. This chapter attempts to discuss how we tried to solve these interoperability challenges using different approaches. In the next chapter 6, we will discuss the main contributions of this study, revisit the research questions, and their implications for future study.

5.5 Limitations of the proposed solution

Our proposed solutions in this chapter have outlined how to achieve technical and semantic interoperability in healthcare information systems (HIS) in general. However, constrained to time, we have not fully integrated HL7 FHIR into the proposed OpenIDPT Framework. Hence, we report the following limitations and immediate future work to obtain interoperability in the proposed framework.

Interoperability

- *Integration of HL7 FHIR into Open-source IDPT System:* The open-source adaptive IDPT system (OSAIS) does not fully integrate HL7 FHIR to communicate. Hence, it is essential to convert endpoints to use HL7 FHIR resources as an immediate future work.
- *Extensions of HL7 FHIR resource server:* We have converted most of the HL7 FHIR resources and their support to the Resource Server. However, some resources are remaining to be implemented.
- *Testing and evaluation:* To achieve 100% code coverage, we need to implement further unit testing and functional testing to the Resource Server codebase.

A conclusion is simply the place where you got tired of thinking.

— Dan Chaon, Stay Awake

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

This chapter revisits the research questions and outlines how we addressed them in this thesis (Section 6.1). Next, we discuss the main contribution (Section 6.2), list the current usage of open-source adaptive IDPT System (OSAIS) (Section 6.3), describe the implication of this work (Section 6.4), and outline the possible extensions of this study for future work (Section 6.5).

6.1 Research questions revisited

The primary aim of this research was to develop an infrastructure that could facilitate personalizing treatments of mental health problems according to user needs and preferences. To realize this aim, we identified three main research questions outlined in Section 1.3. This section revisits those questions and summarizes how we addressed them throughout our study. Table 6.1 provides an overview of different research questions, their description, methods used and which publication addressed them.

RQ1: What are the state-of-the-art works done in creating adaptive IDPT systems? What are their capabilities and limitations? RQ1 attempts to uncover previous and current works related to adaptive IDPT systems. To better comprehend the state-of-the-art works, we split RQ1 into three sub-questions. We address each of

Table 6.1: The table outlines the research questions and their corresponding overview, research methods, and scientific research papers addressing them.

RQ	Sub RQ	Overview	Method used	Addressed in
RQ1	RQ1.1	choice of IA	Systematic literature review	Paper A [98]
	RQ1.2	primary adaptive elements	Systematic literature review	Paper A [98], Paper D [97]
	RQ1.3	adaptive strategies and dimensions	Systematic literature review	Paper A [98], Paper D [97]
RQ2	RQ2.1	create RA and conceptual framework	Grey reviews, DDD, co-design workshops	Paper B [95], Paper C [96], Paper D [97], Paper F [91], Paper G [93]
	RQ2.2	AI-based adaptation	Case study, NLP techniques for symptoms extractions	Paper E [2] and [92]
RQ3	RQ3.1	evaluation of RA	SAAM method, expert evaluation, quality attributes	see Table 6.2
	RQ3.2	clinical setup, and future references	Feasibility studies, RCTs, case study in INTROMAT project	Chapter 6

them in this section.

RQ 1.1: *What are the main choices of Information Architecture (IA) in IDPT? What are the main rationales behind choosing such IA? Does the choice of pervasive IA affect user adherence?* IA deals with how people cognitively process information in any information systems. To facilitate information systems to be cognitively perceived by people, IA helps the development team structure the content to be highly discoverable and comprehensible. An underlying hypothesis of IA is, easily understandable and discoverable content engages users. Accelerated user engagements can reduce dropouts, and hence users can comprehend psycho-education materials provided by IDPT, leading to better treatment outcomes. Thus, the first **RQ1.1** attempts to understand the choices of IA in IDPT. Paper A [98] discloses the answer to this question. Our findings in this paper state that most of the current adaptive IDPT systems are tunnel-based and do not promote personalization. We encourage hierarchical IA or hybrid IA to present helpful information according to patients' needs. The primary rationale behind using tunnel-based IA is that such experience is less likely to overwhelm users with information and options. However, several studies, as mentioned in Paper A, outlines tunnel-based system hinders adaptiveness. Furthermore, several studies (see Paper A [98]) argue better user adherence with the choice of IA.

RQ 1.2: *What are the primary adaptive elements used in the architecture of the state-of-the-art IDPT systems? How do these adaptive elements contribute to enhancing user adherence and intervention outcomes?* Having disclosed the necessity of adaptiveness in an IDPT system, we must unveil what we can adapt. **RQ1.2** attempts to comprehend the primary adaptive elements used in the state-of-the-art IDPT systems. The Systematic Literature Review Paper A [98] discloses the answer to this question. Our finding reveals that an IDPT system provides this information by using different media and elements such as text, video, audio, pictures, presentations, feedback, reminders, reports, and others. These elements have their format, structure, metadata, volume, and dynamism (such as frequency of updates). It is essential to understand these elements and the associated attributes to deliver the right content to the right user in their current context.

RQ 1.3: *What are the primary adaptive strategies used in state-of-art IDPT systems? Can these adaptive strategies increase the outcome of mental health interventions? What are the main dimensions of adaptive strategies used in IDPT systems?* **RQ1.3** helps to comprehend the primary factors that provide context for adaptation, to which we refer as adaptive dimensions. Additionally, **RQ1.3** helps to understand the primary mechanisms of how adaptation can occur. The Systematic Literature Review Paper A [98] discloses the answer to this question. According to the review, the most common way to tailor the behaviour of the IDPT system is based on input regarding user preferences, measures (psychometric tests, user behaviour analysis, and others), and goals (see Table 4 in Paper A). Different types of adaptive strategies such as rule-based, AI-based predictive algorithms and recommendation-based mechanisms [1] are used. While our review findings reveal that the rule-based adaptive approach is the most widely adopted practice, other techniques, especially machine learning, are becoming highly prevalent. Further clinical trials and study are required to evaluate the efficacy of adaptive strategies in increasing treatment outcomes of mental health interventions.

RQ2: How can we utilize MDSE techniques to improve the architecture of current adaptive IDPT systems? RQ2 attempts to exploit software engineering techniques to use knowledge from the literature review and enhance the architecture of an adaptive IDPT system. To better comprehend how we can use the MDSE techniques, we split RQ2 into two sub-questions. We address each of them in this section.

RQ 2.1: *How can we utilize MDSE techniques to build a reference architecture (RA) and conceptual framework for adaptive IDPT systems?* We conducted several incremental studies utilizing MDSE techniques to comprehend and design a software framework for IDPT. Paper B [95] present a cloud-based interoperable architecture built on the top of SOA for Internet-based treatment where patients can directly interact with underlying healthcare systems such as Electronic Health Records (EHRs). We also present a prototype for screening and monitoring mental and neurological health morbidities based on this architecture. The proposed solution is based on the healthcare interoperability standard, HL7 FHIR, that enables healthcare providers to assess and monitor patients condition in a secure environment. Furthermore, to enrich understanding of interoperability and its usage in healthcare applications, Paper C [96] and Paper G [93] exploits GraphQL and HL7 FHIR for HIE. Paper C presents an algorithm to map HL7 FHIR resources to a GraphQL schema and presents a prototype to compare the RESTful approach with the GraphQL approach. In Paper D [97], we used our findings from the Systematic Literature Review to propose a reference model showing how adaptive systems are represented in classical control theory and discuss how the model can be used to specify adaptive IDPT systems. Concerning the reference model, we outline the core components of adaptive IDPT systems, the main adaptive elements, dimensions of adaptiveness, information architecture applied to adaptive systems, and strategies used in the adaptation process. These components form the proposed framework, referred to as *the OpenIDPT Framework*. Finally, in Paper F [94], we used our understanding from the studies mentioned above to design a Reference Architecture (RA) that supports flexible user modelling and adaptive delivery of treatments. To evaluate the proposed RA, we developed an open-source framework based on the proposed reference architecture. We followed Domain-Driven Design (DDD) to implement a prototype of the open-source framework and evaluate it using empirical (case study) and non-empirical approaches (SAAM method [71], expert evaluation, and software quality attributes).

RQ 2.2: *Can we use AI-based predictive algorithms to perform automated adaption on IDPT systems? What type of AI-based adaptive strategies can be used for IDPT systems?* The application of AI-based predictive algorithms to adapt intervention is getting prevalent as aforementioned. Given the premise that we can capture every digital footprint of a user, resulting in a complex and comprehensive data set, there is a possibility of using sophisticated machine learning (ML) or deep learning (DL) algorithms. However, it also raises an essential question about privacy. Categorizing different types of these predictive algorithms and their use cases in the IDPT scenario is beyond the scope of this work. However, we attempt to show how the proposed IDPT framework is capable of consuming such predictive algorithms. An IDPT system encourages user interactions by different HTML form elements. In the case of the IDPT framework, we referred to these as *tasks* (see Section 4.1). These tasks involve assignments where patients enter text about their current context and answers to the different psychological assessment questionnaire. We refer to these texts as *patient-authored text data*. Paper E presents an adaptive strategy based on NLP techniques that analyze patient-authored text data and extract depression symptoms based on a clinically established assessment questionnaire, PHQ-9 [75]. We proposed attention-based deep entropy active learning [2], as an extension of Paper E [91], using a lexical algorithm to detect depression symptoms from the patient-authored text. Furthermore, we also present how an adaptive IDPT system can personalize mental health patients' treatments based on the proposed depression symptoms detection technique.

RQ3: How can we evaluate architecture of IDPT systems? RQ3 considers the evaluation part of the proposed architectures and systems. To better comprehend the evaluation of the proposed system, we split RQ3 into two sub-questions. We address each of them in this section.

RQ 3.1: *How can we use Design Science Research (DSR) principles for evaluating the developed architecture with respect to ISO/IEC 25000:2014 software quality evaluation metrics [65]?*

Artefact evaluation is a vital activity in DSR [56] to prove an artefact's significance for actual life application [106, 127, 139]. Several forms of DSR artefacts exist, and so does several forms of evaluation techniques. Peffers et al. [106] reviews 148 different DSR articles to develop taxonomies of DS artefact type and artefact evaluation methods, and hence providing rationale and justification for an evaluation method selection. The study mentions six different DSR artefacts, *including algorithm, construct, framework, instantiation, method,* and *model*. Furthermore, the same study outlines DSR evaluation types, including *logical argument, expert evaluation, technical experiment, subject-based experiment, action research, prototype, case study*, and *illustrative scenario*. We used these DSR taxonomies to outline the DSR artefacts produced during this study and associated DSR evaluation techniques.

Furthermore, several DSR literature outlines several other types of evaluation criteria for DSR artefacts. For example, Sonnenberg et al. [127] outlines measure of several quality attributes such as ease of use, completeness, effectiveness, efficiency, robustness, simplicity, understandability and others. To cover these scenarios, we used ISO/IEC 25000:2014 software quality evaluation metrics to evaluate the artefacts produced in this study. The results of these evaluation metrics have been mentioned in the corresponding papers mentioned in Table 6.2.

RQ 3.2: *How can we use the adaptive IDPT systems in a clinical setup?* As aforementioned, this study is part of the INTROMAT project, which involved action research. It means a part of artefact produced during the study was used to study their effects on a real-world situation through Randomized Controlled Trials (RCTs). For example,

Table 6.2: The table maps the DSR artefacts produced during this study and associated DSR evaluation techniques used. We used the above mentioned DSR taxonomies developed in the DSR evaluation review by Peffers et al. [106].

Papers	DSR artefact types	DSR evaluation methods used
Paper B	Instantiation and method	Case study
Paper C	Instantiation, method and model	Prototype, technical experiment and expert evaluation
Paper D	Model and method	Illustrative scenario
Paper E	Algorithm and method	Technical experiment
Paper F	Framework	Action research, prototype, illustrative scenario, and expert evaluation
Paper G	Instantiation and method	Prototype, technical experiment, expert evaluation, and case study

Myklebost et al. performed an open-pilot study of an IDPT targeting self-perceived residual cognitive symptoms after major depressive disorder [99]. Similarly, Nordgreen et al. performed an open study to evaluate the effectiveness of guided IDPT for major depression in routine mental healthcare [101]. We provide several paths for future works (see Section 6.5) and possible implementation mechanisms in the clinical setup.

6.2 Summary of contributions

This thesis's main contributions are framed in **health informatics** (adaptive treatments and interoperability) and **software engineering** (*the OpenIDPT Framework* and its components including reference model, reference architecture, information architecture, open-source implementation (OSAIS)).

6.2.1 Contributions to software engineering

Our first contribution is in the theoretical foundations and approaches of software engineering. As mentioned by Sendall et al. [124], models are the primary engineering artefacts in Model-Driven Engineering. This thesis outlines the following models for addressing the problem domain outlined in Chapter 1:

1. *The OpenIDPT Framework:* The proposed OpenIDPT Framework aims to facilitate the development of interoperable, reusable and adaptive IDPT systems. We iteratively constructed the framework based on several studies mentioned in Papers A-G. Based on our research findings, we advocate that the framework will provide directions and guidelines for creating an adaptive system that can adapt interventions based on patient needs and preferences.

2. *A reference model of an adaptive IDPT system:* The proposed model is essential and exciting as it outlines a framework for creating any adaptive IDPT system. The framework guides healthcare providers and developers to comprehend the main adaptive elements, dimensions of adaptiveness, information architecture, and primary adaptive process. Healthcare providers and software developers

can easily extend this framework to fit into several other healthcare treatments systems.

3. *Reference architecture for adaptive and data-driven IDPT system:* The proposed RA is created after a shared understanding from several action research, case studies, prototypes and technical experiments. Hence, the proposed RA provides guidance for architectural principles and practices that forms the baseline for future implementations in the domain.

4. *Open-source software for adaptive IDPT system (OSAIS):* As mentioned by the DSR evaluation framework [106], prototype implementation is an essential evaluation method for DSR artefacts. We developed an Open-source software of the IDPT system that is based on the proposed RA. We refer to it as Open-Source Adaptive IDPT System (OSAIS). Additionally, we open-sourced a user profiling library that any IDPT system can use to build a comprehensive user profile.

6.2.2 Contributions to health informatics

Our second contribution falls within the approaches of health informatics. We outline the following contributions in the health informatics domain:

1. *A system for creating adaptive intervention:* The Open-Source Adaptive IDPT System (OSAIS) incorporates detailed CMS and user profiling feature that can help adapt interventions. The framework can be extended to create several digital healthcare treatments.

2. We provide *comprehensive guidelines on developing an adaptive IDPT system based on the Person-Based Approach (PBA)* [13]. This approach is explicitly developed for mental health interventions and health management. Hence, the proposed reference model and the guidelines are comprehensible to domain experts.

3. *Open-source Resource server:* We present an open-source Resource Server based on GraphQL and HL7 FHIR for enhancing interoperability in healthcare systems. This server is interesting as it can be used in any healthcare system that wishes to communicate with HL7 FHIR. Moreover, it uses GraphQL, hence inheriting its benefits over RESTful approaches.

6.3 Current usage of Open-Source Adaptive IDPT System

Some researchers are currently using the Open-Source Adaptive IDPT System (OSAIS) designed and developed to evaluate the reference architecture proposed in this study. The framework extensions serve as an evaluation of the current work and provide several opportunities to enhance the system's features.

1. **Mood-tracking mobile application**: *Astrid Hamre-Os*, a master student at the University of Bergen (https://www.uib.no/), extended the Open-Source Adaptive IDPT System (OSAIS) to use it as a back-end system for a mood tracking mobile application. Her thesis is entitled, "*A mood tracking interface for a mobile application*

- *to help assess well being in students*". She is using this OSAIS to illustrate students' profile for emotions.

2. **Headless CMS API by Helse Vest IKT**: HelseVestIKT [1] delivers all ICT services to specialist health services in Western Norway. We had an opportunity to collaborate with their team, organize several workshops and present our adaptive IDPT reference model and architecture. Based on these models, their team developed a headless CMS API[2] for healthcare providers. This API is intended to be used by mental health treatments providers who can consume the API to develop different user interfaces like web applications, mobile applications, conversational agents and games. The CMS API acts as a library for reusing IDPT.

3. **Lifekeys project:** Lifekeys[3] is a Norwegian mental health treatment provider that gives online psychologist services in video consultations and theme-based seminars with selected psychologists. As a part of their study, we used the self-assessment mobile application developed during Paper B [95] and the Open-Source Adaptive IDPT System (OSAIS) as the backend system to collect responses given by the mobile app users.

4. **Usage of Resource Server and Authorization server in mUzima Project**: mUzima[4] is an android-based mobile application for health workers and providers facilitating the collection of healthcare data. It has been deployed in Western Kenya to care for diabetes, hypertension, HIV/AIDS patients through community extension health workers and nurses. The mobile applications use OpenMRS as the backend system. We collaborated with this project to help them migrate from OpenMRS to HL7 FHIR. During this process, we used our open-source Resource Server and Authorization Server. We attempted to communicate between two different EHR systems during this project, namely OpenMRS and HL7 FHIR based Resource Server. The methods, workflow and results are published in Paper G [93].

5. **Master students at HVL**: Open-source projects produced during this thesis gave opportunities for several master students at HVL to use, analyze, and extend in several directions. Following are the students who used or are currently extending open-source projects:

    - *Marianne Luengo Fuglestad*, a master student at HVL, is extending the Open-Source Adaptive IDPT System (OSAIS) by building an ontology system for IDPT. The working title of her master thesis is "*Facilitating Flexibility and Reuse in Internet-Delivered Psychological Treatments with Hierarchical Structures*". She is extending user profiling with hierarchical models.
    - *Roger Wisnes*, a master student at HVL, is extending the Open-Source Adaptive IDPT System (OSAIS) to facilitate the dynamic assessment of the

[1] https://helse-vest-ikt.no/
[2] https://dev-content-intromat-apim.developer.azure-api.net/api-details#api=intromat-content-api&operation=GetMyToken
[3] https://lifekeys.no/
[4] https://www.muzima.org/

psychological intervention. The working title of his master thesis is "*Dynamic assessment of psychological interventions*". His work is expected to produce GUI for Graph-based information navigation.

6.4 Implications of this work

It is not easy to predict how technologies will develop over time and whether these technologies will continue adapting to clinical use. However, based on the preliminary results of this thesis, we outline some implications for ICT researchers and healthcare researchers:

Implications for ICT Researchers: With an increasing trend in user adherence toward online interventions on the one hand and the prevalence of the Internet of things (IoT), with growth in ambient intelligence technology, on the other, there is an expectation that the IDPT systems will flourish over time. Many health care interventions delivered via the Internet have a similar format, as most of them are based on psycho-education. All such interventions attempt to create adaptive elements and tailor these elements based on adaptive dimensions using adaptive strategies. Hence, it makes sense to create a conceptual framework that we can utilize in several health care domains.

Findings from the study can help to identify the essential variables that are associated with an adaptive system. With this IDPT framework, ICT researchers and formulate Domain-Specific Language that can be used to capture requirements for several healthcare cases. The proposed framework adopts a comprehensive user profiling technique. User profiling data open the gate for using several Artificial Intelligence algorithms, recommendation engines, and recent ambient intelligence. The proposed open-source framework has the potential to be used for several healthcare scenarios. Hence, it can be extended in several directions, including the introduction of ontology, creation of DSL, visualization techniques, and others.

Implication for Health Care Researchers: While the current research evidence is fragmented about the benefit of an adaptive IDPT system on treatment outcomes, this review suggests that adaptive IDPT systems can benefit people with mental health issues by providing personalized psycho-education. Such an education will help mental health patients to manage their illness. In addition, a high number of health care researchers have published about adaptive interventions. Their results indicate that both health care researchers and computer researchers believe that adaptive interventions are an essential phenomenon to accelerate user adherence.

There are underlying theories behind interventions that are designed for treatments of mental and neurological disorders. Hence, cooperation between ICT and health care researchers is essential during designing and developing any healthcare system. While more randomized controlled trials are required to validate the effectiveness of adaptive treatments, the results of this study suggest that the adaptation of mental health interventions can enhance user adherence and treatment outcomes. Healthcare researchers can help to validate the proposed architecture, framework and open-source

IDPT system by applying the system in several use cases. Such use cases can reveal the bottlenecks for the current system and provide guidelines for future improvements.

6.5 Future work

Our work puts a foundations milestone of creating a Healthcare Information Systems (HIS) using the OSS paradigm. The presented reference model, RA and the framework for the IDPT system unveils many directions for future work, including in the areas of *theoretical foundations and approaches of software engineering*, *health informatics*, *artificial intelligence*, and *human-computer interactions* (HIC). This section outlines some of these possible future works.

6.5.1 Future work in the Software Engineering direction

We envision the following work in the directions of software engineering:

- One of the challenges we faced during this study was the lack of standard methods to elicit healthcare requirements from the domain experts. In the future, we need Domain-Specific Languages (DSL) for the healthcare domain to facilitate the development of scalable, interoperable, and secure systems.
- There is a need for visualization tools that assist therapists and other medical practitioners to comprehend the patients' history, current context and the possible presence of patterns.
- Immediate work is to continue adopting OSS in the healthcare domain, motivate healthcare providers, the open-source community and researchers to work on it.
- Improvement of the proposed model, RA, and open-source framework for the IDPT system based on current technology is essential for future work. Furthermore, we motivate researchers and healthcare providers to evaluate the proposed OSAIS.
- Our current open-source framework lacks unit testing in several modules. The inclusion of extensive Test-Driven Development (TDD) and its empirical measures are an interesting direction to explore.

6.5.2 Future work in the Artificial Intelligence direction

AI is practised, researched and applied in both academia and industry. Consequently, several trained models and algorithms are available with better and higher precisions. With comprehensive user profiling models included in the IDPT system and the open-source framework, the data captured from this profiling can be used to build different comprehensive conversational agents, interactive systems and predictive algorithms. While there are several directions on how AI can be integrated into IDPT context, we envision following immediate future directions:

- According to ARK Investment Management LLC report of 2021 [5], *conversational agents* are among the top industry in the upcoming future. Conversion of the IDPT system into conversational agents, as illustrated in Chapter 4, could increase user adherence. Increased user adherence is justified because conversational agent hides the underlying complexity, hence not overwhelming patients with several exercises and activities at once. Moreover, conversational agents provide a feeling of two-way communication for people. An underlying assumption here is, these agents have higher accuracy of comprehending and responding to user queries.

- AI-practitioners in both Researchers and industry open-sources trained model, for example, models by AI Hub [5]. These models provide opportunities for using user profile data to build predictive models, recommendation engines or pattern mining.

- It is interesting to use AI techniques in healthcare. However, privacy is a burning question in AI. Exploring privacy-related issue in the case of the IDPT system is essential as well as attractive.

- Humans should understand the results of AI-based models. This concept is advocated by **Explainable AI (XAI)** and is relevant in the current HIS. XAI can improve the user experience by enhancing user trusts and can facilitate making informed decisions. Hence, future works in the direction of XAI in HIS is exciting and required.

6.5.3 *Future work in the Human-Computer Interaction direction*

To further improve the user-friendliness of the presented open-source IDPT System (OSAIS), we can perform several HCI studies. Enhancing usability, performance and interaction designs are on the top priority.

- The creation of adaptive systems for mental health involves designing and developing web, mobile, VR and AR applications. When designing and developing software systems, usability plays an essential role in determining user adherence to it. One way to extend the current work is to perform extensive usability evaluation and enhance the system.

- Interaction design (IxD) is another field that fits well in the current study and worth extending. Our goal is to increase user adherence and hence treatment outcomes. Hence, how the users interact with the system is an essential phenomenon. While the objective is to increase user engagement, understanding these engagements' philosophies, principles, and behaviours is essential. This understanding is essential as user interaction comes with *interaction cost*. For example, in a conversational agent, we would encourage patients to provide as much information as possible. However, in a psychological intervention course, we aim to reduce the number of interactions required to enrol by removing multi-step forms. It is an exciting and crucial study direction from the current status of this study.

[5]https://cloud.google.com/ai-hub/docs/use-model

6.5.4 Future work in the Health Informatics direction

IDPT systems belong to the health informatics branch. The health domain is sensitive as it deals with users, health, personal data, and privacy. Hence, it is imperative to research and find a secure way to design, develop and implement healthcare systems. The same applies to the Open-Source Adaptive IDPT System (OSAIS). We envision the following essential future study in the health informatics domain:

- **Patients' privacy:** We made an underlying assumption in the current IDPT system that the system creates, stores, and uses informed patients data. In other words, the patients are provided with clear information about what data is being stored in the system, and they provide proper consent to store those data. However, we may extend this paradigm to find methods to anonymize dataset such that users sensitive information is not stored. Analyzing, designing and implementing privacy algorithms in this study is beyond the scope of this work. However, it is considered a crucial and ongoing study as part of the INTROMAT project.

- **Factors associated with user adherence:** Several factors affect user adherence towards digital therapy and are often associated with patients personal context. Hence, further study must comprehend the user's current context and variables associated with user adherence. Patients beliefs and expectations towards the treatment are more significant for a successful intervention than demographic or clinical factors [3]. Hence, future healthcare systems need to model their domain to increase trust in the treatments provided.

- **Interoperability:** While we have laid some groundwork on interoperability using HL7 FHIR and GraphQL, further investigation is needed, especially in techniques required to migrate from legacy systems to new HL7 FHIR systems. Further development, testing and maintenance of the presented resource server and using them in healthcare systems, testing their performance and enhancing their capabilities are some of the immediate work.

- **Clinical trials:** It is essential to test the developed system with actual users. While a part of artefacts produced during this study was tested with RCTs, there is further need to perform action research. Corrections can be done in a pilot trial where the developed adaptive IDPT system is accessed by users who test if an intervention is technically working, the presence of logical errors, and other functionalities by initial requirement specifications. The testing of adaptability in a clinical trial requires an evaluation of all potential configurations of adaptive components. User study, testing and clinical trials are core ways to extend and improve the current work.

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Part II

ARTICLES

PAPER A

SCIENTIFIC PAPER I

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Review

Adaptive Elements in Internet-Delivered Psychological Treatment Systems: Systematic Review

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Abstract

Background: Internet-delivered psychological treatments (IDPTs) are built on evidence-based psychological treatment models, such as cognitive behavioral therapy, and are adjusted for internet use. The use of internet technologies has the potential to increase access to evidence-based mental health services for a larger proportion of the population with the use of fewer resources. However, despite extensive evidence that internet interventions can be effective in the treatment of mental health disorders, user adherence to such internet intervention is suboptimal.

Objective: This review aimed to (1) inspect and identify the adaptive elements of IDPT for mental health disorders, (2) examine how system adaptation influences the efficacy of IDPT on mental health treatments, (3) identify the information architecture, adaptive dimensions, and strategies for implementing these interventions for mental illness, and (4) use the findings to create a conceptual framework that provides better user adherence and adaptiveness in IDPT for mental health issues.

Methods: The review followed the guidelines from Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The research databases Medline (PubMed), ACM Digital Library, PsycINFO, CINAHL, and Cochrane were searched for studies dating from January 2000 to January 2020. Based on predetermined selection criteria, data from eligible studies were analyzed.

Results: A total of 3341 studies were initially identified based on the inclusion criteria. Following a review of the title, abstract, and full text, 31 studies that fulfilled the inclusion criteria were selected, most of which described attempts to tailor interventions for mental health disorders. The most common adaptive elements were feedback messages to patients from therapists and intervention content. However, how these elements contribute to the efficacy of IDPT in mental health were not reported. The most common information architecture used by studies was tunnel-based, although a number of studies did not report the choice of information architecture used. Rule-based strategies were the most common adaptive strategies used by these studies. All of the studies were broadly grouped into two adaptive dimensions based on user preferences or using performance measures, such as psychometric tests.

Conclusions: Several studies suggest that adaptive IDPT has the potential to enhance intervention outcomes and increase user adherence. There is a lack of studies reporting design elements, adaptive elements, and adaptive strategies in IDPT systems. Hence, focused research on adaptive IDPT systems and clinical trials to assess their effectiveness are needed.

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KEYWORDS

cognitive behavioural therapy; internet-delivered psychological treatment; adaptive treatment; internet-based treatment; adaptive system; mental health; literature review; architecture centric development; tailored internet interventions; flexible mHealth internet interventions

Introduction

Research accounts for internet-delivered psychological treatment (IDPT) as a useful therapeutic tool [1] with increased potential to provide evidence-based mental health interventions for the far-reaching population at a lower cost [2,3]. However, actual user adherence to such interventions is low [4-8]. These results raise a critical question in IDPT: how can the clinical effect of IDPT be improved? Therefore, it is relevant to focus on the factors associated with enhancing user adaption toward such interventions.

Some studies have found that providing therapist contact for online guidance and support during interventions increases adherence and effect sizes [7,9-14]. Clarke et al [15] added telephone calls and postcard reminders from therapists to increase user adherence. The study concluded by discovering no significant difference between intervention groups with or without reminders. However, a similar study done by Farrer et al [16] to evaluate the effectiveness of a 6-week IDPT for depression with and without telephone interaction concluded that IDPT is effective both with and without tracking for reducing depression. The results indicated that the success of an intervention depends on the environmental settings in which they are performed [16]. Similarly, some studies increased the frequency of emails from therapists to increase user adherence. Klein et al [17] conducted a study to examine if the frequency of therapists' contact (from 1 email per week to 3 emails per week) made a difference in user adherence. The study concluded that the effectiveness of IDPT might be independent of the frequency of therapist support. Hilvert-Bruce et al [18] conducted a study to investigate if the drop out of users of IDPT was caused by lack of treatment efficacy, if changes in the choice of treatments, reminders, and financial cost improves adherence, and finally, if the addition of clinical contact improves user adherence. The results of the study showed that adding reminders, and increasing the choice of treatments, cost, timing, and contact with clinicians improved user adherence [18]. These findings illustrate that the baseline predictors of adherence vary across studies.

A systematic review by Christensen et al [7] discovered that disease diversity, treatment length, and predicted chronicity are essential factors contributing to user adherence in IDPT. Similarly, clinical severity has also been indicated as one of the crucial factors contributing to user adherence in web-based interventions targeting problematic drinking [19]. Similar factors have been identified as the most prominent factors in user adherence toward IDPT. However, only a few studies have discussed why the target group chose not to adhere to any specific IDPT system. The most common reasons cited for nonadherence in state-of-art studies were that (1) people believe they have made sufficient progress, (2) users reported there was too much content without much flexibility, (3) users reported that treatments were too complicated, (4) treatments did not match users' expectations, (5) there was a lack of therapist contact, and (6) there was a lack of personalization. A meta-analysis by Vandereycken and Devidt [20] concluded that the target groups chose not to adhere to the eating disorder treatment because they believed they had achieved sufficient progress. However, a lack of progress is not related to nonadherence, according to several other studies [7,17]. According to a survey done by Johansson et al [21], participants chose not to adhere to the treatment when they were unable to perceive a compatible correlation between the length of weekly text modules and the conditions in their personal life. Moreover, the participants found the content to be a tiresome burden because of the length of the text modules and time consumed to go through them. Furthermore, the fixed format of the content sent to the participants each week was perceived as inflexible for some participants. Content complexity was perceived as challenging to comprehend and to process by individuals participating in interventions [8,21], especially when these individuals considered themselves to have attention problems or limited reading and writing skills. Participants' knowledge and expectations about the treatment process have shown to influence user trust and hence adherence [22]. Johansson et al [21] outlined in their study that participants mentioned they were grateful for being offered the treatment. However, not all of them appeared to be fully aware of the treatment and its significance. A similar conclusion was drawn by Alaoui et al [23], who identified higher treatment credibility to be the most influential prognostic factor for user adherence. Feedback has been thought to increase user adherence for 65% of intervention participants [19]. Similarly, a study by Johansson et al [21] revealed that the lack of therapist support during interventions was perceived by patients as a sign that therapists did not care about their health care issues. Furthermore, some participants reported that they never prioritized their personal development because they were aware that face-to-face meeting was not required. A recent study on mental health indicated that compliance failure can result from a lack of personalization [24]. A study by Doherty [25] claimed to have improved user adherence with the IDPT system by focusing on user personalization.

Most of the research examining the causes of low user adherence to IDPT has discovered that the reasons associated with patients were about personal and interpersonal competencies, and lack of resources rather than the diagnosis or health problem severity [7]. Moreover, it was about the patient's intrinsic motivation to change, their self-relatedness, and their receptivity to change. Levey and Clarkin [26] characterized this reason as the patient variable. Considering this as the reason for premature termination of interventions indicates a need to investigate the reasons and circumstances for nonadherence further. Specifically, this indicates a gap in the literature concerning the in-depth exploration of the subjective reasons for nonadherence in online psychological interventions. In general, the factors affecting premature termination of participants from IDPT, as outlined by Johansson et al [21], can be characterized by the interaction between the participant's perception of the treatment (content complexity, therapist feedback, and information about significance) and the participant's situation (awareness about the treatment, availability, daily routines, treatment expectations, and perceived language skills). Analogously, a report by the World Health Organization [27] distinguished five interacting dimensions affecting adherence to medication, therapy, and health care in general: socioeconomic factors, therapy-related factors, patient-related factors, condition-related factors, and health system/health care team–related factors. The same report claimed that relatively limited research has been done on the effects of health system/health care team–related factors on adherence.

In this paper, we propose that in addition to these two factors (perception of treatment and personal situations), a third factor is contributing to user adherence: the adaptiveness of the IDPT system. There are two perspectives here: adaptiveness and information architecture (IA) [28]. First, IA is associated with how people cognitively process information and enhances the ability of the participants to find information. Second, adaptiveness refers to an ability in the system to change in response to environmental changes. The former perspective makes the information presented in IDPT comprehensible and discoverable, while the latter makes the IDPT more personalized. In this paper, we argue that both adaptiveness and IA are essential elements that contribute to user adherence in IDPT. Hence, we aim to investigate the following research questions in this literature review: (1) what are the most prevalent choices of IA in existing IDPT systems, and what is the primary rationale behind choosing an IA?, (2) what are the primary adaptive elements in IDPT systems, and how do these elements contribute to enhancing user adherence and intervention outcomes?, (3) what are the primary adaptive strategies used in IDPT systems, and how do these adaptive strategies consume adaptive elements to generate personalized experience for mental health patients?, and (4) how can we generalize the results to create a conceptual framework that can be used in the creation of an adaptive IDPT system for mental health interventions?

To the best of our knowledge, limited research has examined the experience of nonadherence in the IDPT system based on IA and adaptiveness as affecting factors. In this study, we focus on reviewing the adaptive elements and IA in the current IDPT systems used for the treatment of mental illness. Our review shows that several different terms are being used to describe similar IDPT systems. Interventions involving the internet as the communication mechanism are referred to as web-based treatments, web-based interventions, online treatment, computerized psychotherapy, e-therapy, eHealth, internet-based cognitive behavioral therapy, digital interventions, web app–based psychotherapy treatments, therapeutic web-based interventions, eHealth interventions [29], and others. Analogously, other variations include creation of technical platforms such as Interapy [30], Deprexis [31], ULTEMAT [32], digital behavior change interventions [33], and smartphone-based apps with specific brand names [34]. The absence of any taxonomic preferences and professional ontology makes the field of IDPT inconsistent and ambiguous. The use of a multitude of terms and labels to describe similar health interventions makes it difficult to search the results of studies. To be consistent, we chose to use the term IDPT, as suggested by Andersson et al [35].

Methods

We conducted the review according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [36]. Here, we present the methodology we used to search, analyze, and extract pertinent information from relevant studies.

Search Strategy

We searched the databases recommended by Cochrane [37], including Medline (PubMed), ACM Digital library, PsycINFO, EMBASE, CINAHL, and Cochrane, to identify studies. In addition, we hand-searched the reference list of the selected publications to retrieve additional relevant publications. The search string included Adaptive, OR Flexible, OR Tailored, AND Internet, AND Interventions, AND Mental Health (see Multimedia Appendix 1 for detailed search string). Each term included medical subject headings, and the search was done on full-text papers. The search was limited to all papers published in English from January 2000 to January 2020. The database searches and subsequent review were performed by the same two authors (SKM and JDW) independently in a double-blind process.

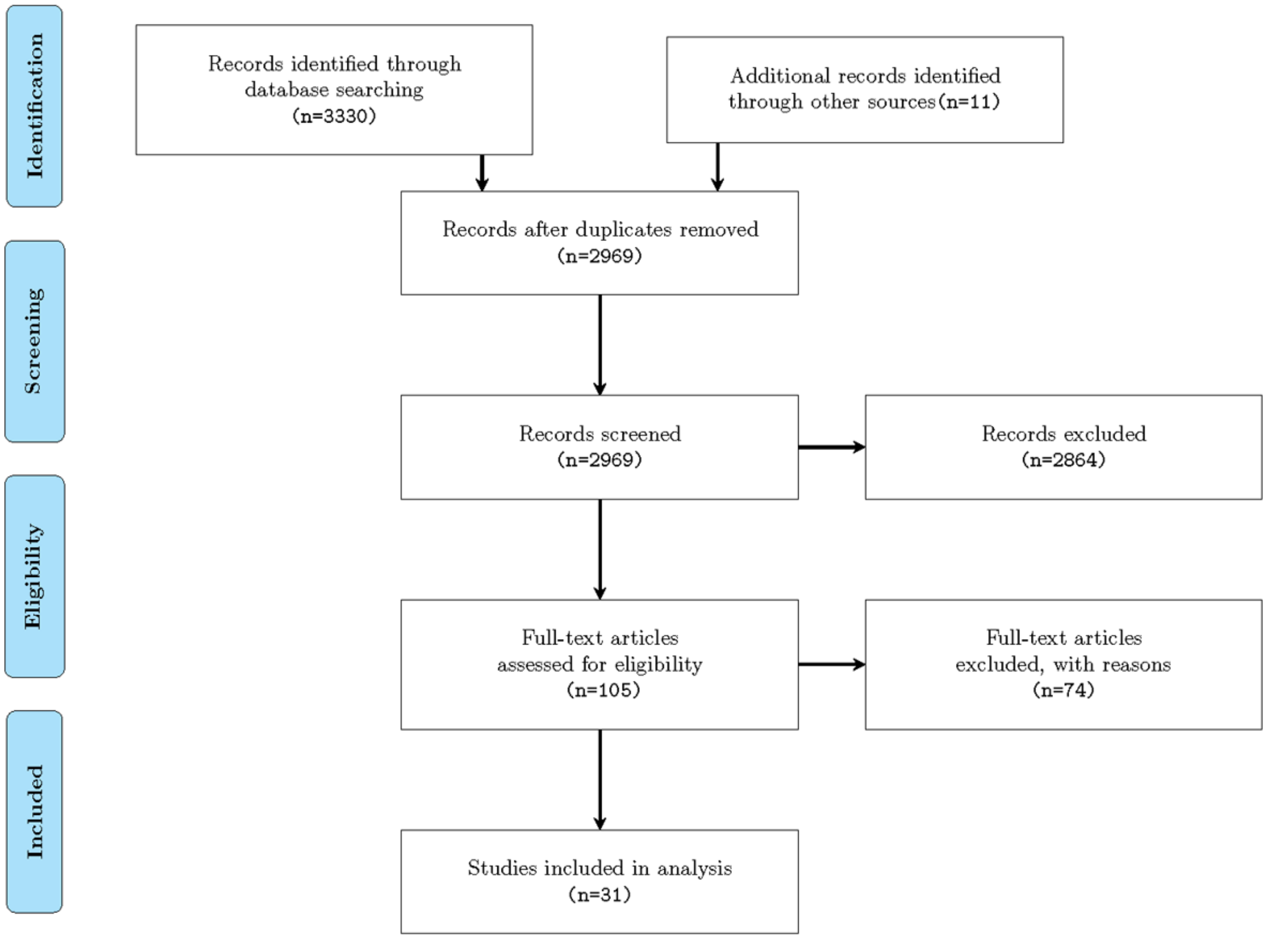
Eligibility Criteria

We included studies in which the articles met the following inclusion criteria: (1) discussed an intervention delivered through the internet (web- or mobile-based), (2) attempted to provide adaptive (dynamic, tailored, flexible) interventions by using adaptive strategies, (3) targeted a mental health disorder defined by the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) [38], and (4) was published between January 2000 and January 2020. No data restrictions were imposed. The following exclusion criteria were used: (1) not written in the English language, (2) not a full-text paper or published in the form of a short paper, extended abstract, abstract or poster, (3) designed as nonempirical findings such as opinion papers, reviews, editorials, letters, agendas, or study protocols, (4) dealt with adaptive technology in any domain other than mental health, or (5) was not about adaptive technology.

Review Procedure

The selection of studies took place in three phases based on the review of the title, keywords, abstract, and full text. Title and abstract screening were carried out blinded for author, journal, and date of publication. Any doubtful papers were included in the next phase, and disagreement was resolved through discussion. After identifying 3341 relevant papers in the initial database search, 372 duplicate papers were removed, and 2969 unique papers remained. In the screening step, the resulting list of 2969 papers was reviewed independently by the same two authors according to inclusion and exclusion criteria. By reviewing the title, abstract, and keywords, 105 eligible papers were retrieved. Two main reasons for the substantial exclusions were (1) the search engine returned the results containing any of the search terms, although they were logically connected, and (2) most of the papers were related to mental health without any reference to IDPT. Full texts were evaluated to determine the eligibility of the remaining papers. The full texts of the 105 eligible papers were assessed independently by the same authors. Any discrepancies between the authors regarding the selection of the papers were resolved through discussion. In total, 74 papers were excluded in this round, and the selection process led to the inclusion of 31 papers, as illustrated in Figure 1. The most common reason for exclusion in this phase was that the publication did not discuss an intervention delivered via the internet. Other publications were excluded because they focused on other types of health care interventions without clear information about IA, user adherence, or adaptive strategies.

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for this systematic review.



Data Extraction and Synthesis

Data from the included studies were extracted, verified, and tabulated for review by the authors. From the selected studies, we chose to obtain the main adaptive elements, adaptive strategies used, adaptive dimension, and actor involved in adaptation. Multimedia Appendix 2 provides a detailed summary of the analysis of the 31 articles in the review. All of the articles in the analysis are listed in the references [11-14,24,32,39-63]. We evaluated all of the relevant studies based on the adaptive IDPT model previously described [28]. As mentioned in the study [28], we extracted the core components of the adaptive reference model, including adaptive elements, adaptive dimensions, IA, and adaptive strategies. The rest of our results are based on these core components.

Data and Software Availability

For purposes of transparency and reproducibility of our study, we have published the resulting data, code, and procedures on GitHub [64]. The GitHub repository includes raw articles extracted from database searches, keyword formulation documents, preprocessed article lists, and a literate programming script used for data preprocessing, analysis, and visualization.

Results

Mental Health Illnesses Addressed

A significant number of the included studies addressed depression (n=11) and anxiety disorder (n=7), followed by general mental health issues (n=8), such as well-being, mindfulness, and goal achievement. Furthermore, some studies reported the use of adaptiveness in other areas such as insomnia (n=2), social psychology (n=1), attention deficit hyperactivity disorder (n=2), posttraumatic stress disorder (n=2), suicidality (n=2), and substance misuse (n=1). The full list of types of mental health problems addressed in the relevant studies is presented in Table 1.

Table 1. Types of mental illness for which an adaptive system was built.

Mental illnesses	Study references
Depression	Tsiakas et al, 2015 [40]
	Levin et al, 2018 [41]
	Burns et al, 2011 [50]
	Rebar et al, 2016 [51]
	Malins et al, 2020 [54]
	Van Gemert-Pijnen et al, 2014 [56]
	Lillevoll et al, 2014 [24]
	Achtyes et al, 2015 [57]
	Wallert et al, 2018 [58]
	Kop et al, 2014 [61]
	D'Alfonso et al, 2017 [63]
Anxiety disorder	Tsiakas et al, 2015 [40]
	Levin et al, 2018 [41]
	Walter et al, 2007 [45]
	Batterham et al, 2017 [48]
	Malins et al, 2020 [54]
	Achtyes et al, 2015 [57]
	Wallert et al, 2018 [58]
Insomnia	Forsell et al, 2019 [59]
	Erten-Uyumaz et al, 2019 [60]
Substance use	Batterham et al, 2017 [48]
Suicidality	Delgado-Gomez et al, 2016 [42]
	Batterham et al, 2017 [48]
Social psychology	Rachuri et al, 2010 [62]
Bipolar disorder	Dodd et al, 2017 [14]
Stress	Konrad et al, 2015 [47]
Posttraumatic stress disorder	Tielman et al, 2019 [43]
	Eisen et al, 2016 [46]
Smoking cessation	Lagoa et al, 2014 [44]
Attention deficit hyperactivity disorder	Nahum-Shani et al, 2012 [12]
General mental health	Iorfino et al, 2019 [39]
	Bannink et al, 2012 [11]
	Berrouiguet et al, 2018 [49]
	Ketelaar et al, 2014 [52]
	Coyle et al, 2010 [53]
	Kitagawa et al, 2020 [13]
	van Os et al, 2017 [55]
	van de Ven et al, 2017 [32]

Intervention Platform

Based on our findings, the communication media used to administer internet-facilitated interventions to patients can be classified into three categories: web apps, mobile apps, and computer games. A significant number of the included studies were based on web apps [11,14,24,39,43,49,50,52,54,56,63], followed by mobile apps [13,32,41,49,50,55,60,61] and a game-based intervention [53]. There was only one paper that applied both web and mobile technologies for internet-based intervention. However, a lot of studies did not report the mode of delivery.

IA

IA is concerned with the art and science of organizing and labelling components of web apps, intranets, software, and online communities to enhance their usability and accessibility. IA plays a vital role in web app development, and a good architecture can improve the ability of employees and customers to find information and decrease the app's maintenance cost [28]. Finding the type of IA used in IDPT systems and their relevancy to treatment outcomes is one of the research questions of this study. However, a significant number of studies (20/31, 65%) did not report the type of IA they used in their IDPT system. Based on the IA of the intervention reported in the 31 reviewed articles, 4 (13%) studies reported the use of tunnel-based IA, and 3 (10%) studies reported the use of matrix IA and hierarchical IA. The full list of types of IA used in the relevant studies is presented in Table 2.

Table 2. Types of information architecture used in the reviewed studies.

Information architectures	Study references
Tunnel-based IA	Iorfino et al, 2019 [39]
	Konrad et al, 2015 [47]
	Batterham et al, 2017 [48]
	Kitagawa et al, 2020 [13]
Hybrid IA	D'Alfonso et al, 2017 [63]
Matrix IA	Levin et al, 2018 [41]
	Lagoa et al, 2014 [44]
	Van Gemert-Pijnen et al, 2014 [56]
Hierarchical IA	Tielman et al, 2019 [43]
	Bannink et al, 2012 [11]
	Berrouiguet et al, 2018 [49]
Not clear/not reported	Coyle et al, 2010 [53]
	Tsiakas et al, 2015 [40]
	Delgado-Gomez et al, 2016 [42]
	Walter et al, 2007 [45]
	Bannink et al, 2012 [11]
	Burns et al, 2011 [50]
	Rebar et al, 2016 [51]
	Ketelaar et al, 2014 [52]
	Malins et al, 2020 [54]
	Kitagawa et al, 2020 [13]
	van Os et al, 2017 [55]
	Lillevoll et al, 2014 [24]
	Dodd et al, 2017 [14]
	Achtyes et al, 2015 [57]
	Wallert et al, 2018 [58]
	Forsell et al, 2019 [59]
	Erten-Uyumaz et al, 2019 [60]
	Kop et al, 2014 [61]
	van de Ven et al, 2017 [32]
	Rachuri et al, 2010 [62]

The analysis of Table 2 answers our first research question. Most of these IAs fall into four categories: (1) tunnel-based design, (2) matrix design, (3) hierarchical design, and (4) hybrid design. A previous study [65] showed that 90% of the available IDPT systems used a tunnel-based design, where users navigate sequentially to search for information. A tunnel-based design is analogous to watching TV series, reading textbooks, attending academic classes, or attending multiple clinical sessions. An argument for tunnel-based design is that the experience is less likely to overwhelm users with information and options [66]. The tunnel-based design is probably also the default IA design alternative in many projects and is the easiest to implement.

Adaptive Elements

Adaptive elements are the main components that are personalized for the user. As reported in a previous study [28], the main adaptive elements can be intervention content, design, assessment tests, IA, content presentation, content complexity, content recommendation, user interface (such as navigation system, search engines), feedback, notifications/reminders/alerts, behavioral activities, exercises, and reporting/dashboards. We report the full list of adaptive elements found in the relevant studies in Table 3.

Numerous studies (9/31, 29%) reported adapting the content of the intervention. However, most of these studies did not explicitly report the type of content, level of complexity, or modality (audio, video, presentation, pictures, assignments, activities, and assessments). Knowledge of the modalities of the content and their associated complexity provides insight into how interventions could be adapted and personalized for patients.

Another notable observation is that several studies (11/31, 35%) used feedbacks as adaptive elements. Numerous studies described the process of adaptive feedback in different forms, including sending personalized motivational messages [43], tailored messages by therapists [11,13,54], and providing general support [14]. In contrast, a few studies aimed to adapt reminders and alerts by sending an email or SMS text message or making a phone call [24,48,50]. Only 2 studies targeted the adaptation of exercises [41,47] and 1 study targeted the adaptation of behavioral activities [60]. We identified a total of 7 papers (7/31, 23%) that adapted assessment tests or psychometric assessment tests [39,42,45,46,55-57].

Table 3. Types of adaptive elements identified from the relevant studies.

Main adaptive elements	Study references
Intervention content	Iorfino et al, 2019 [39]
	Lagoa et al, 2014 [44]
	Batterham et al, 2017 [48]
	Rebar et al, 2016 [51]
	Coyle et al, 2010 [53]
	Nahum-Shani et al, 2012 [12]
	Van Gemert-Pijnen et al, 2014 [56]
	D'Alfonso et al, 2017 [63]
	Kop et al, 2014 [61]
Content presentation	Iorfino et al, 2019 [39]
Feedback message, support	Iorfino et al, 2019 [39]
	Tielman et al, 2019 [43]
	Bannink et al, 2012 [11]
	Batterham et al, 2017 [48]
	Burns et al, 2011 [50]
	Ketelaar et al, 2014 [52]
	Malins et al, 2020 [54]
	Kitagawa et al, 2019 [13]
	Van Gemert-Pijnen et al, 2014 [56]
	Dodd et al, 2017 [14]
	van de Ven et al, 2017 [32]
Assessment tests	Iorfino et al, 2019 [39]
	van Os et al, 2017 [55]
	Van Gemert-Pijnen et al, 2014 [56]
	Achtyes et al, 2015 [57]
	Delgado-Gomez et al, 2016 [42]
	Walter et al, 2007 [45]
	Eisen et al, 2016 [46]
Behavioral activities (sleep pattern)	Erten-Uyumaz et al, 2019 [60]
Reminder messages (SMS text messages, emails, phone calls)	Burns et al, 2011 [50]
	Lillevoll et al, 2014 [24]
	Batterham et al, 2017 [48]
Exercises	Levin et al, 2018 [41]
	Konrad et al, 2015 [47]
Reports	Iorfino et al, 2019 [39]
	Burns et al, 2011 [50]
Not clear	Tsiakas et al, 2015 [40]

Table 3 presents the list of the primary adaptive elements in the adaptive IDPT systems. The list includes (1) intervention content, (2) content presentation, (3) feedback messages, (4) assessment tests, (5) behavioral activities (sleep pattern), (6) reminder messages (email, SMS text messages, phone calls), (7) exercises, and (8) reporting (dashboard for the patients and the therapists). The central concept of adaptiveness is to create different levels of these adaptive elements and provide these elements based on a personalized profile. For example, if a person watches videos more than they listen to audio, read text, or view slides, then based on the principle of adaptiveness, it makes sense to present upcoming interventions in a video format.

Dimensions of Adaptation

The way an adaptive system changes its behaviors depends on a multitude of factors: (1) users' data and preferences, (2) goals of the intervention, (3) measures, (4) adaptation actors, and (5) adaptation strategies. We refer to these aspects as the dimensions of the adaptive IDPT system [28]. Table 4 presents a list of adaptive dimensions extracted from the included studies.

Table 4. Dimensions considered for adaptation in the relevant studies.

Adaptation dimensions	Study references
User data and preferences (user context, needs, and location)	Iorfino et al, 2019 [39]
	Delgado-Gomez et al, 2016 [42]
	Tielman et al, 2019 [43]
	Lagoa et al, 2014 [44]
	Walter et al, 2007 [45]
	Eisen et al, 2016 [46]
	Van Gemert-Pijnen et al, 2014 [56]
	Dodd et al, 2017 [14]
	Forsell et al, 2019 [59]
	Erten-Uyumaz et al, 2019 [60]
	Kop et al, 2014 [61]
	van de Ven et al, 2017 [32]
	Rachuri et al, 2010 [62]
	D'Alfonso et al, 2017 [63]
Measures	
Psychometric tests/screening	Tsiakas et al, 2015 [40]
	Levin et al, 2018 [41]
	Bannink et al, 2012 [11]
	Batterham et al, 2017 [48]
	Berrouiguet et al, 2018 [49]
	Burns et al, 2011 [50]
	Rebar et al, 2016 [51]
	Ketelaar et al, 2014 [52]
	Coyle et al, 2010 [53]
	Malins et al, 2020 [54]
	Nahum-Shani et al, 2012 [12]
	Kitagawa et al, 2019 [13]
	Van Gemert-Pijnen et al, 2014 [56]
	Achtyes et al, 2015 [57]
	Wallert et al, 2018 [58]
User behavior analysis based on interaction data	Berrouiguet et al, 2018 [49]
	Burns et al, 2011 [50]
Goals of intervention	Konrad et al, 2015 [47]
Not clear	van Os et al, 2017 [55]
	Lillevoll et al, 2014 [24]

The relevant studies were mainly grouped into two clusters based on the choice of adaptive dimensions: user preferences (13/31, 42%) or outcome measures (14/31, 45%). Only 1 study used a goal-based adaptive dimension. Among the studies using user preferences, some studies [32,42-46,62] used user context, while some studies used user location [32,62] to adapt interventions. The studies based on outcome measures used either psychometric tests or user behavior analysis based on interaction data to measure the performance outcome.

Adaptive Strategies

The adaptive strategy indicates the techniques used to tailor the intervention. In a recent study [28], four significant clusters of adaptive approaches were identified, namely rule-based adaptation, predictive algorithm-based (such as machine learning) adaptation, goal-driven adaptation, and adaptation through a feedback loop. Similar to the study [28], we identified the following adaptive strategies, presented in Table 5, in the reviewed studies.

Table 5. Types of adaptive strategies found in the relevant studies.

Types of adaptive strategies	Study references
Rule-based strategies	Iorfino et al, 2019 [39]
	Tsiakas et al, 2015 [40]
	Levin et al, 2018 [41]
	Delgado-Gomez et al, 2016 [42]
	Tielman et al, 2019 [43]
	Walter et al, 2007 [45]
	Eisen et al, 2016 [46]
	Bannink et al, 2012 [11]
	Konrad et al, 2015 [47]
	Batterham et al, 2017 [48]
	Rebar et al, 2016 [51]
	Ketelaar et al, 2014 [52]
	Coyle et al, 2010 [53]
	Malins et al, 2020 [54]
	Nahum-Shani et al, 2012 [12]
	Kitagawa et al, 2019 [13]
	van Os et al, 2017 [55]
	Van Gemert-Pijnen et al, 2014 [56]
	Lillevoll et al, 2014 [24]
	van de Ven et al, 2017 [32]
Predictive algorithm- or machine learning–based strategies	Tsiakas et al, 2015 [40]
	Lagoa et al, 2014 [44]
	Berrouiguet et al, 2018 [49]
	Burns et al, 2011 [50]
	Nahum-Shani et al, 2012 [12]
	Wallert et al, 2018 [58]
	Rachuri et al, 2010 [62]
	Erten-Uyumaz et al, 2019 [60]
	Kop et al, 2014 [61]
Recommendation-based strategies	D'Alfonso et al, 2017 [63]
General or unclear strategy	Dodd et al, 2017 [14]
	Achtyes et al, 2015 [57]

The list of strategies includes rule-based strategies, predictive algorithm-based strategies, and recommendation-based strategies. As expected, a significant number of studies (20/31, 65%) used some form of rule-based adaptation mechanism. For example, some studies [42,45,46] used item-response theory [8] to tailor psychometric tests. The primary motivation toward adapting psychometric tests is to extract essential information from patients without asking them too many questions. The study by Van Gemert-Pijnen et al [56] applied user behavior analysis by inspecting web-log data and combined it with a rule-based engine to adapt the intervention. The same study concluded that pattern recognition can be a useful tool to tailor interventions based on usage patterns from earlier lessons [56]. With the hype of data science, several studies [12,40,44,49,50,58,60-62] attempted to use some form of predictive algorithm to adapt the intervention. While some studies did not report the outcome of the overall study [40,49], most of them reported that the use of predictive algorithms had a positive effect on the adaptation of interventions [12,44,50,58,60-62]. However, these studies concluded that further research is required to study the effectiveness of performance outcomes.

Efficacy of Treatment Outcomes

In general, this systematic review shows that tailoring interventions according to patients' needs and preferences has a positive effect on user adherence and hence treatment outcomes. Several studies reported that the personalization of interventions [13,32,39,41,43,47,50-52,54,56,59] and assessments [42,45,46] increased user adherence. Similarly, a study by Coyle et al [53] reported that a personalized system provided a higher degree of user satisfaction. However, some studies reported a lack of noticeable improvement in treatment outcomes. For instance, a study by Batterham et al [48] reported that there was no significant difference between tailored and static versions in the effectiveness of treatment or adherence. However, the same study reported that participants in the tailored conditions were more satisfied than those in the control conditions [48]. Lillevoll et al [24] made a similar conclusion, reporting that tailoring of feedback and dispatching weekly email reminders did not improve the intervention outcomes or user adherence. Given the scenario with two different clusters of results, further research and clinical trials are required to comprehend how user adherence and personalization of interventions are correlated.

Discussion

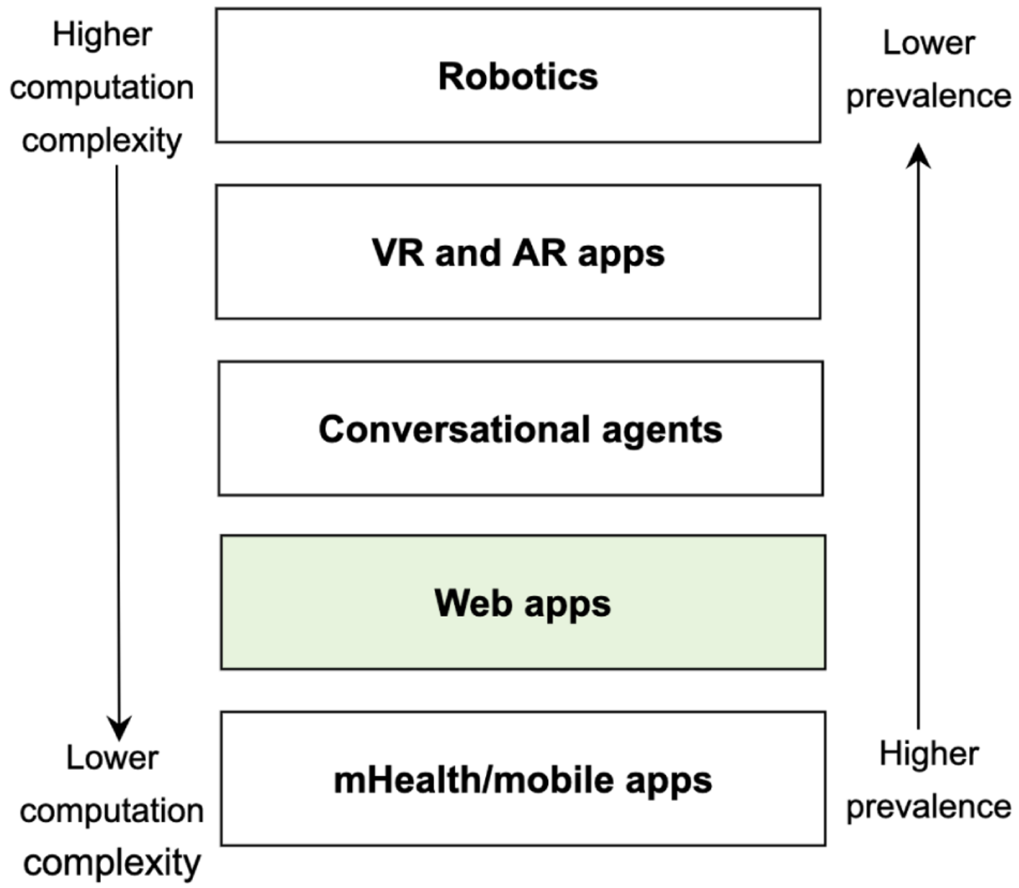
Key Findings

A total of 3341 studies were initially identified based on the inclusion criteria. Following a review of the title, abstract, and full text, 31 studies that fulfilled the inclusion criteria remained, most of which attempted to tailor interventions for mental illnesses. Approximately 68% (21/31) of the studies had a first author with a health care background. The most common adaptive elements were feedback messages to patients from therapists (11/31, 35%) and intervention content (9/31, 29%). However, how these elements contribute to the efficacy of IDPT in mental illness was not reported. The most common IA used was tunnel-based IA (4/31, 13%), while many studies (20/31, 65%) did not report the IA used. The rule-based technique was the most common adaptive strategy used in these studies (20/31, 65%). All the studies were broadly grouped into two adaptive dimensions based on user preferences or using performance measures such as psychometric tests.

Intervention Platform

Our findings show that web apps, mobile apps, and computer games are the primary platforms used to facilitate interventions. Apart from these, other communication media include robotics, virtual reality (VR) [67], augmented reality (AR), conversational agents, or chatbots [68]. A key finding in the literature study was that most of the IDPTs were made available on mobile apps [69] and web-based apps. This is as expected, as these are the most prevalent platforms used for personal computing. Smartphones contain a plethora of sensors and other data sources that inform aspects of users' well-being, context, activities, behaviors, and intentions. However, only a few attempts have been made to provide IDPT using conversational agents [68], or VR or AR apps. As depicted in Figure 2, higher placement in the chain indicates higher computational complexity but lower prevalence. Conversely, lower placement in the chain indicates lower computational complexity but higher prevalence. The most obvious explanation for the selection of web and mobile apps for intervention platforms is their prevalence. It makes the most sense to develop for platforms that are being used the most.

Figure 2. Mode of delivery for internet-delivered psychological treatments (IDPTs). AR: augmented reality; mHealth: mobile health; VR: virtual reality.



IA

Although a significant number of the studies failed to report which IA was used in their IDPT system, IA is still present in all software systems. Understanding the IA of a system helps a user to store, find, and interpret information readily, as IA is the design principle that is applied to making information discoverable and understandable. Finding the underlying IA of the IDPT system can help in making systems accessible and discoverable for end users, and knowledge about information design, structure, organization, and labelling can facilitate the development and evaluation phase. As explained in a previous study [70], IA consists of three major components: user, content, and context. Hence, IA helps to discover content for users based on their context. Assisting users with the correct piece of information they are looking for can increase user adherence by reducing bounce rate [71] and hence improve treatment outcomes. While our findings show most of the current adaptive IDPT systems are tunnel-based and don't promote personalization, we promote the use of hierarchical IA or hybrid IA in order to present useful information according to patients' needs and argue that the latter designs offer richer opportunities for adaptive IDPT systems.

Adaptive Elements

The primary context for building adaptive IDPT systems is to assist patients suffering from mental health disorders to learn about and recover from their illnesses. An IDPT system provides this information by using different media and elements such as text, video, audio, pictures, presentations, feedback, reminders, reports, and others. These elements have their format, structure, metadata, volume, and dynamism (such as frequency of updates). It is essential to understand these elements (contents described by Pakkala et al [71]) and the associated attributes in order to deliver the correct content to the right user in their current context. For example, understanding the complexity of the text describing sleep disorders can help to personalize the content based on the educational background of the patients. A general assumption is that an educated person can comprehend more complex language and medical terms than a nonspecialist. For a nonspecialist, it is more valuable to present the same content in terms of animated videos or pictures.

Adaptive Dimensions

The adaptive dimension provides the context for an adaptive IDPT system to tailor its behavior. A common way to tailor the behavior of the IDPT system is based on input regarding user preferences, measures (psychometric tests, user behavior analysis, and others), and goals, as shown in Table 4. In the context of user preferences, a study by Yardley et al [72] outlined that users can feel overwhelmed by the quantity and complexity of information presented to them. Hence, it is advisable to meet the needs of different users based on their needs and preferences. Personalization is critical mainly because users have different cognitive skills, educational backgrounds, content format preferences, comprehension capabilities, and other qualities. A similar conclusion was made by Sundar and Marathe [73]. Their study identified two types of users: those influenced more by the affordance of agency (power users) and those influenced by the relevancy of the resulting content. The results of the study revealed that nonpower users preferred personalized content, whereas power users rated content quality higher when the website had a customizable feature. Similar to user preferences, other dimensions of adaption are performance measures such as the use of psychometric tests (eg, Patient Health Questionnaire-9 [74] for depression), user behavior analysis, and others.

Adaptive Strategies

Adaptive strategies provide a mechanism to present the right content to the right people based on their needs and preferences. While our review findings reveal that the rule-based adaptive strategy is the most widely adopted practice, other strategies, especially machine learning, are becoming highly prevalent. Given the premise that we can capture every digital footprint of a user, resulting in a complex and comprehensive data set, there is a possibility of using sophisticated machine learning or deep learning algorithms on the one hand, but it also raises an essential question about privacy on the other. In general, to build an adaptive IDPT system, it is crucial to understand which adaptive strategies can be used. Based on the selected strategies, one needs to collect and store the data. No matter which adaptive strategy is chosen, the adaption in an IDPT system is an iterative cycle where data is collected and preprocessed; preprocessed data are then analyzed and, based on the results of the analysis, an action is taken to tailor the intervention. However, how the data are analyzed and the result is extracted affect the way an IDPT system is developed, the choice of IA, the method of data storage, and other parameters.

Challenges in Contemporary IDPT Systems

Although the integration of health care systems has emerged as a policy for several health care agencies, there is a large gap between current policy, program implementation efforts, and evidence for health care integration. The results of our review led us to list the following challenges in current IDPT practice.

Lack of Standard Taxonomy in IDPT

There is a lack of a standardized definition of the health care system and proper taxonomy to allow the grouping of similar interventions. As mentioned in the introduction, the use of nonstandard terms to refer to the same system causes inconsistencies and makes it hard to draw conclusions. Based on this challenge, several researchers [75-77] have made an effort to formalize the health care system to support interoperability [76], such as the Fast Healthcare Interoperability Resources (FHIR) created by the Health Level Seven International (HL7) health care standards organization [78] and others. If there is a standard followed by researchers for building adaptive IDPT systems, it will become easier to learn from their findings and extend the current understanding to improve treatment outcomes.

Scientific Foundation

The outcome of trials of IDPT systems has demonstrated comparable results as face-to-face therapies. However, despite considerable attention to IDPTs, user adherence is low, and there is remarkably less literature on the underlying science of the field of IDPT system design and development [79]. Many pieces of literature claim IDPT to be based on psychoeducation that helps in the modification of behavior change and symptom improvement. While this assumption may be correct, the underlying science behind how psychoeducation about particular symptoms enhances behavior modifications and symptom improvement is less evident in the literature. Lack of a scientific foundation behind IDPT systems may be the reason behind users' lack of trust toward interventions [21-23] and hence lack of adherence. In the same way, an IDPT system is an application software that follows an IA (see Table 2) and design patterns [80]. The application software such as IDPT are well formalized and studied in the research community. Lack of such reporting makes it challenging to conclude how adaptive elements or the IA influence the outcome of an intervention.

Ethical and Safety Issues Associated with Predictive Adaptive Strategies

Technology has matured to the point where several researchers envision the creation of automated, adaptive IDPT systems that work without much human involvement. However, there are controversies between what is possible and what is acceptable in adaptive systems. Hence, it requires careful consideration of both ethical and legal issues; focusing solely on technological and operational perspectives can lead to low value or utility for patients. As a result, both information and communication technology (ICT) researchers and medical practitioners must consider the capabilities, limitations, and needs of patients when designing adaptive systems. The primary objective of the adaptive IDPT system is to tailor the intervention based on user needs or any other adaptive dimensions. The adaptive IDPT system can understand the user's needs by creating detailed user profiling. User profiling includes storage of the patient's previous diagnosis, sensitive personal information, as well as the current status. Moreover, to maximize the benefits of data-driven adaptiveness, the adaptive IDPT system needs to store interaction data, including the time of login, the frequency of login, and the interaction with the system at the granular level (clicks, keystrokes). For example, the study by Van Gemert-Pijnen [56] analyzed the log data in order to understand the use of the content. Storing such user interaction data requires proper user consent on the one hand and directly deals with the privacy of the patient on the other. Hence, it is one of the critical challenges in the development of an adaptive IDPT system. It requires further research into the problem of storing user interaction data securely. For example, many psychological interventions aim to characterize patients' symptoms based on their mobile phone usage. This type of study is possible because mobile phones come with built-in sensors and standard application programming interfaces to measure and collect patients' data, including mobility patterns, physical activities, crowd density, time spent indoors versus outdoors, and locations. Although these capabilities are possible with the advances in ubiquitous computing, they deal directly with privacy and ethical issues.

Implications and Future Directions

It is not easy to predict how technologies will develop over time and whether these technologies will continue adapting to clinical use. However, based on the results of this systematic review, we outline some implications and future directions in the field of IDPT system development and innovation.

Implications for ICT Researchers

With an increasing trend in user adherence toward internet-delivered treatments on the one hand and the prevalence of the internet of things (IoT), with growth in ambient intelligence technology, on the other, there is an expectation that the IDPT system will flourish over time. A plethora of health care interventions delivered via the internet have a similar format, as most of them are based on psychoeducation. All such interventions attempt to create adaptive elements (see Table 3) and attempt to tailor these elements based on adaptive dimensions (see Table 4) using adaptive strategies (see Table 5). Hence, it makes sense to create a conceptual framework that can be utilized in several health care domains. Moreover, the creation of domain-specific languages for incorporating adaptive health care interventions is also required. We also need better dashboard tools that help therapists and other medical practitioners to comprehend patients' status better and adapt their interventions based on their engagement with the interventions.

We analyzed the state-of-the-art studies concerned with adapting psychological interventions. The analysis yielded the answers to the most critical questions, including (1) what are the essential elements that therapists wish to tailor? (2) what are the main dimensions in which these elements can be tailored to meet patients' needs? and (3) what are the primary adaptive strategies used to trigger adaptation in those dimensions? Findings from the analysis helped to identify the essential variables that are associated with an adaptive system. As McGaghie et al [81] outlined, once ICT researchers and developers know the essential variables, they can utilize these findings to create a conceptual framework that sets the stage for the presentation of a particular problem, which in this case is the creation of an adaptive IDPT system. Further, ICT researchers and developers can validate the conceptual framework by building domain-specific language.

Implication for Health Care Researchers

While the current research evidence is fragmented about the benefit of an adaptive IDPT system on treatment outcomes, this review suggests that adaptive IDPT systems can benefit people with mental health issues in providing personalized psychoeducation. Such an education will help mental health patients to manage their illness. In addition, a high number of health care researchers have published about adaptive interventions, as shown in Figure 2. This indicates that both health care researchers and computer researchers believe that adaptive interventions are an essential phenomenon to accelerate user adherence. However, tailoring the feedbacks given by therapists or providing reminders are simple forms of adaptation (see Table 3). The intervention can be adapted for several dimensions, including user preferences, outcome measures, and different adaptive strategies [28], with the amalgamation of ambient technology. Hence, cooperation between ICT and health care researchers is essential to develop an adaptive IDPT system. While more randomized controlled trials are required to validate the effectiveness of adaptive treatments, the results of this review show sufficient evidence to suggest that the adaptation of mental health interventions can enhance user adherence and treatment outcomes.

Implication for Computer Science Research

The development of an adaptive IDPT system that increases user adherence and treatment outcomes requires more extensive research to establish clinical appropriateness. Given the potential benefit of the IDPT system for cost-effective delivery to the far-reaching population, further research should be conducted on how to personalize adaptive strategies. Furthermore, reporting back to the research community is the part of any discipline of transparency that keeps studies honest and accountable. In addition, it fits into the broader responsibilities of scientists to communicate their work and foster public understanding. Such understanding can be used by other researchers to gain insight into new research directions.

Future Work

An immediate future task involves the creation of a conceptual framework for adaptive IDPT systems. In addition to this, we envision the development of domain-specific language that can model such an adaptive IDPT system. Furthermore, it is imperative from the review that there is a need for a comprehensive visual dashboard for therapists and patients where they can receive the intervention, monitor their symptoms, and manage their illness.

Limitations

Given that the health ICT literature is quite diverse and extensive, the current study focused exclusively on internet-delivered interventions for mental health morbidities. Notwithstanding this limitation, this paper highlights the significance of the continued study of this intervention method. Another limitation is that our literature exploration only encompassed articles in the English language; therefore, it is plausible that some research conducted in other parts of the world and published in other languages were missed. A third limitation pertains to IDPT apps developed by industry that were not accessible for review. Hence, we have less knowledge about the adaptive elements involved in their architecture.

Conclusions

Adaptive psychological interventions tailor the type of content or tasks to individuals based on their needs and preferences in order to improve saliency and intervention efficacy. This systematic review describes the investigation and analysis of existing studies about adaptive psychological intervention delivered through the internet. The study outlines the main elements used in the process of adaptation, the IA used in the adaptive systems, the main dimensions of adaptation, and the main adaptive strategies. Based on these findings, we envision the development of a conceptual framework that researchers and clinicians can utilize to build adaptive models of several health care interventions.

The findings of our review indicate the use of web-based and mobile apps to deliver mental health interventions, such as for depression (most studied), anxiety, and others. However, a number of these studies did not report the IA used in their system, and those that did report mostly used tunnel-based systems. Similarly, several studies used rule-based adaptive strategies to adapt intervention based on performance measures such as psychometric tests. Feedback messages, reminders, and support were the most used adaptive element. Further study is required to explore the role of IA, adaptive elements, adaptive dimensions, and adaptive strategies in building a successful IDPT system. Knowledge about these core elements of the adaptive IDPT system can serve to create a conceptual framework that can be used for several health care interventions.

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Conflicts of Interest

None declared.

Multimedia Appendix 1

Search terms that were used to execute the search in different databases.
[PDF File (Adobe PDF File), 90 KB-Multimedia Appendix 1]

Multimedia Appendix 2

The main table that helped to extract the adaptive elements, adaptive strategies, information architecture, and other information about the internet-delivered psychological treatment system.
[XLSX File (Microsoft Excel File), 68 KB-Multimedia Appendix 2]

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Abbreviations

AR: augmented reality
DSM-5: Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition
FHIR: Fast Healthcare Interoperability Resources
HL7: Health Level Seven International
IA: information architecture
ICT: information communication technology
IDPT: internet-delivered psychological treatment
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
VR: virtual reality

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PAPER B

SCIENTIFIC PAPER II

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An architectural design for self-reporting e-health systems[◇]

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***Abstract*—Worldwide, public healthcare is challenged to deliver consistent and cost-efficient services. The cost of healthcare is increasing primarily due to growing populations and more expensive treatment. Health facilities in many countries are reaching their full operational capacity, and the resources of these hospitals are less than what is required to deliver the expected quality of care. Under these circumstances, ICT has a major role to play in mitigating the growing need for hospital care. In this paper, we present a cloud-based interoperable architecture built on the top of Service-Oriented Architecture (SOA) for Internet-based treatment where patients can directly interact with underlying healthcare systems such as Electronic Health Record (EHR). Based on this architecture, we also present a prototype for screening and monitoring of mental and neurological health morbidities. The proposed solution is based on healthcare interoperability standard, HL7 FHIR, that enables healthcare providers to assess and monitor patients condition in a secure environment.**

***Index Terms*—service-oriented architecture, healthcare, self-screening, HL7 FHIR, SMART on FHIR, Internet-based Treatments**

I. Introduction

E-health is an emerging field of medical informatics which refers to the use of information and communications technologies in healthcare. According to World Health Organization (WHO), e-health is the cost-effective and secure use of information and communications technologies to support health and health-related fields, including healthcare services, health surveillance, health literature, health education, knowledge and research [42]. Today e-Health infrastructures and systems are being considered as central to the provision of high quality, citizen-centered healthcare. A very common requirement for e-health applications is to exchange information between healthcare systems and to support patients while they are staying at home. Although there exist many techniques such as electronic surveys to get data from patients for screening and monitoring, they are not integrated with existing electronic health record systems (EHRs), the data are not standardized, not interoperable and not easily accessible to researchers and clinicians [7]. As a result, healthcare providers are in general unable to use any standardized system for collecting and analyzing information from patients while they are not inside a hospital and cannot share the information with other care providers if needed. To resolve these issues, we propose an architectural design for a self-reporting e-health system that uses healthcare standards for interoperability.

WHO states that one in four people in the world will be affected by mental or neurological disorders at some point in their lives and around 450 million people currently suffer from such conditions [42]. People suffering from mental health problems may have difficulty in comprehending, acting or processing the experiences and information appropriately. This is due to the illness which can affect the mental or neurological functioning including concentration, memory, initiative, ability to plan, summing up the information, experience of time, and generalization [36]. Lack of such cognitive functioning can have a serious impact on patients, families, friends, and society. Dealing with such mental health patients can be economically [13], [33], [44], physically and emotionally challenging. Several types of research have been carried out to facilitate automated and personalized screening and treatment to such mental health patients. Human Brain Project[1], eMEN [15], and INTROMAT [25] are among the European projects that address such mental health problems. In particular, the goal of INTROMAT is to offer *personalized* treatment for patients suffering from mental and neurological disorders.

In this paper, we focus on the mental healthcare domain and envision developing an adaptive system for the mental healthcare domain which can support citizen-centered mental healthcare. We focus on the assessment and monitoring process in order to develop a patient-centered healthcare solution. As part of the INTROMAT project, we are developing core services that will be made available to research projects through the Internet of Things (IoT) and application platforms. Examples of such services are data processing services, data storage, security and privacy services, artificial intelligence (cognitive computing, machine learning, deep learning), event processing, analytical services, and others. We provide an overview of the proposed solution which includes: (i) a cloud-based interoperable architecture built on the top of SOA, named as INTROMAT Core, for self-assessment and evaluation of mental or neurological morbidity, (ii) HL7 FHIR standard questionnaire, (iii) a working prototype of self-assessment and monitoring mobile app, and (iv) a list of research challenges and opportunities in the field.

The paper is structured as follows: Section II outlines the

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[1]https://www.humanbrainproject.eu/en/

main motivation for building a self-reporting e-health system, Section III presents INTROMAT core architecture, its workflow and quality attributes. In Section IV we describe a case study for depression with corresponding domain model for self-reporting system. Section V outlines some of the related works. Section VI concludes the paper with a discussion addressing some challenges and also mentions future work.

II. Motivation

In this paper, we will be addressing the following three challenges:

- heterogeneity of healthcare information across various healthcare service providers
- lack of integrated Internet-based treatment that is accessible for patients and healthcare providers
- lack of adaptiveness in patient-centered care

Healthcare ICT technologies have substantial contributions in uplifting the quality of life and reducing socioeconomic burdens. Technology provides a variety of promising approaches to mental health and neurological practices, training, and supervision in several ways including therapeutic intervention [19] and Cognitive Behavioral therapy [40]. Despite this high prevalence of ICT system in healthcare, the inadequacy provision of interventions for the prevention and treatment of mental or neurological problems has become a global challenge. This is mainly due to lack of standardization in data collection and data preparation methodologies, and heterogeneity of the data [24]. This limits the sharing of data among different healthcare providers. The limitation in sharing health data is detrimental to patient care, provider satisfaction, and healthcare cost [20]. Moreover, providing access to and sharing of health data have been shown to benefit and empower the patients [43]. The complexity of heterogeneity in data and restriction in sharing patient data have hindered standardization and interoperability in the healthcare industry [1]. In this project, we propose to overcome these problems of data collection and interoperability by following a common health standard HL7 FHIR (Fast Healthcare Interoperability Resource) [2], [10]. HL7 FHIR solutions are designed for web standards like XML, JSON, HTTP, and OAuth, are constructed from a set of modular components called Resources which can be grouped into working healthcare systems. HL7 FHIR specification component terminology is supported by the coding system that defines the content being exchanged. This coding system is established by external organizations including SNOMED-CT, LOINC, RxNorm, ICD family and others [2]. OpenEHR[2] is an alternative to HL7 FHIR, which is maintained by the openEHR foundation. Both HL7 FHIR and OpenEHR have open-standard and data interoperability as the main vision. HL7 FHIR is created to exchange data using REST API using the block of around 100 FHIR resources. In contrast to HL7 FHIR resources, openEHR uses over 300 more complex Archetypes which are designed to provide a maximal set of data elements.

People suffering from mental health require continuous monitoring and treatment. It is not only costly to provide the continuous monitoring and treatment using hospital facilities but it also has a social burden for patients and families. Internet-based psychotherapy treatments play a major role to resolve these issues and evidence illustrates that some forms of Internet-based treatments have comparable outcomes as conventional face-to-face psychotherapy [11]. Moreover, these Internet-based interventions can be presented to a large population flexibly and inexpensively. Internet-based psychotherapy includes treatments programs that are delivered via the Internet such as CBT, CRT, and Mindfulness. Self-assessment is a major component of these Internet-based treatments. Self-assessment provides a possible way such that people suffering from such morbidity can self-evaluate and manage their illness. The concept of self-assessment is not new in the healthcare domain and dates early back to 1977 where Alert Bandura published a theory of self-assessment process incorporating self-observation, self-judgment, and self-evaluation [29]. This is to say, self-assessment comprises behavior observation, behavior evaluation and a response to the evaluation or progress performance. Self-assessment can be a convenient and economical tool for understanding areas for improvement, accelerating self-esteem and enhancing self-awareness [12]. A self-reporting mobile application can provide a virtual therapist in everyone's pocket and help overcome the issue of stigma. Such stigma towards neurological or mental disorders is one of the main causes why some ethnic minority group does not seek and adhere to clinical treatments [18]. Moreover, the study done in [41] shows people suffering from mental health issues undergoes a fear of discomfort in facing a practitioner or choosing services, fear of community and psychosis. However, there is a need for self-assessment tool that a therapist can access in situations where the patients require the involvement of therapist in their treatment program. We address this issue by providing a prototype application for self-assessment and monitoring which is accessible by therapists.

People with different mental or neurological health problems require various types of screening, monitoring, and treatment. Based on the patients monitoring condition, the intervention should be adapted accordingly. But the current Internet-based treatment programs are not flexible enough to support such customization of the treatment plan based on patients need. In INTROMAT project, we envision an architecture where we continuously monitor the mental health conditions and provide a personalized intervention. In this paper, we mainly focus on self-reporting part and leave the discussion of adaptive treatment for future work.

III. Architecture

In this section, we outline the cloud-based INTROMAT core architecture which is based on Service-Oriented Architecture (SOA). The proposed architecture is built around the healthcare process model as shown in Fig. 1. The process model is based on evidence-based treatment where the healthcare provider optimizes patient outcomes through a series of in-

[2] https://www.openehr.org

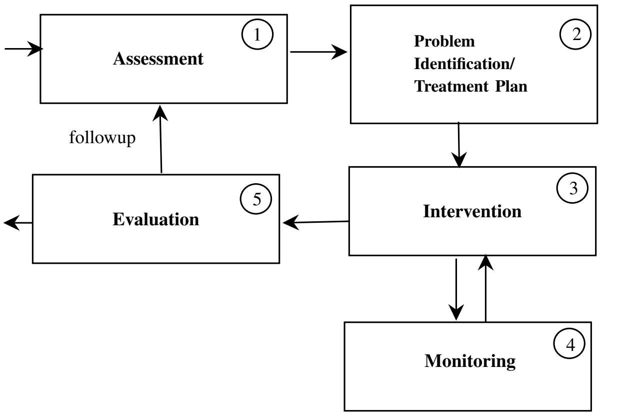

Fig. 1. Work-flow Model for mental or neurological clinical interventions

teractions during which they (1) obtain and examine patients' perspectives and clinical information (assessment); (2) identify the problem and create a treatment plant (problem identification/treatment plan); (3) administer clinical and behavioural interventions; (4) monitor patient progress; and (5) evaluate the progress and ensure follow-up if required. Clinical and behavioral intervention includes evidence-based treatments including Cognitive Based Therapy (CBT), Cognitive Remedial Therapy (CRT) and mindfulness.

Our SOA based solution is centered on the exchange of information using HL7 FHIR resources. The architecture uses services that are given by application components through some communication protocol over a network [6]. The reference model for SOA [30] is an abstract framework that illustrates how significant entities communicate within a service-oriented environment. SOA is a standard for creating and using distributed components as services that may be maintained by different ownership domain.

In the rest of the section we outline the main components of INTROMAT core architecture (Section III-A), discuss communication between different components (Section III-B), and discuss its quality attributes (Section III-C).

A. Components

Fig. 2 is a reference model [30] illustrating significant components and relationship between them with their relevant environments. As illustrated in the figure, the service provider component will reside in the cloud to perceive the benefits of distributed architecture. In this section, we outline the most significant entities in the architecture and discuss the communication between them.

1) Mobile Client: Mobile client facilitates data acquisition, data transmission from wearable sensors. Moreover, mobile apps can be used to provide evidence based treatments.

2) Web Client: A web client provides interfaces for login, authentication, and authorization for practitioners, abilities to create evidence-based treatments for patients and provide a comprehensive dashboard to visualize lists of patients, associated interventions, progress, and their activities. Both mobile and web clients form the service requester/consumer components of the architecture.

3) Authorization Server: The authorization server is an OpenID connect [38] compliant web server with an ability to authenticate users and grant authorization access tokens. Moreover, authorization server manages scopes and permission of the clients, introspects token and requests for the resource server.

4) SMART on FHIR: SMART on FHIR [34] performs the role of service broker [6] and provides identity and access management, access to data and launch sequence management. SMART on FHIR incorporates OAuth2 [21] for authorization, OpenID connect [38] for authentication, data models from FHIR, and supports EHR UI integration through SMART launch specification like EHR context and UI embedding for web apps [32].

5) Resource Server: Resource server is an FHIR [2] compliant web server with an ability to respond to FHIR REST requests consuming access tokens granted by Authorization Server. This component performs the role of service provider [6] in the SOA architecture.

6) Health Provider Clients: Health Provider clients can be external tools and applications, national resources, regional clinical and core systems, as well as legacy systems. While external EHRs following FHIR standards can communicate with Resource Server inside INTROMAT Core using web services, the legacy systems require a middleware, that transcribes legacy standard into FHIR standard.

7) Data Analysis: Data Analysis is one of the important aspects of INTROMAT Core Infrastructure. Data collected and stored in the core will be available to researchers for analysis and to practitioners for medical interventions. The core will provide services through IoT and application platforms enforcing research services including data processing, artificial intelligence, event processing and analytical services. Explaining such research services and how it will be implemented is not within the scope of this paper.

B. Communication Flow

SMART on FHIR specifies three different workflows including contextless flow, EHR launch flow, SMART application launch flow [34]. Our architecture supports all three types of workflows, but for building self-reporting technology, we adopt contextless workflow and is explained in Fig. 3. Development and support for other workflows are entitled to the extension of this work and further development.

The contextless communication between different components is illustrated by the sequence diagram in Fig. 3 and the steps involved as follows.

1) SMART applications (mobile/web clients) makes conformance request to the Resource Server.
2) The Resource Server responds back with valid conformance endpoints (/token, /authorize, /manage).
3) The end users generate an OAuth 2.0 authorization grant request (with valid scopes and headers) and redirect the end users to the authorization server.

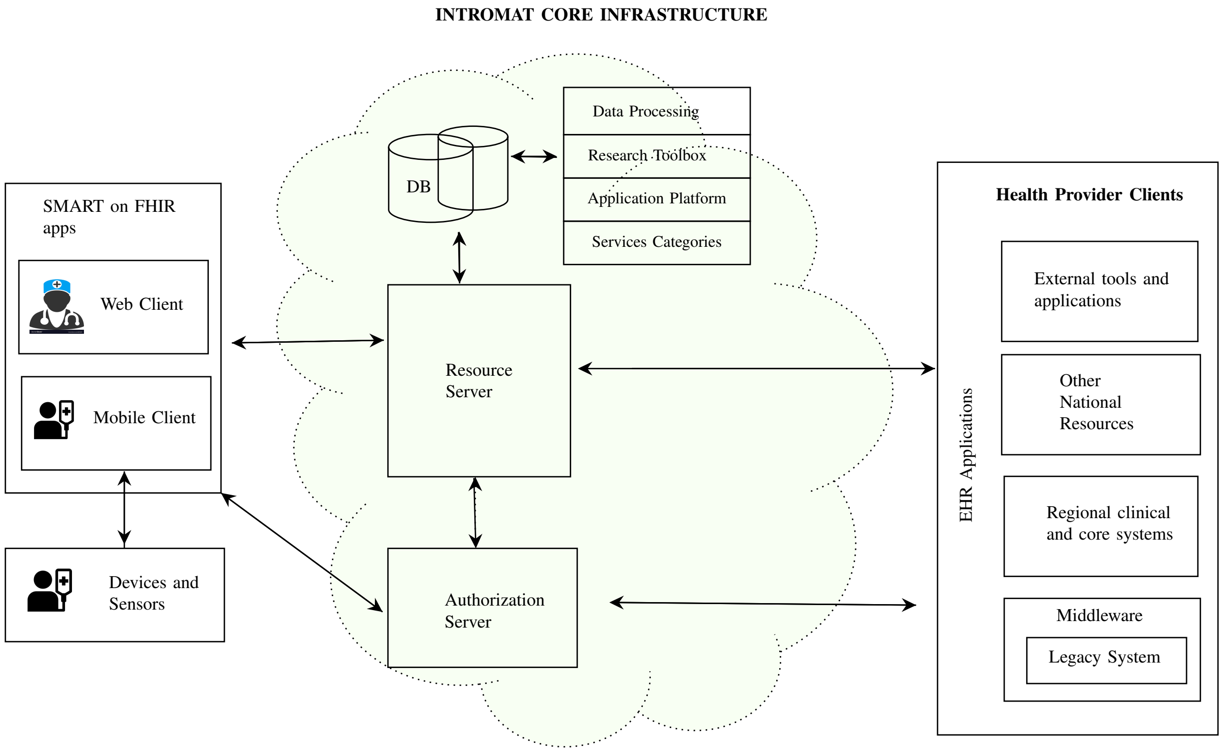

Fig. 2. Service-oriented architecture for adaptive healthcare system

4) The authorization server validates the identity and creates access tokens for the valid clients.
5) The end user creates a request to the Resource Server with Authorization headers (access token)
6) The Resource Server performs token introspection in order to know more about the user and scopes.
7) The authorization server responds with valid scopes, permissions and other token parameters including the token type and token expiration.
8) The Resource Server makes a DB query with valid requests.
9) The DB responds back with requested resources.
10) The Resource Server then forwards the requested resources to the SMART applications.

C. Quality Attributes

In this section, we present the quality attributes of the proposed INTROMAT architecture to characterize the runtime behavior of the system, its design and user experience. To describe the quality attributes of the architecture, we have adopted the notational convention keywords 'MUST', 'MUST NOT', 'REQUIRED', 'SHALL', 'SHALL NOT', 'SHOULD', 'SHOULD NOT', 'RECOMMENDED', 'MAY', and 'OPTIONAL' in this section and are to be interpreted as described in RFC 2119 [22].

1) Interoperability: Mandl and Kohane recognized implications of the inflexibility of the contemporary EHR system and proposed a need for health platform with inherent characteristics like liquidity of data, suitability of applications (modularization and interoperability), based on open-standard and supports diverse applications [32]. The same study emphasis interoperability is a key requirement for the success of Healthcare Information Systems. One of the approaches to make system interoperable is to follow open-standard for defining syntactic and semantic meaning of information. We adopt one of such open-standards HL7 FHIR [2], [3], which is based on web standards including XML, JSON, HTTP, OAuth, ontology-based, and OpenID connect. To enforce interoperability, health records SHOULD be stored based on FHIR standards. However, legacy EHR systems MAY choose to utilize middleware that converts legacy data structure into FHIR standard before a successful communication can be established.

2) Security: The authorization server and the resource server MUST be TLS-secured [23] and should be improved using the contemporary practices mentioned in [23]. The authorization server SHOULD issue short-lived tokens and have a mechanism open to administrators and end users to eliminate tokens in the case of a security conflict. Moreover, the authorization servers MUST NOT use the value of the launch code as a mechanism for transferring the authenticated state. Using such a mechanism can lead to a session injection attack and a session fixation attack [27].

3) Modifiability: Modifiability incorporates evolvability, customizability, configurability, and extensibility [16]. SOA-based architecture facilitates modifiability [30] by allowing

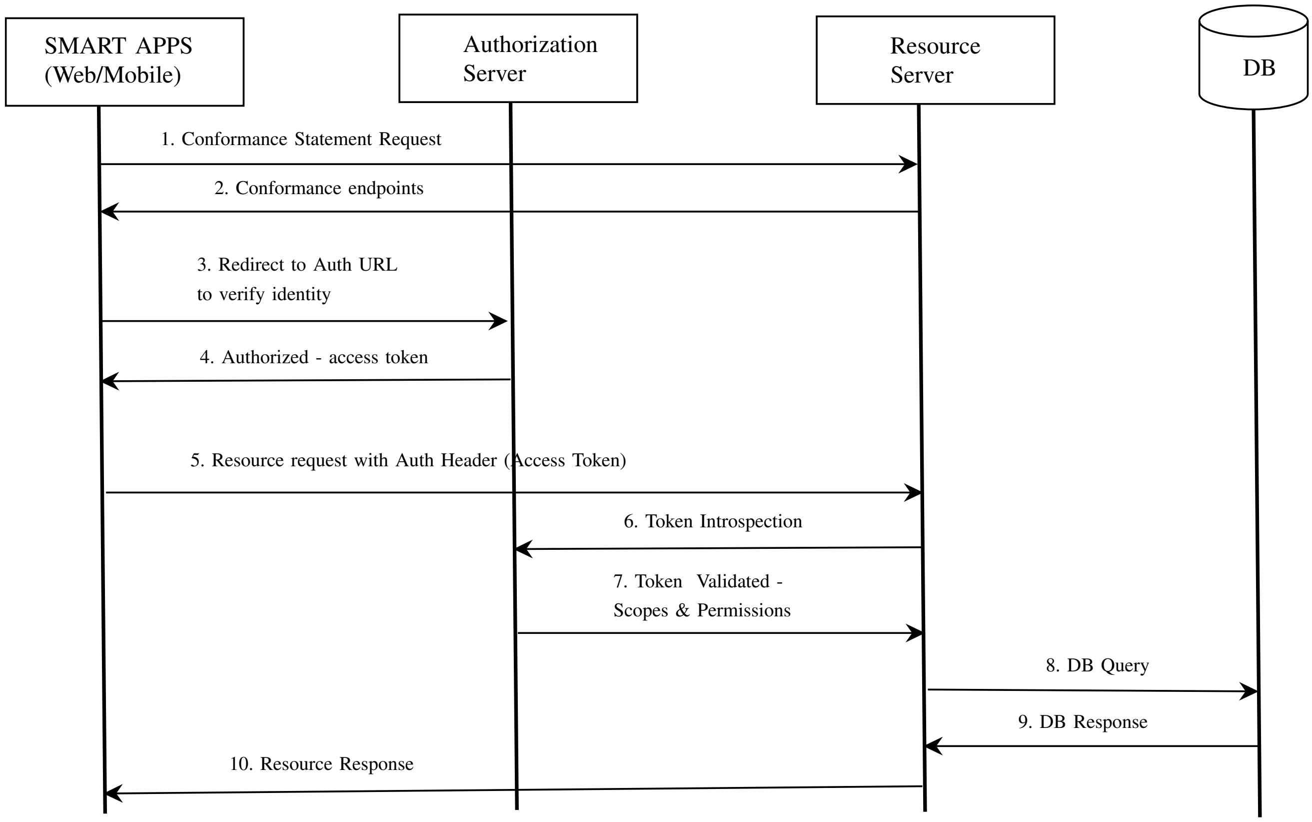

Fig. 3. Communication between different components

manageable growth of large-scale enterprise systems. These enterprise systems or components are independent of vendors, products, and technologies. This makes it easy for individual components to be managed and modified. For example, the Resource server in the architecture (described in Section III-A) MAY update the HL7 FHIR version or create an additional service that consumes the data and performs business intelligence, without affecting other components. Similarly, the authorization server MAY create a customized interface for managing authorized clients, their scopes and permissions without broadcasting its development complexity, structure and patterns, and technological compliances to other components. However, the constituting components MUST follow a common standard for data storage and transmission.

4) Scalability: Scalability can be motivated by simplification of the architectural components, distribution of services across many components [30] and control of configurations and interactions between constituting components [16]. SOA, as mentioned in Section III-A, enforces scalability by organizing services into several components communicating over a network. Each component of the architecture can be updated and evolved in terms of hardware and software independent of other components. For example, the data storage capacity of resource server can be increased or decreased without affecting other components.

5) Testability: As described in Sections III-C3 and III-C4, each component of the architecture is independent and MUST be tested independently to ensure their integral functional components. In addition to unit testing, functional testing and domain testing [17], detailed integration testing MUST be performed in order to ensure different components can communicate with one another.

IV. Case Study

To assess this architecture, we have implemented a prototype based on the proposed architecture for self-assessment and monitoring of mental health problems. We use the prototype for our case study which include depression (MADRAS-S [31], PHQ-9 [28], MDI [9]), anxiety disorder (GAD-7 [39]), ADHD (ASRSV1.1 [14]) and bipolar disorder (ASRM [5]). The self-assessment tool, developed using React Native[3], is in the form of mobile application for both IOS and Android.

In this section, we present the domain model of the self-assessment mobile application and discuss how information from the mobile application is exchanged from the device to Resource Server in INTROMAT core based on FHIR standard.

A. Domain model

We use Diagram Predicate Framework (DPF) [37] for domain modeling. DPF formalizes software development ac-

[3]https://facebook.github.io/react-native/

tivities such as metamodelling [4] and model transformations based on category theory and graph transformations [8]. By applying DPF we can formalize clinical guidelines and clinical domain models at the different abstraction levels in form of diagrammatic specifications. The diagrammatic nature of DPF also facilitates visual representations of guidelines that can be presented at different level of abstraction. A model in DPF is represented by a diagrammatic specification $\mathfrak{S} = (\mathcal{S}, C^{\mathfrak{S}} : \Sigma)$ which consists of a graph $\mathcal{S}$ and a set of constraints $C^{\mathfrak{S}}$ specified by a predicate signature Σ.

The predicate signature is composed of a collection of predicates, each having a name and an arity (shape graph). A constraint consists of a predicate from the signature together with a binding to the subgraph of the models underlying graph which is affected by the constraint. Table I shows a sample DPF predicate signature with three predicates: multiplicity, injective and commutative. The table shows the arity, visualization and the semantic interpretation of the predicates. In Figure 4 we present a portion of the domain model we used for this case study. It illustrates a model M_1 which is typed by metamodel M_0. The model M_1 is constrained with some predicates which specify the following constraints:

1) For each response instance, there exists a source reference and a questionnaire reference.
2) A questionnaire instance may have one or more question items. An example of question item is shown in Listing 1.
3) A question item may have zero or more answer options. FHIR provides two ways to specifies options: *answerValueSet* and *answerOption*. Listing 1 shows an example of *answerValueSet*. In addition, each answer option has a score which is used to get a total score from the response of a user. The score of the options is created by the FHIR concept of extension and StructureDefinition as shown in Listing 2.
4) A question item must have at least one code; An answer option must have at least one code. Listings 1 and 3 shows example of code.
5) A response instance must have the same number of response items as the number of question items the questionnaire instance has.
6) For every response item of a response instance, there exists an answer.

A questionnaire instance has a way to interpret the total score. This can be realized by the concept of extension. Listing 2 shows an example of how a total score should be calculated and interpreted. Moreover, it gives an evaluation expression that can be used to calculate total score by means of a path based navigation and extraction language, fhirpath[4]. The constraints mentioned above are imposed on M_1 by means of three DPF predicates: multiplicity, injective and commutative (see Table I). We transform this DPF model with constraints into an HL7 FHIR profile where Response, Questionnaire, Patient classes are mapped to QuestionnaireResponse, Questionnaire, and Patient FHIR resource type respectively. The purpose of these constraints is to link and validate the responses against the questions being asked by the self-assessment tool. Therefore, the benefits of using an FHIR profile on top of existing HL7 FHIR QuestionnaireResponse is to maintain the validity of the self-assessment tools.

[4]http://hl7.org/fhirpath/

TABLE I
A SAMPLE DPF PREDICATE SIGNATURE

Predicate p, Symbol	Arity, α(p)	Visualization	Semantic Interpretation
Multiplicity, [n..m]	1 —*f*→ 2	X —*f* **[n..m]**→ Y	∀x ∈ X : m ≤ | f(x) | ≤ n, with 0 ≤ m ≤ n
Injective, [inj]	1 —*f*→ 2 —*g*→ 3	X —*f*→ Y —*g*→ Z **[inj]**	∀y ∈ f(x) where x ∈ X there exists g(y’) where y’ ∈ y.
Commutative, [=]	1 —*f*→ 3, 1 —*h*→ 2, 3 —*g*→ 4, 2 —*k*→ 4	X —*f*→ Y, X —*h*→ W, Y —*g*→ Z, W —k→ Z **[=]**	∀x ∈ X : f;g = h;k.

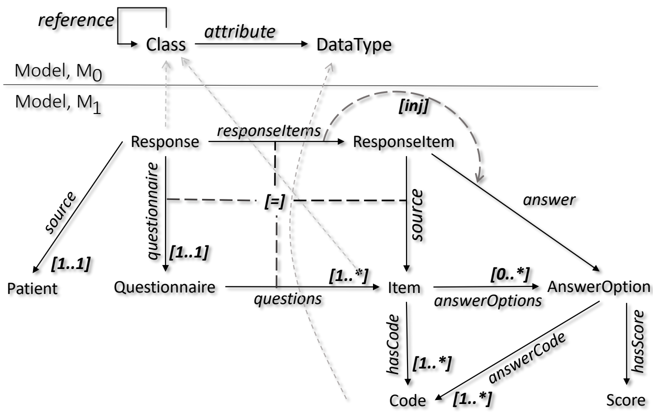

Fig. 4. Example: Diagrammatic model with constraints in DPF

```
{
  "linkId": "LittleInterest",
  "code": [
  {
   "system": "http://loinc.org",
   "code": "44250-9"
  }
  ],
  "text": "Little interest or pleasure in
      doing things",
  "type": "choice",
  "required": true,
  "answerValueSet": "http://loinc.org/vs/LL358
      -3"
}
```

Listing 1. An example question item extracted from PHQ-9

```
"extension": [
 {
  "url" : "http://hl7.org/fhir/
      StructureDefinition/questionnaire-
      calculated-value",
  "valueExpression" : {
```

```
  "description" : "Minimal or none (0-4), Mild
       (5-9), Moderate (10-14), Moderately
      severe (15-19), Severe(20-27)",
  "language" : "text/fhirpath",
  "name" : "score",
  "expression" : "QuestionnaireResponse.item.
      repeat(answer.valueCoding.extension.
      valueDecimal)"
  }
 }
],
```

Listing 2. Specifying scoring criteria using FHIR for PHQ-9

```
{
  "code": "LA6569-3",
  "display": "Several days",
  "extension": [
    {
      "url": "http://hl7.org/fhir/
          StructureDefinition/valueset-
          ordinalValue",
      "valueDecimal": 1
    }
   ],
},
```

Listing 3. Specifying option score for PHQ-9

B. Depression

In this section, we present a self-assessment tool for screening patients with depression and a CBT for managing depression in adults. We implemented MADRS-S [31] using SMART on FHIR. The MADRS-S score is used to evaluate the level of depression of a patient. Based on the level of depression, different CBT modules are created and assigned to patients. One of such CBT training is offered by Helse Bergen, Norway for depression management called eMeistring[5]. Anyone who wants treatment using the eMeisting program must be referred from a General Practitioner, specialist health service, other doctor or psychologist. The patients are offered a CBT to manage mild to moderate depressions. The patients who receive treatment through the eMeistring program are requested to give their consent to use their information for doing research.

A CBT program consists of several modules and each module includes reading, writing, listening or watching tasks. The patients are encouraged to perform these tasks regularly. Moreover, to better understand how patient activities affect the mood, each patient is provided with a mobile client to create a weekly plan consisting of a list of activities. The patients can also annotate the activities with a positive or negative flag to indicate their mood. These activities are shared with their therapist who helps them personalize the CBT based on their activities and mood.

V. Related Work

Balsari and et al. [7] proposed a concept of federated, patient-centric healthcare system after the Government of India announced to provide automated healthcare to 500 million citizens in India. The proposed healthcare system comprises various features including API enabled, authentication and authorization, open-standards (e.g., FHIR), block-chain based and the ability to share the personal health record with researchers and medical practitioner. The concept of transforming collected data into EHR from wearable sensors and using it for medical and research intervention is similar to the INTROMAT project. However, in INTROMAT project we have broader scope focusing on the entire mental health domain. We propose a cloud-based interoperable architecture based on SOA that uses the personal health data in machine learning to get deeper insights and use these insights for creating a personalized Internet-based treatment.

The ALZCARE [35] project developed a mobile application for screening dementia in elderly people. The proposed prototype contains questionnaires tests, whose response could be exported as XML in FHIR format. The proposed system incorporated the web-based clinical Information System for clinical settings and functionality for patient tracking. The system is based on RESTful client-server architecture, while our work is based on SOA. Moreover, we use the latest HL7 FHIR standard, support multiple mental health cases, and provide service for a higher level of cognitive computation.

HABIT [26], funded by the New Zealand Ministry for Business, outlines an IT infrastructure to provide appropriate data management and scalable system for youth mental health intervention. The paper reports the initial design of the platform and intended HABITs platform requirements. While the vision of having identity management, assessment storage, reasoning, usage logging, and consent is similar to INTROMAT project, the approach of implementation, technological eco-system preferences, assessment by a data-driven approach using wearable sensors and cognitive computation, usage of a recent version of the HL7 standard and SMART on FHIR technology are distinct.

VI. Conclusion

This paper presents some results from the INTROMAT project. We give an overview of the proposed solution including a cloud-based SOA for self-assessment and evaluation of mental or neurological morbidity, HL7 FHIR standard questionnaire, a working mobile application prototype for self-assessment and monitoring, a list of research challenges and opportunities in the field. The proposed solution solves the problem of interoperability and stigma on the one hand and provides a self-assessment tool that is accessible and available to patients and healthcare providers on the other. Future work includes the use of mobile applications to collect biological markers using wearable sensors. We will be using these sensors data to perform a cognitive computation to derive useful insights and utilize them to create personalized evidence-based treatments. These treatments will be provided through various types of applications such as mobile, VR application, and voice assistant.

[5]https://helse-bergen.no/emeistring

VII. Acknowledgement

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PAPER C

SCIENTIFIC PAPER III

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A GraphQL approach to Healthcare Information Exchange with HL7 FHIR

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Abstract

Interoperability is accepted as a fundamental necessity for the successful realization of Healthcare Information Systems. It can be achieved by utilizing consistent standards defining syntactic and semantic meaning of the information being exchanged. HL7 FHIR is one of such open standards for Health Information Exchange (HIE). While HL7 FHIR supports Representational State Transfer (REST) architecture and Service-oriented Architecture (SOA) for seamless information exchange, it inherits the inflexibility and complexity associated with the RESTful approach. GraphQL is a query language developed by Facebook that provides promising techniques to overcome these issues. In this paper, we exploit the use of GraphQL and HL7 FHIR for HIE; present an algorithm to map HL7 FHIR resources to a GraphQL schema, and created a prototype implementation of the approach and compare it with a RESTful approach. Our experimental results indicate that the combination of GraphQL and HL7 FHIR-based web APIs for HIE is performant, cost-effective, scalable and flexible to meet web and mobile clients requirements.

Keywords: `GraphQL`; `HL7 FHIR`; `REST API`; `overfetching`; `underfetching`; `Health Information Exchange`; `Interoperability`; `REST vs GraphQL`

1. Introduction

Software interoperability in the healthcare domain [10] can be realized by utilizing consistent standards like `HL7 FHIR` that supports `SOA` and `RESTful` approach to seamless information exchange. The `RESTful` architecture enables a machine to machine communication using only the ubiquitous `HTTP` protocol without additional layers. In addition, `REST API` [7] is a standard for deploying Application Programming Interfaces (APIs) for both simple and complex

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web applications. REST provides a comprehensive set of rules and constraints that can deliver fully functioning web services and structured access to resources [17]. However, these rules and constraints become inflexible and complex due to various reasons: i) the increase in the complexity of the systems being built, ii) the demand in the higher quality of services by the system end users, iii) the development of highly efficient real-time systems, and iv) the dynamic data fetching requirements of the mobile and web clients. To mitigate this inflexibility and complexity associated with REST, a new standard, known as GraphQL [5], has been developed by Facebook. Specifically, the following issues that are associated with REST are addressed by GraphQL:

- **Query Complexity**: REST requires multiple and complex HTTP requests to fetch multiple resources.
- **Overfetching**: Overfetching is characterized by returning more data than required by an application.
- **Under-fetching and n+1 request problem**: Under-fetching indicates that a particular endpoint does not give sufficient information. This results in making an additional request by a client application to a server. This is referred to as n+1 request problem.
- **API versioning**: An API creates a contract between two systems for information exchange and hence it should be stable and consistent. However, the business goals of any organizations change, so the APIs must be adaptable for modifications according to their behavior. This is handled by API versioning. An empirical study [12] addresses the perennial issue of REST API versioning and how evolution of such API affects the clients.

GraphQL has the potential to overcome these issues as it can be used to create scalable, sustainable, flexible, maintainable, interoperable, and secured APIs [11]. GraphQL functions as a service abstraction layer [16] providing a single API endpoint for resource fetching, creation or modification. GraphQL APIs holds the following characteristics: i) strongly typed schema; ii) introspection that allows clients to query about fields, types and supported queries; iii) enabling rapid product development; iv) rich open-source ecosystem; v) composable API (schema federation which allows merging multiple GraphQL APIs) [5]; vi) faster request-response cycles; vii) client-specified queries; and viii) being hierarchical (a GraphQL query itself is structured hierarchically and is shaped just like the data it returns) [5]. The *introspection features* provided by GraphQL allows users and developers to comprehend the interface easily and *machine-readable representation* enables dynamic and loose coupling between server and clients.

Despite these features, to the best of our knowledge, GraphQL based APIs are not adapted for exchanging healthcare information in general and especially not using *HL7 FHIR*. In this paper, we present a quantitative constructive research to evaluate the applicability of GraphQL based APIs for HIE based on HL7 FHIR [4]. We also propose an algorithm to automatically produce GraphQL schema for HL7 FHIR resources. The schema generation is a model transformation approach which reduces the number of errors typically occurring at the time of schema development.

The rest of the paper is structured as follows: Section 2 provides a mapping of existing HL7 FHIR resources to GraphQL schema. Section 3 describes the prototype implementation from healthcare context. Section 4 explains evaluation criteria and results. Section 5 discusses related works, existing challenges and concluding remarks.

2. Mapping HL7 FHIR Resources to GraphQL Schema

HL7 FHIR is based on *Resources* which are the common building blocks for all information exchanges. A single resource (e.g., Patient) contains several *Element Definitions* (e.g., name) which has *Data Type* (e.g. String) and cardinality associated with it (Figure 1). DataType can be Scalar Type, Enumeration Type or other HL7 FHIR resource types. Moreover, *Element Definition* can also reference another HL7 FHIR resource. GraphQL supports Interface Definition Language (IDL) that defines schemaes. A GraphQL document [5] can contain one to many schemas. As shown in Figure 1, each schema contains at least one RootOperationTypeDefinition (e.g., query) and several Types definition. Each Type definition can have several Fields which may contain Name(picture), Arguments(size) and Type(URL) definition. Based on the transformation model illustrated in Figure 1, we present an algorithm to transform from HL7 FHIR resources to GraphQL schema. In Algorithm 1, the recursive function recursive_hl7fhir_graphql_mapper takes the HL7 FHIR resource as an input and returns a GraphQL schema as an output. The function iterates over each field in the HL7 FHIR resource and based on field type and cardinality, an equivalent schema is generated as follows:

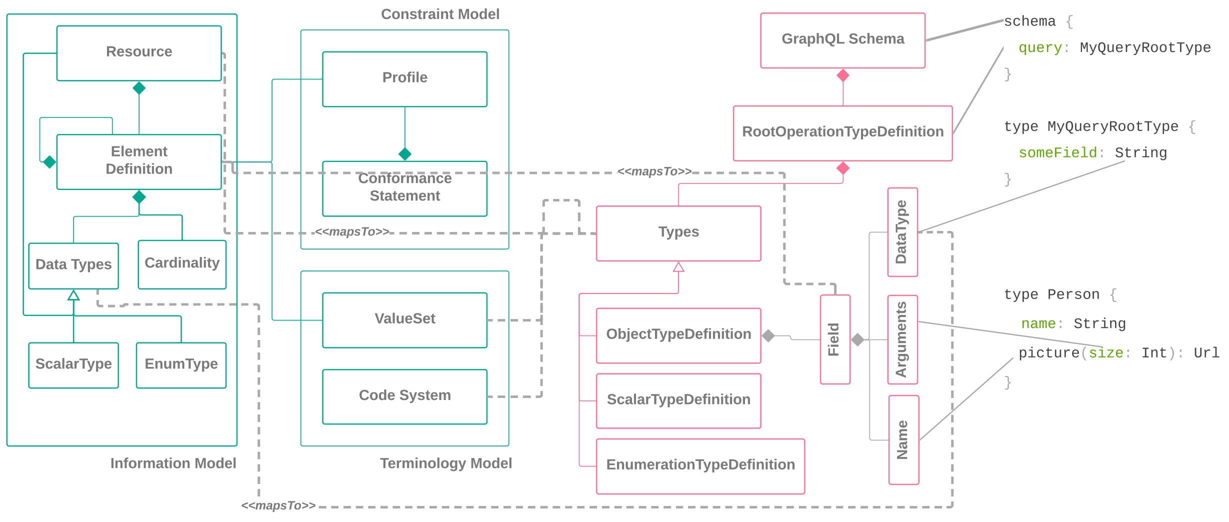


Fig. 1: A `HL7 FHIR` resource contains *information model, constraint model and terminology model*. Each field (Element Definition) in `HL7 FHIR` resources is mapped to an equivalent `Type` in `GraphQL` schema

Algorithm 1: Mapping `HL7 FHIR` resources to `GraphQL` schema

```
Input: FHIR Resource: Element Definition(field), Data Type(type)
Output: GraphQL Schema
function recursive_hl7fhir_graphql_mapper (Resource)
schema = {};
foreach field ∈ HL7 Resource.fields do
switch Resource.field do
    case field.Type is ScalarTypeDefinition do
        if field.cardinality is 0,1 then
            add_to_schema(field, type)
        end if
        if field.cardinality is 0,* then
            add_to_schema_as_list(field, type)
        end if
    end case
    case field.Type is EnumTypeDefinition do
        if EnumTypeDefinition already exists then
            - reference to schema
        else
            - define_new_type_enum(**args)
            - reference to schema
        end if
    end case
    case field.Type is Custom OR field.Type is HL7 FHIR
     Resource do
        if Custom OR Resource already exists then
            - reference to schema
        else
            - define new type Resource
            - reference to schema
            - recursive_hl7fhir_graphql_mapper(Resource)
        end if
    end case
end switch
;
return schema
```

```
{
  "family" : "<string>",
  "given" : ["<string>"],
  "use" : "<code>", // usual | official | temp |
       nickname | anonymous | old | maiden,
  "period" : { Period }
}
```

Listing 1: Patient Name in HL7 FHIR format

- If the `field` type is `ScalarTypeDefinition` (`String`, `Float`, `Int`, `Boolean`, `ID`) and `cardinality` is either `0` or `1`, we simply add to the schema with same `field` name and `type`. If the `cardinality` of `field` is `0` to `*`, we add to the schema as `ListType`. For example Listing 1 shows a patient name in `HL7 FHIR` format. The field `family` has data type `string`, so the field is simply added to `GraphQL` schema with the same name and data type. The field `given` is an array of datatype `string`. Hence, it is added as `ListType` in the `GraphQL` schema.
- If the `field` type is `EnumTypeDefinition`, and if it is already defined, we add `field` to schema and reference it to the `field`. If it is not defined, we create a new schema of `enum` type with required arguments and reference it to the `field`. A generated schema for the field `use` in Listing 1 can be found in Listing 2.
- If the `field` type is `HL7 Resource` or Custom, and if it is already defined in the schema, we reference it to that `field`. If it is not yet defined, a recursive call to `recursive_hl7fhir_graphql_mapper` is made with this `field` as the argument.

3. Prototype Implementation

This section outlines a typical health information exchange scenario in the context of healthcare. The scenario is taken from an ongoing project INTROMAT [9], which aims to support mentally ill patients with adaptive technologies. We discuss the need for GraphQL based API with respect to a self assessment mobile application, and to `INTROMAT` core architecture [14] that consumes `GraphQL`-based API for HIE.

3.1. INTROMAT Core Architecture

As illustrated in Figure 2, `INTROMAT` core architecture contains the following main components communicating over SOA standards:

- **Authorization Server** is an OpenID connect [15] compliant web server with an ability to authenticate users and grant authorization access tokens. Moreover, the authorization server manages scopes and permission of the clients, introspects token and requests for the resource server.
- **Resource Server** is a FHIR [1] compliant web server with an ability to respond to `HTTP` requests consuming access tokens granted by the Authorization Server.
- **Web Client** provides an interface for therapist and administrators to login and view the list of patients, questionnaires and other resources.
- **Mobile Client** is a self-assessment mobile application (Section 3.2) that consumes `Questionnaire HL7 FHIR` resources and sends response by using `QuestionnaireResponse` resource.

```
enum enumNameType {
    official
    usual
    temp
    nickname
    anonymous
    old
    maiden
}

type Period {
    start: Date,
    end: Date
}

type HumanName {
    family: String
    given: [String]
    use: enumNameType
    period: [Period]
}
```

Listing 2: Generated GraphQL schema from Listing 1

A detailed technical documentation of the prototype [13] of the above architecture is available to interested readers. All the components of the prototype are hosted on Amazon Web Server[1] (AWS) on `t3.micro` (EU, Stockholm) Red Hat Linux instances to perform the evaluation under similar environment.

3.2. Self Assessment Mobile Application

The main aim of developing the self-assessment application is to provide a possible way for people suffering from mental health morbidity to self-evaluate and manage their illness. In addition to, the application showcases the exchange of information based on `HL7 FHIR` standard [14] to support interoperability. The application utilizes the `REST API` standard to exchange information between *mobile client* and *resource server*. The application contains several views including: i) a list of available self-assessment questionnaires (`name, id`), and ii) a detailed view of a questionnaire (`id, questions(id, text), and options (id, text)`). The listing view (all available questionnaires) shows the name of the questionnaire and only requires to have `id, name` of the questionnaire. However, to support interoperability and maintain the semantics, we require to support all the available attributes[2] of the questionnaire resource mentioned in the `HL7 FHIR`

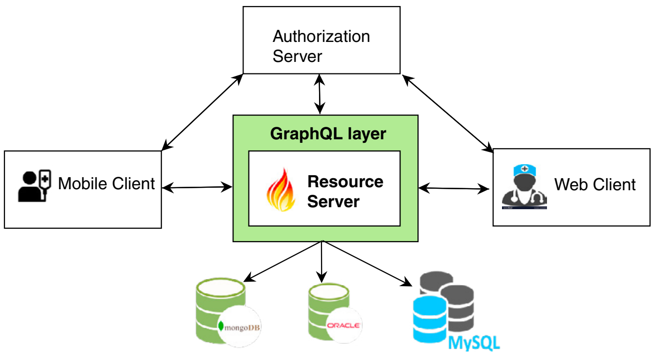


Fig. 2: The prototype contains five major components: a) mobile client for self-assessment, b) resource server based on `HL7 FHIR`, c) authorization server for authentication and authorization, d) web client: to provide web interface for therapist and e) mongoDB to store data.

[1] https://aws.amazon.com
[2] http://hl7.org/fhir/questionnaire.html#resource

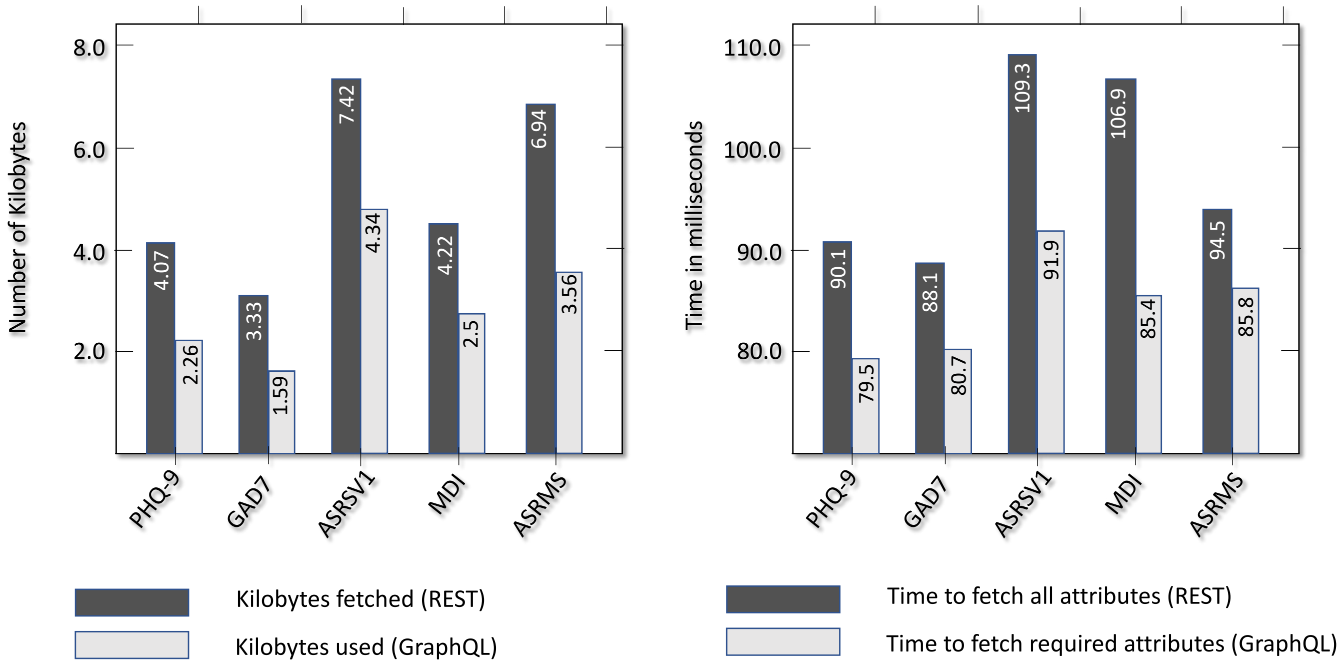


Fig. 3: (Left:) Response size – *Questionnaire:* types of self-assessment questionnaire for mental health, *Kilobytes Fetched:* bytes of data fetched by REST API, *Kilobytes Used:* data actually used by mobile client, (Right:) Response Time – *All attributes*: Time taken to fetch all attributes, *Required attributes*: Time taken to fetch used attributes

[3] standard. These API endpoints fetch a plethora of additional metadata that are irrelevant for the application. The `RESTful` approach to solving this problem is to define a new API endpoint or update an existing endpoint that would only return `id` and `name` of the questionnaire list. However, creating new endpoints or modifying existing endpoints for solving different requirements of the clients become quickly inflexible and expensive. This is because different clients require different attributes for different views and these requirements are very dynamic which are liable to change according to demographics, organizational ethics, and application views. This can be solved by providing an endpoint with a higher level of abstraction for clients to query the server based on their requirements. The need for such endpoints is supported by the empirical study [12].

4. Evaluation

We aim to evaluate whether migrating from `RESTful` approach to `GraphQL` based API is scalable and performant. To evaluate, we performed *response size/time test* and *performance test*. As aforementioned, all the components are hosted at Amazon Web Server with the same configuration for testing to keep evaluation metrics consistent.

4.1. Response size and time

The aim of this evaluation is to explore how much extra information was fetched from the endpoints when fetching a single `Questionnaire` item using REST and how much is actually being used by our self-assessment mobile application (see Section 3). Figure 3 (left) illustrates the overall difference in the amount of data returned by `HTTP` responses while fetching a single questionnaire resource. The figure shows that approximately 50 percent of information is not used by our self assessment mobile application. We also evaluated the time taken to fetch all the attributes in `RESTful` approach and compare the result with the time taken to fetch only used information using GraphQL API. Figure 3 (right) shows the time taken in milliseconds to fetch all the attributes versus the time taken to fetch only the required attributes for various types of questionnaire. To keep the measurement uniform, Postman[3] was used to send HTTP requests to the server; the evaluation was performed on the same machine and we took an average reading (10 requests were recorded for each questionnaire type).

4.2. Performance Testing

Performance testing inspects responsiveness, stability, scalability, reliability, speed and resource usage of software and infrastructure. We used BlazeMeter[4] which is powered by Apache JMeter[5] for creating performance tests. Each HL7 FHIR resource requires the endpoints for CRUD (Create, Read, Update, Delete). Presenting performance tests for each endpoint is out of the scope of the paper. However, we present performance tests for getting an Questionnaire resource, where the questionnaire GAD-7 is for anxiety disorder. Table 1 shows the metadata for the performance evaluation, which include two parts: one for fetching all the attributes from questionnaire, and one for fetching only required attributes). Both were performed on the same server and have the same configurations. Fifty virtual users requested resources concurrently for 20 minutes. Based on this test, we have made the following observations:

Description	All attributes	Required Attributes
Average Throughput	100.6 hits/second	157.7 hits/second
Average Response Time	484 millisecond	308 millisecond
Time Elapsed	20 minutes	20 minutes
Concurrent Users	50	50

Table 1: Performance test meta-data for fetching GAD-7 Questionnaire resource. Column 1: description of the meta data, column 2: meta data for fetching all attributes from the endpoints. column 3: meta data when fetching only required attributes

- Figure 4a illustrates concurrent users versus average throughput[6] (Hits/s) when requesting all the attributes using RESTful approach from GAD-7 Questionnaire.
- Figure 4b illustrates concurrent users versus average response time[7] when requesting all the attributes using RESTful approach .
- Figure 5a illustrates concurrent users versus average throughput (Hits/s) when requesting only required attributes using GraphQL approach.
- Figure 5b illustrates concurrent users versus average response time when requesting only required attributes using GraphQL approach.

Figures 5a and 5b clearly show that there is an increase in average throughput and that response time is faster if only the required attributes are fetched by using the GraphQL based API. The result is interesting to related stakeholders as the throughput and response time are directly associated with operating costs and performance of the system, which in turn are associated with the user adherence.

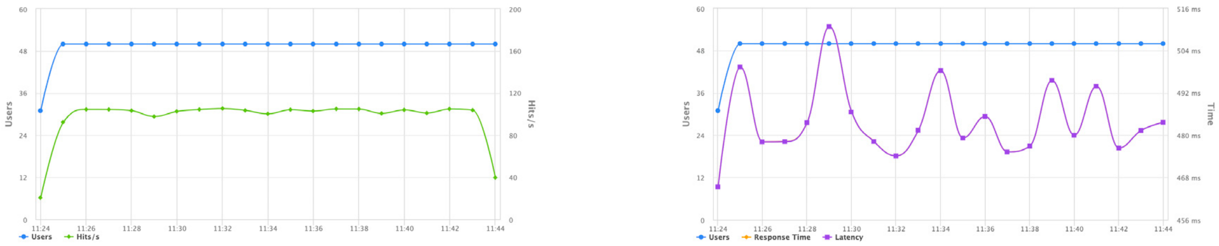
4.3. Expert Evaluation

The code for all the components mentioned in Section 3.1 has been evaluated by three senior front-end developers to check their compliance with ISO/IEC 25000:2005 software product quality requirements and evaluation [11] criteria and any presence of anti-patterns [2].

4.4. Discussion

Although GraphQL provides a sophisticated technology to develop client-centric applications with very complex queries, there are some challenges. For example, unmanaged queries can have security implications. A malicious

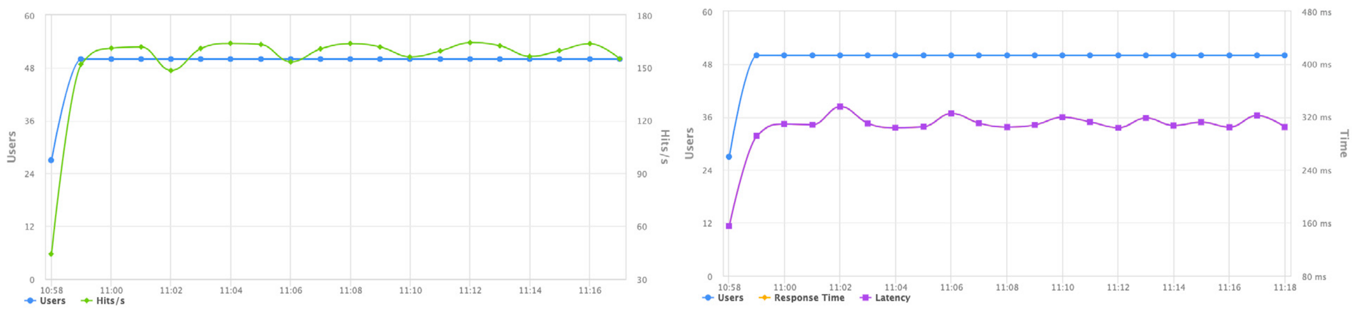
[3] https://www.getpostman.com/
[4] www.blazemeter.com
[5] https://jmeter.apache.org/
[6] average number of HTTP/s requests per second generated by the test
[7] average amount of time from first bit sent to the network card to the last byte received by the client.



(a) Concurrent users and number of hits per second when fetching all the available attributes from the `Questionnaire`

(b) Concurrent users and response time (milliseconds) when fetching only the required attributes from the `Questionnaire`

Fig. 4: Performance test results representing concurrent access using `RESTFul` approach



(a) Concurrent users and number of hits per second when fetching only the required attributes from the `Questionnaire`

(b) Concurrent users and response time (milliseconds) when fetching only the required attributes from the `Questionnaire`

Fig. 5: Performance test results representing concurrent access using `GraphQL` approach

actor could submit an expensive, nested query to overload a `GraphQL` server, database, and network. The absence of appropriate protections can open up to a `DoS` attack [6]. Another challenge is to deal with schema duplication. The creation of `GraphQL` based backend, which acts as a database service abstraction layer, involves a plethora of similar but not-quite-identical code, especially schema definition. It requires i) a schema definition based on the choice of the database being used (`MongoDB` is used in this paper, and therefore schemaes are based on `Mongoose`[8]); and ii) a schema definition for a `GraphQL` endpoint. This creates schema redundancy and requires synchronization between two independent sources of truth.

5. Related Work

There is a number of emerging solutions in the `GraphQL` echo-system including `PostGraphile`[9] that generates `GraphQL` schema from `PostgreSQL` database, and `Prisma`[10] that allows generating queries and mutations. In addition to this, various other transformation libraries are being developed by the community to support various database systems. There has been research on the syntax and semantic representation of `GraphQL`. A recent study by Ulrich et. al [16] introduces QL^4MDR, an ISO 11179-3 compatible `GraphQL` query language, which promotes interoperability by defining a uniform interface between different metadata repository (MDR) allowing querying over a distributed network. However, their study does not explicitly give the answer to how `HL7 FHIR` can be used for HIE and how `HL7 FHIR` resources can be transformed into the `GraphQL` schema. Our work helps bridge this gap and is different from the work in [16] as we focus on experimental evaluation to demonstrate the applicability of `HL7 FHIR` and `GraphQL` based API in a healthcare setup. Another study was presented in [8] which formalizes the semantics of `GraphQL` queries

[8] https://mongoosejs.com/
[9] https://www.graphile.org/postgraphile/
[10] https://www.prisma.io/

based on the labeled-graph data model and analyzes the language to demonstrate that it admits efficient evaluation methods. Moreover, the study proves that the complexity of `GraphQL` evaluation problem is `NL-complete` and the enumeration problem can be solved with constant delay.

6. Conclusion

Interoperability in healthcare information system can be achieved by using standards like `HL7 FHIR` which supports `RESTful` and SOA approaches by default. However, the `RESTful` approach comes with certain shortcomings. We have summarized a list of challenges with the `RESTful` approach in HIE and presented a `GraphQL` based API for HIE using `HL7 FHIR` standard as the solution to those challenges. Moreover, we have presented a transformation algorithm that takes `HL7 FHIR` resource definition as input and produces `GraphQL` schema as output. Furthermore, we present a healthcare application (self-assessment mobile application) based on a reference architecture proposed in [14]. The evaluation of the healthcare application shows that the use of a `GraphQL` based API is both performant and cost-effective. In addition, it solves problems associated with the `RESTful` approach, including the over-fetching, under-fetching and, `n+1` request. The most prominent future work involves removal of schema duplication by using transformation tools, and creation of comprehensible dashboard for better visualization for therapists.

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PAPER D

SCIENTIFIC PAPER IV

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Adaptive Systems for Internet-Delivered Psychological Treatments

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ABSTRACT Internet-Delivered Psychological Treatments (IDPT) are based on evidence-based psychological treatment models adjusted for interaction through the Internet. The use of Internet technologies has the potential to increase the availability of evidence-based mental health services for a far-reaching population with the use of fewer resources. Despite evidence that Internet Interventions can be effective means in mental health morbidities, most current IDPT systems are tunnel-based, inflexible, and non-interoperable. Hence it becomes essential to understand which elements of an Internet intervention contribute to effectiveness and treatment outcomes. By analogy, adaptation is a central aspect of successful face-to-face mental health therapy. Adaptability to patient needs can be regarded as an essential outcome factor in online systems for mental health interventions as well. While some aspects of rule-based and machine-learning-based adaptation have attracted attention in recent IDPT development, systematic reporting of core components, dimensions of adaptiveness, information architecture, and strategies for adaptation in the IDPT system are still lacking. To bridge this gap, we propose a model that shows how adaptive systems are represented in classical control theory and discuss how the model can be used to specify adaptive IDPT systems. Concerning the reference model, we outline the core components of adaptive IDPT systems, the main adaptive elements, dimensions of adaptiveness, information architecture applied to adaptive systems, and strategies used in the adaptation process. We also provide comprehensive guidelines on how to develop an adaptive IDPT system based on the Person-Based Approach.

INDEX TERMS Adaptive systems, Internet delivered psychological treatments, person based approach, information architecture, personalized Internet interventions, tailored Internet interventions, ICBT.

I. INTRODUCTION

In face-to-face therapy for mental health, therapists adapt their behavior towards their patients, to ensure the highest likelihood of successful therapeutic outcomes. The therapist's behavior is partly dynamic and can change in response to the patient's development. In Cognitive Behavioural Therapy (CBT) for social anxiety and fear of public speaking, for example, the therapist will begin with helping the patient to become comfortable with one particular social space. Once the patient is comfortable with that space, the therapist will adapt and help the patient generalize the progress and become comfortable in a broader range of social settings. In the case of reversal of development, the therapist will return to focusing on tasks previously managed by the patient. The therapeutic goals, dynamic guidance from the therapists, and the feedback that the patients experience with the therapists are essential outcome factors for mental health therapy.

Currently, online systems for mental health therapy are becoming widely available. Human beings are adept at understanding and communicating with others, and creating interpersonal contexts that are conducive to reaching a predetermined goal. These conditions are more challenging to re-create in online environments, however. It requires the re-alignment of roles, activities, and the remediation of information and intervention materials. While it is impossible to

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emulate face-to-face therapy in online settings completely, and online interventions are therapeutic constructions in their own right, one measure to help to ensure successful therapeutic outcomes is to make the environment adaptive to the user.

Building Adaptive Internet-Delivered Psychological Treatments (IDPT) requires input and competencies from both computer science and psychology, each presenting different challenges to building an adaptive system. From the computer science perspective, one challenge lies in the perpetual evolution of software systems and the integration of technology. As a result of this continuous evolution, software systems must be versatile, flexible, resilient, dependable, robust, energy-efficient, recoverable, configurable, customizable, and self-optimizing by adapting to operational changes in contexts, environments and system characteristics [1]. Additionally, the complexity and uncertainties of the problems arising in software systems are dynamic. These complexities prevent the use of a common *a priori* solution. Instead, an endeavor is made to solve this problem adaptively by dynamically collecting information about the problem at hand and using this information to generate an acceptable solution [2]. From the psychotherapy perspective, the ideal mental health treatment administered to one patient is not necessarily the same as that given to another patient exhibiting similar symptoms [3]. The individual nature of mental health problems makes it difficult to successfully make technology that resonates with human behavior and creates positive outcomes. People with similar mental health problems require different kinds of treatment. So, the technological solution needs to be adaptive to disseminate personalized treatments.

The Person-Based Approach (PBA) is a development methodology aimed at overcoming both Information and Communications Technology (ICT)-related and human-related challenges to build successful interventions for people to manage their health or illness [4]. PBA is explicitly developed for mental health interventions and health management and is meant to complement evidence, and theory-based treatment approaches by capturing and incorporating user perspectives in the design process [5]. PBA draws on methods from user-centered design [6], particularly behavioral analysis, and in-depth qualitative research [5], and seeks to understand both digital and non-digital behavioral aspects of interventions [7]. For mental health interventions to be effective, they must have a positive effect on the quality of life of the patient, they have to be technologically robust, flexible, and evidence-based, and they must have taken user interaction and engagement into account. Through building knowledge about user views, context and experience, the goal is to create interventions that are ‘‘maximally meaningful, feasible and engaging for all users’’ [7, p. 464], and ultimately to ensure the effectiveness of the intervention [5]. In this study, we further bridge the gap between approaches for participatory/user-centered and systems architecture design by adapting and expanding PBA to provide guidelines to build successful *adaptive* IDPT interventions. Adaptive systems for mental health therapy and PBA combine well, as both share the aim of increasing the usefulness for and relevance to the user. Furthermore, successful implementation of online mental health interventions requires the combination of several perspectives, including computer science and behavioral science. Hence, we consider the main contribution of our study to be a conceptual framework combining the systemic approach of model-driven software development of adaptive systems supporting online mental health therapy, with the empirically driven design framework of PBA. Both perspectives share the goal of facilitating the highest possible use of digital mental health interventions. We furthermore envisage that the resulting framework will allow developers, designers and researchers to reuse the same intervention system for multiple mental health issues.

We have tabulated a list of related works in Table 2 and compared them with our work in Section IX. To summarise, although some studies attempted to personalize interventions using the rule-based method and machine learning methods, none of the studies, to our knowledge, reported a reference model of an adaptive system and its core components systematically. We aim to fulfill this gap by proposing a reference model and outlining its core components.

The contributions of this study are the following:

- First, we propose a model that shows how adaptive systems are represented in classical control theory and show how the model can be used to specify adaptive IDPT systems. Moreover, concerning the reference model, we outline the core components of adaptive IDPT systems, the main adaptive elements, dimensions of adaptiveness, information architecture applied in adaptive systems, and finally, several strategies used in the adaptation process.
- Second, we provide comprehensive guidelines on how to develop an adaptive IDPT system building on the Person-Based Approach.

The rest of the paper is structured as follows: Section II outlines a definition of adaptive systems. Section III discusses adaptive IDPT systems and their types. Section IV describes several dimensions of adaptive IDPT systems. Section V outlines elements that can be adapted in an IDPT systems. Section VI describes different information architectures that can be observed in IDPT systems. Section VII outlines strategies that are used in the adaptation of IDPT systems. Section IX outlines a list of related work where we compare and relate our work with previous studies. Finally, Section VIII provides a guideline on how to develop an adaptive IDPT system with respect to the Person-Based Approach.

II. ADAPTIVE SYSTEMS

An *adaptive system* is a set of interacting or interdependent entities, real or abstract, forming an integrated system that changes its behavior in response to its environmental changes [8], [9]. The changes that occur in its behavior are relevant and directed towards the fulfillment of the

TABLE 1. Different dimensions of adaptive Internet delivered interventions.

Dimension	Descriptions
User preferences	Temporal preferences, content presentation preferences, lingual preferences, based on interaction log analysis
Goals of the interventions	Therapists oriented goals, patient-centric goals, which are characterised by evolution, flexibility, duration, multiplicity and dependencies.
Measures	*Psychometric tests*: (Depression (MADRAS, MDI, BDI), Generalized Anxiety Disorder (GAD-7), Bipolar Disorder (Altman Self-Rating Mania Scale), ADHD (Adult ADHD Self-Report Scale) and others.), *user behavior analysis based on interaction data*
Adaption actor	Automatic, semi-automatic (algorithm + therapist) and manual (Therapist/Users)
Adaptation strategies	Rule-based, Goal-based, Machine Learning-based, Hybrid approach

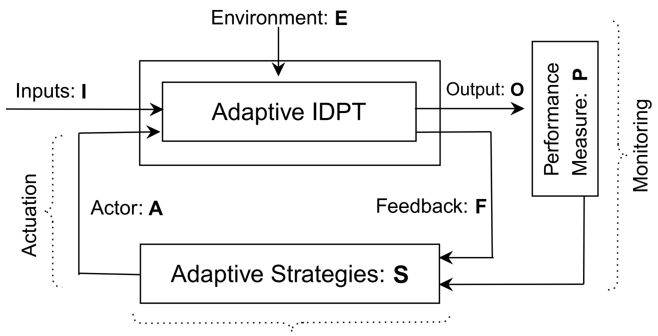

FIGURE 1. We propose an Adaptive IDPT model based on classical control theory. It illustrates IDPT systems as a complex function that works in an environment (E), consumes controlled inputs (I), generates outputs (O). The system measures the performance of the outputs using some measures (P) and uses some feedback function (F) to create adaptive strategies (S). Actors (A) trigger the adaptation. These strategies control how the IDPT system should adapt.

objectives defined for the system. Self-adaptive software is context-dependent and has the ability to modify its structure and behavior in response to the contextual changes. This kind of software provides the users with context-dependent functionalities (presenting users with correct lingual interventions based on the country, for example – if a user is using IDPT system from any particular country, the intervention is presented in the language of that country) and context-independent functionalities (for example login form for authentication and authorization where different users credentials are checked for validity and permission with database). We chose to define adaptive IDPT abstractly, based on literature [10], [11], using classical control theory as illustrated in Figure 1.

The formal representation of the adaptive IDPT system constitutes the following components:

- a set of environments **E** in which IDPT is working as a complex process.
- a set of controlled inputs **I** consumed by IDPT systems for changing the behavior of the process. These inputs can vary from text-based inputs, sensor-based data such as heart rate, electro-dermal activities (EDA), user activities data, sleep data, voice data, eye movement data, and other types of biological markers.
- a process to measure the performance of the system **P** indicating performance of the IDPT in environment **E** when consuming **I** as input. Psychometric tests (see Table 1) are the principal performance measures for IDPT systems.
- a feedback function **F**, which generates an adaptive strategy with dynamic information about the process being controlled.
- a set of strategies **S** (see section VII), which use the knowledge learned from information and performance of the system.
- a set of actors **A** (see Figure 3) who trigger adaptation.

In general, adaptive software systems include monitoring, decision making, and actuation to maintain dependable behavior despite sudden, unpredictable changes like application workload fluctuations and hardware failures. As depicted in Figure 1, a set of inputs is monitored by an adaptive IDPT system to produce some output. Several performance measures, like psychometric tests and goal achievements, are used to evaluate the efficacy of the results (monitoring). Based on these measures, several strategies (decision-making process) are used to change the behavior of the system (actuation).

III. IDPT SYSTEMS

Internet-Delivered Psychological Treatment (IDPT) systems refer to any software applications that facilitate interaction with psychological therapy through the Internet. These mainly include web-applications, mobile applications, augmented reality, and virtual reality applications. Several terms are used in research to refer to IDPT systems, for example *web-based treatments, web-based interventions, online treatments, computerized psychotherapy, e-therapy, Internet-based cognitive behavioral therapy (ICBT or iCBT), digital interventions, internet-based interventions, online interventions, web-application based psychotherapy treatments, therapeutic web-based interventions, eHealth interventions [12], and others.* In addition to this, researchers use different technical terms to represent the IDPT systems, for example *Interapy* [13], *Deprexis* [14], ULTEMAT [15], dBCIs (digital behaviour change interventions) [16], smartphone-based applications with specific brand names [17]. To be consistent, we chose to use the term

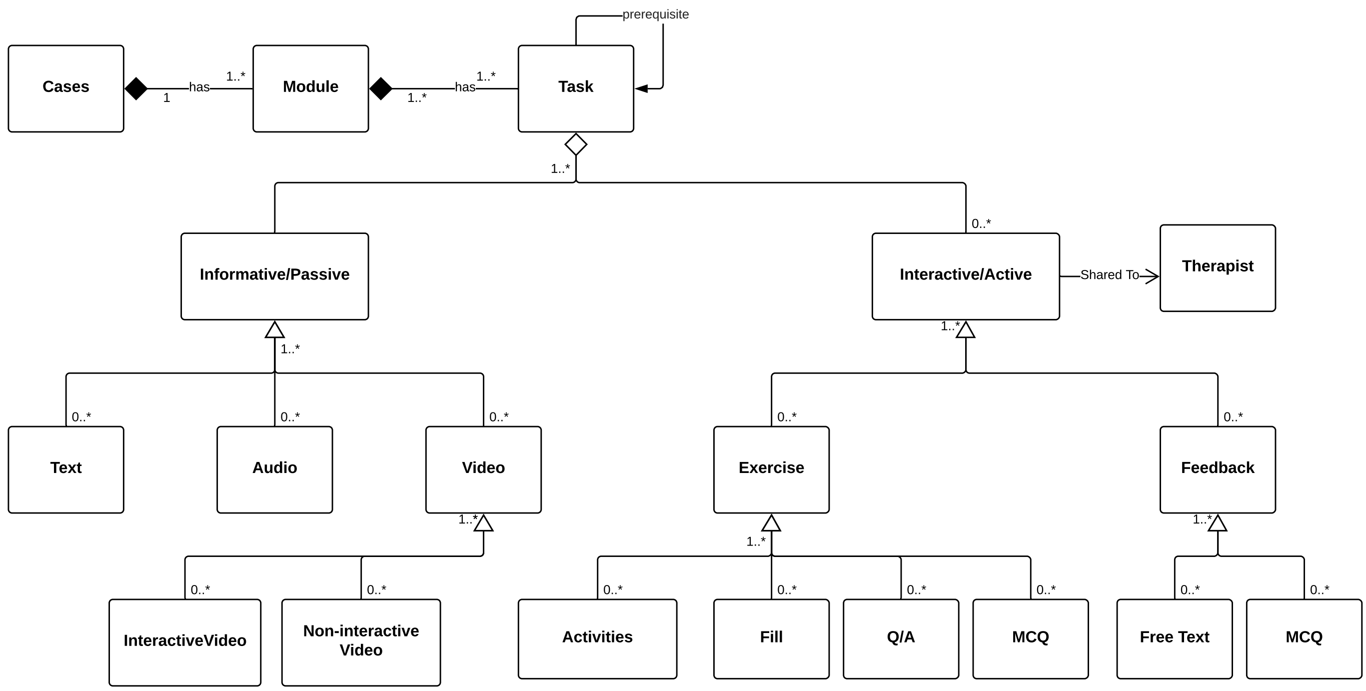

FIGURE 2. **The conceptual model of Internet-Delivered Psychological Treatments (IDPT) includes one to many cases (Depression, Social Anxiety, and other mental health issues.). Each case contains one to many modules (Sleeping issues, Speaking issues, improving concentration, and others.) Each module, in turn, includes one to many tasks, which has prerequisites as the constraints. Each task contributes to collecting passive or active data in the system. Based on what type of data these tasks can accumulate, they consist of text task, audio task, video, exercises, or feedback.**

Internet Delivered Psychological Treatments, as suggested by Andersson *et al.* [18].

IDPT has surfaced and grown as one of the most commonly practiced and widely researched forms of psychotherapy [19]. The evolution of IDPT, coupled with the exponential growth of Internet access throughout the world, has the potential to reshape the landscape of mental healthcare. Despite evolution in IDPT, several patients suffering from mental health issues go untreated [20], [21]. Obstacles to receiving treatment for mental health problems include long waiting lists, limited access to psychiatric medications, perceived stigma of seeking help, and treatment costs [21]–[23]. IDPT systems have been proposed as one solution to bridge this treatment gap. IDPT removes several barriers over traditional face-to-face therapy that hinders the majority of patients from efficient psychiatric care [24]. The use of IDPT tools can enhance patient health in several ways: 1) IDPT can be available and accessible from anywhere with an Internet connection [3]; 2) the temporal aspects of access can be substantially improved; 3) the scalability of IDPT can drastically enhance the functional capacity of the care; 4) makes the treatment cost-effective for individuals who do not have insurance or can not afford the out-of-pocket fees for treatment, and 5) removes the discomfort and the stigma related issues associated with the face-to-face approaches.

A. COMPONENTS OF IDPT

Figure 2 depicts a conceptual model of IDPT. A typical IDPT contains several components:

- **Cases**: Typically, IDPT includes one or more cases such as Depression, Social Anxiety, Bipolar Disorder, ADHD, and other mental health issues [25].
- **Modules**: Each case contains one to many modules that focus on any particular dimension of the case. For example, for depression, there can be a module for sleeping issues, concentration issues, speaking issues, and others. One module can belong to one or many cases. The modules can have dependencies.
- **Tasks**: Each module, in turn, includes one to many tasks and have constraints as the prerequisites. Examples of such constraints include task dependencies, task availability, publication date, and others. Each task contributes to collecting passive (informative) or active (interactive) data in the system. *Informative tasks* provide learning materials about the mental health issue (case), symptoms, use cases, and several ways to manage them. The main objective of such educational materials is to provide psycho-education so that a) patients and their families can learn about symptoms, causes, and treatment concepts; b) patients can comprehend self-help program and steps required to manage their illness; c) patients can correlate their situations with similar others which helps to ventilate their frustrations. Such educational materials are in the form of reading tasks (text), listening (audio), and watching (video). In contrast to informative tasks, *interactive tasks* involve user interactions and often in the form of exercises. The exercises can be physical activities or computerized

tasks. Examples of activities include physical workouts and mindfulness exercises such as breathing exercises, walking certain distances, stretching, or physically performing any other activities. Examples of the computerized exercises involve fill in the blanks, question answering (Q/A), multiple-choice questions (MCQ), and feedback. The feedback type of task consists of using free text, rating systems, or multiple-choice questions.

B. TYPES OF IDPT

- **Guided vs unguided**: IDPT can be either guided [26] or unguided [27]. In guided IDPT, a therapist is a planned part of the online intervention environment, and available to the patient to some degree. In unguided online therapy, the intervention is automated and independent of human support [28]. Several review studies (e.g., [28], [29]) find that participants in guided online interventions overall benefit more from the intervention compared to unguided interventions. The qualification of the therapist in these settings affects the patient results to a lesser degree [28]. A therapist in guided IDPT can make a diagnosis and determine the suitability of the treatment for a patient. The adherence rates in guided IDPT are also higher [29]. Several authors (e.g., [28], [30], [31]) have also found that the presence of accountable and trusted moderators, for example, enhances participant motivation and adherence in online therapy environments. There are, however, potential reasons for patients to prefer unguided options, such as privacy and increased likelihood of self-disclosure in stigmatic cases, and there are also ways of making unguided online intervention environments adaptive, such as automated notifications [32] and pre-intervention screening and tailoring [33].
- **Personalized care vs. stepped care**: There are two types of mental health care:
  - **Personalized Care:** Personalized medicine in P4 medicine [34] holds a great promise in improving the quality of treatments for mental health conditions [35]. The term P4 medicine stands for **personalized** (the focus of care is on the individual), **predictive** (signs of the illness can be recognized before it manifests), **preventive** (with correct tools and pre-diagnosis, can be prevented), and **participatory** (informed about the health conditions and healthcare decisions). With personalized care, treatment outcomes are improved by giving individual patients a treatment that is precisely right for them [36]. Personalized medicine is usually thought of as a way to match patients to the optimal intervention before initiating treatment [36], [37].
  - *Stepped Care:* In stepped care, all or most of the patients are given the same, least intensive, and most readily available treatment [38]. In stepped care, the treatments initiate with simpler form and are gradually stepped up for those who can not benefit from simpler treatments [38].

IV. DIMENSIONS OF ADAPTIVE IDPT

The way an adaptive system changes its behavior depends on a multitude of factors: a) users' preferences, b) goals of the interventions, c) measures, d) adaptation actors, and e) adaptation strategies. We refer to these aspects as the *dimensions* of adaptive IDPT. Andersson *et al.* [39] propose a classification of modeling dimensions for the self-adaptive software system. According to the study, the authors distinguish four dimensions of self-adaptive systems: *goals of the system, change that causes adaptation, mechanism which is the reaction of the system towards the change* and finally *effects which is the impact of the adaptation upon the system.* Similar to these dimensions, we propose five distinct dimensions as illustrated in Table 1 in the IDPT systems.

A. USER PREFERENCES

Most of the mental health interventions have been modeled on a psychological therapy format with variation in the intervention period, content types, mode of delivery, and health issues. In general, the content is structured and designed to allow users to learn and practice new skills that help them to manage their illness. However, Internet content is often not designed in this way. Arguably, this is one of the reasons users spend less than 70 seconds on 80% of IDPT web applications [40]. It is reasonable to infer that users of IDPT have preferences for different models of engagement. User preferences [41] may influence other aspects of design, the modality of content, choice of videos, images, texts, or a combination of these that impact user engagement with online content [42]. User preferences can be the temporal, content presentation, and lingual. In *temporal preferences*, users tend to engage with interventions at different time instances of a day. In the *content presentation preferences*, the contents can vary from texts (reading), audio (listening), videos (watching) and exercises (writing). Users have different preferences regarding the type of content they like to interact with. In the *lingual preferences*, the users prefer to interact with the system in their language.

User preferences can be captured in two ways: explicitly asking and implicitly inferring, by recording the actions of the users as the form of a log. The latter choice is less intrusive. Log analysis helps therapists to understand their patients' preferences on the one hand and shows the bottlenecks in the system on the other. Agosti and Di Nunzio [43] presents a general methodology for gathering and mining information from Weblogs.

B. GOALS OF THE INTERVENTIONS

Goals are the primary objective of the entities under consideration. Here, we outline two major types of goals: *patients goals* and *therapist goals.* In general, the goal of patients is to learn to manage their illness where the therapists' goal is to increase treatment outcomes so that the patients get better treatments. Goals of IDPT can have the following characteristics:

- Evolution: Goals can change within the intervention lifetime.
- Flexibility: Goals can be flexible in the way they are expressed. For example, *users must complete module one before going to module two* indicates a rigid goal. *A user can choose between assignments from the first module*, indicates an unconstrained goal.
- Duration: Goals of the intervention may hold validity throughout the intervention's lifetime or may be temporary.
- Multiplicity: The number of goals associated with the adaptive aspects of IDPT. An IDPT can have a single goal or multiple goals. Single goal IDPT systems are easier to implement.
- Dependency: In any IDPT system, goals can be related to each other. The goals can be dependent and independent.

C. MEASURES

As illustrated in Figure 1, an adaptive IDPT system contains a way to capture user behavior. Behavioural data are essential inputs to an IDPT system, to make it possible to adapt to the user in a meaningful way. Several data sources can be used as relevant indicators of patient behavior and symptom development. In guided online interventions, self-assessment using validated screening tools, telephone, video conversations, and written communications can be used. Counselors in guided IDPT also assess written responses to assignments and patient diaries. Additionally, also for non-guided interventions, it is possible to use indicators such as system interaction data to gauge patient engagement with an intervention. The potential of using sensors embedded in smartwatches, mobiles, and other devices has also been explored, for example, to measure physical mobility, sleep patterns, voice, medication adherence, and heart rate variability, to name a few. Here we consider the measures of psychometric tests and user behavior analysis:

- *Psychometric tests*: Psychologists have developed an effort to quantify people's preferences, behavior, and intelligence through self-assessment questionnaires referred to as psychometric tests. For example *PHQ-9 [44], MADRS-S [45], and BDI [46]* is used for assessment of depression. *GAD-7* [47] is used in self-assessment of general anxiety disorder. Scores from these tests can be utilized to adapt the modalities of content.
- *User behavior analysis*: We can analyze user behavior based on the interaction between the user and an adaptive IDPT system to gather user preferences and learn what a user likes the most. These insights can be extracted by analyzing the usage intensity of the system, such as the time a patient spent on watching videos, listening to audios, reading texts, interacting with intervention exercises, and other activities. The analysis of intensity can reveal user preferences and the engagement of the patients [48]. We can use the preferences information to personalize the adaptive elements (see Section V). Moreover, therapists can compare the expected behavior of the user and the actual behavior. This comparison can reveal where the bottlenecks are in the system and guide us to improve the structure of an IDPT system.

D. ADAPTATION ACTORS

There are three different types of adaptive systems based on the actors involved in triggering adaptation. First, the *automatic systems* that have the capability for self-adaptation. Second, the *semi-automatic systems* where a portion of adaptation is done by algorithms and a portion of adaptation is controlled by the therapists. Finally, *manual systems* where an actor (therapist/medical practitioners/trained medical personnel) manually adapts the interventions in IDPT. The use case diagram, as Figure 3 illustrates different types of actors involved in an adaptive IDPT system. The actors *adaptive systems* and *medical practitioners* are actively involved in the task of triggering/creating an adaptation. The actor *patients* uses the adaptive system, and finally, the actor *IT admin* monitors and maintains the adaptive system to ensure proper functioning. We like to highlight that the use cases functionalities illustrated in Figure 3 provide a generic example and can differ according to the context of the project.

E. ADAPTIVE STRATEGIES

Adaptive strategies refer to a set of techniques applied to change the behavior of an adaptive system. In Section VII, we outline four different types of adaptive strategies including *rule-based, goal-based, feedback-loop based* and *ML-based* approaches.

V. ADAPTIVE ELEMENTS: WHAT CAN BE ADAPTED

Having argued for the necessity of adaptation and different dimensions of the adaptive system, in this Section, we identify what can be tailored in IDPT. Although there is no explicit study done, to our knowledge, to categorize what can be adapted, we present a list of elements in IDPT that can be adjusted.

- *Content presentation*: IDPT systems use psychoeducation as the primary technique to educate patients on any healthcare problems. To do so, therapists prepare several educational materials such as use cases, events, activities, and physical exercises to familiarize patients with the symptoms of any particular illness. We refer to these educational materials as intervention content. We can present these contents in several modalities (e.g. slides, audio, video, animations, and texts) and layouts in any IDPT system. How we present the content to the user can be adapted based on several dimensions, as shown in Section IV.
- *Information architecture*: Section VI presents four different types of Information Architecture (IA) that can be adapted based on various dimensions.

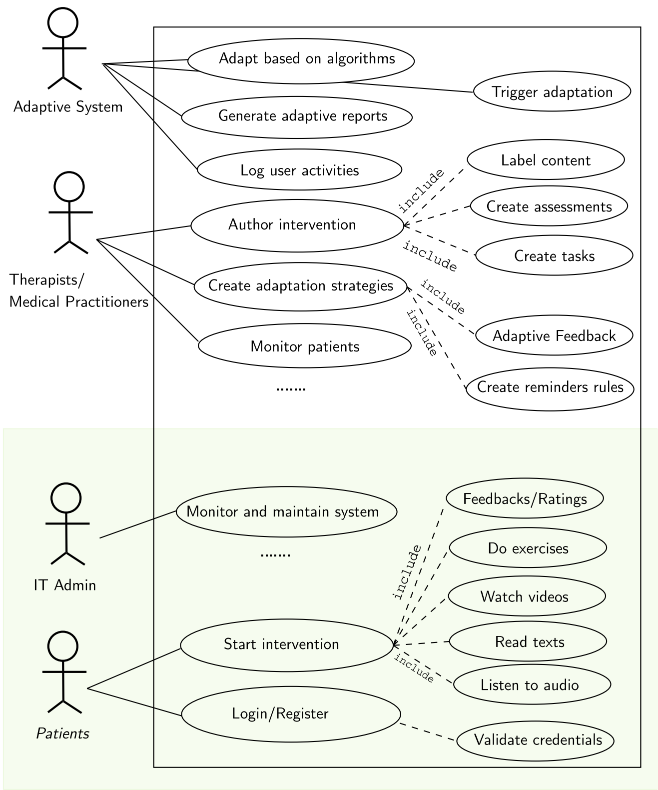

FIGURE 3. The Figure illustrates the different types of actors involved in adaptive IDPT systems. The actors' *adaptive systems* and *medical practitioners* (top block) are actively involved in the task of triggering/creating adaptation. The actor *patients* (bottom block) use the adaptive system, and finally, the actor *IT admin* (bottom block) monitors and maintains the adaptive system to ensure proper functioning. The dots illustrate the actors can perform several other actions defined by the context of any project.

- *Content complexity*: Content complexity is associated with cognitive demands inferred from the language of a content standard. In essence, content complexity incorporates several factors such as prior knowledge, processing of concepts, skill set, sophistication, application of content structure, number of parts, and length of the content. Because of its dependency on prior knowledge and processing skills that vary between person to person, content complexity adaptation based on several dimensions is essential.
- *Content recommendation*: If an IDPT is recommending content to the participants, it should be adapted based on the user preferences, interests, and other dimensions mentioned in Section IV.
- *User Interface*: Adaptive User Interface (AUI) changes its layouts and its elements according to the need of the user or the context [49]. Often, creating AUI is primarily based on the features of IDPT systems, and the knowledge levels of the users that will use the systems. By making these adaptations, the IDPT systems gain an ability to conform to the users' needs. For example, *adaptive presentation* aims to display certain information based on the current user. If the current user indicates novice knowledge, the system can adapt to display minimal information. Conversely, if a user shows advanced understanding, the system adapts to illustrate with more detailed information. Using adaptive strategies is likely to overwhelm less [50], [51] novice users with complex content. Similarly, *adaptive navigation* intends to guide a user to their specific goal within the system by transforming the way the system is navigated based on certain factors (like goals of the user, previous history information, current skill levels) of the user.
- *Feedback*: Several studies indicate that incorporating feedback mechanisms increases user adherence. Several forms of feedback mechanism has been used including *email, SMS, phone calls, conversational agents (chatbots [41])* and *support forms*. However, there can be several perspectives on how patients perceive feedback. Hence, it should be adapted based on the patients' needs.
- *Notifications/Alerts/reminders*: In an information system, personalized information is sent to patients as reminders, alerts, or notifications. Notification is a technique of bringing something to notice to the users. Reminders are specific types of notifications that are sent to stress about upcoming events. In an IDPT system, reminders have been used to notify clinicians and patients about appointments, screenings, upcoming interventions, tasks, or activities. An alert is a type of indicator such as a badge, sounds, missed required fields, success, or fail messages to inform users that they should look at something. Unlike alerts, a notification is accompanied by more information and is not always in the current task context.
- *Reports*: Reports are reflections of data collected by IDPT that are sent back to the users. Reports may include a subset of visualization techniques conveying specific information generated from the previous state of the users and current assessment. For example, a graph showing the current calorie count of the users, thoughts records.

VI. INFORMATION ARCHITECTURE OF CURRENT IDPT

Information Architecture (IA) plays a vital role in web application development, and a good architecture can enhance the ability of employees and customers to find information and decrease the application maintenance cost [52]. Despite some recommendations for using Architecture Centric Development (ACD) in behavioral and mental health interventions, there is still a lack of empirical evidence for the role of architecture in IDPT [50]. Current IDPT using ACD primarily focus on navigation systems [53] and their architecture can be *hierarchical, matrix, hybrid* and *tunnel based* [50], [54].

1) **Tunnel design**: 90% of the available IDPT systems use tunnel-based design [55] where users navigate sequentially through the intervention. Tunnel based design is analogous to watching TV, reading textbooks, attending academic classes, or attending multiple clinical sessions. An argument for this model is that a tunnel

design experience is less likely to overwhelm users with information and options [50], [51].

2) **Matrix design**: Matrix IA is designed on the principle of hypertext HTML. In a matrix design, the user can freely pursue their interests by using their path available through information. The designers of matrix IA use several organizational schemes to group the content into several categories. Examples of organizational schemes include alphabetical order, chronological order, topic scheme, and audience scheme. The primary rationale of using the matrix design is to provide maximum information within a system. According to Lynch and Horton [56], matrix design may not be well-suited to helping users to become familiar with new content. However, it is more applicable to web applications that are designed for highly educated and experienced users.
3) **Hierarchical design**: Information is organized in a top-down manner so that users can review specific content in a non-sequential way. The hierarchical design provides a simplified view of the content, making it easy to retrace steps. However, deeply nested information may be difficult to locate [57].
   As outlined in Subsection, III-A, we view an adaptive IDPT to follow the hierarchical Information Architecture. A common representation of the hierarchical IA is in the form of a graph. Here, a graph can illustrate the components of an IDPT system. Formally, we define a graph G as a pair (V, E) where V is a set of vertices, and E is a set of edges between the vertices $E \subseteq (u, v)|u, v \in V$ [58]. The vertices of the graph represent the components of an IDPT system, and the edge represents the constraints. For example, a module in an IDPT system contains several tasks. Each task represents the vertices. A patient must fulfill one or more constraints before we mark the task as completed by the user. We indicate these constraints by edges. For example, task dependencies constraint indicates the patients must complete a certain task before other tasks are available. Formalizing an IDPT system using graph theory is beyond the scope of this paper, and is marked as one of the immediate future work.
4) **Hybrid design**: It is a combination of one or more IA designs that best-fit content and purpose. Several current web application takes advantage of hybrid design [57] as it combines merits from other models.

It is not straightforward to know what components make up an Information Architecture [52] because people directly interact with some components. In contrast, other components are behind the scenes that people are not aware of their existence. In general, any IA consists of four different components:

1) *Organization systems:* It deals with how we categorize the information, such as by subject, by chronological order, by alphabetical order, by geographical order, by audience types, and so on. Organizing information is crucial because it reduces ambiguity in finding information, reduces heterogeneity, and labeling systems are intensely affected by the creators' perspectives. The difference in attitude makes information organization a problematic task.
2) *Labeling systems:* Labeling deals with the form of representation. A label illustrates a chunk of information. For example, Frequently Asked Questions (FAQ) is a label that describes a piece of content that most of the users typically wonder. Labeling is crucial as it 1) communicates with the patients revealing them the essential information, and 2) the interaction data with labels help in using supervised machine learning algorithms [59].
3) *Navigation systems:* It deals with how we allow users to browse or move through the information in a system. The navigation system facilitates browsing and contains several types, such as global navigation, local navigation, and contextual navigation. A global navigation system is present on every page throughout the application. Local navigation helps to browse on a specific page. For example, often, we provide an index of the main sections in any application page. Contextual navigation aids providing contextual navigation links that are specific to any particular piece of information. Such contextual navigations are applicable when we intend to provide extra contextual information if the user intends to. For example, in an adaptive IDPT system, we offer tasks that facilitate psycho-education related to any particular symptoms of mental health. However, we do not discuss in detail about the symptoms. In such a case, we can provide contextual navigation by using a hyperlink that links to a document providing detailed information about the symptoms. Once we design the navigation system, we can adapt these based on the user search behavior. Gobert *et al.* [60] presents SAM, a modular and extensible JavaScript framework for self-adapting menus on the web pages. According to the study, SAM provides a mechanism to self-adapt the navigation systems, which in turn offers personalized web experience.
4) *Searching systems:* It deals with how users search for information. A searching system is a challenging and well-established field on its own. Hence, before investing time and budget on creating a search system, we recommend determining whether the product needs a search system. If we decide to build a search system, then it requires defining the basic anatomy of the search engine, what is searchable, choice of retrieval algorithms, understanding retrieval results, and the search interfaces.

Explaining all the components of IA in depth is beyond the scope of this paper. The book by Morville [52] outlines these components in detail.

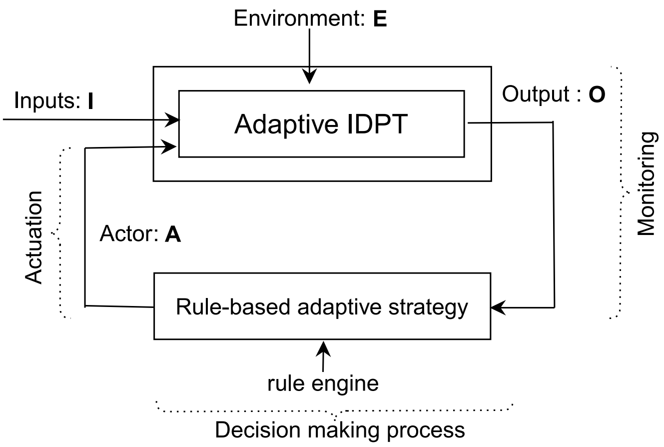

FIGURE 4. In a rule-based adaptive strategy, a set of predefined rules (managed by the psychiatrists and referred to as rule engine) modifies the behavior of the system. When these rules are truthy, an adaptive actor triggers the adaptation.

VII. STRATEGIES FOR ADAPTATION

In the last decade, several strategies for adaptation has been practiced to improve the effectiveness of IDPT, and a multitude of endeavors to generalize these strategies into discrete classes has been carried out. For example, Salehie and Tahvildari [61] identified two categories of self-adaptation based on impact and cost factors. Qureshi *et al.* [62] categorized four different categories of self-adaptive systems: Type 1 consists of systems that anticipate both changes and possible reactions at the design stage; Type 2 consists of systems that own many alternative strategies for reacting to changes; Type 3 consists of systems aware of its objectives and operating with uncertain knowledge about the environment and; Type 4 is inspired by biological systems that are able to self-modify their specifications when no other possible refinements are possible. Analogously, the paper [63] represents four similar types (like [62]) of self-adaptive systems using a metamodel. For IDPT systems, we categorize four different types of adaptive strategies: a) rule-based adaptation, b) adaptation through feedback loops, c) goal-driven adaptation and d) adaptation through predictive algorithms.

A. RULE-BASED ADAPTATION

As depicted in Figure 4, the rule-based adapting systems, changes its behavior based on pre-defined rules. The psychiatrists manage these rules based on their domain expertise. These rules are in the form `IF <condition> THEN <action>`. We can use the Horn clause [64] to formulate one or more pairs of the conditions. In an adaptive IDPT system, the logical structure of the clauses are of the form:

$$< C_1 \wedge C_2 \vee C_3 \vee \ldots \vee \neg C_n > \implies A_1 \quad (1)$$

$$< C_{k1} \vee \neg C_{k2} \wedge C_{k3} \vee \ldots \vee C_{kn} > \implies A_2 \quad (2)$$

where:

C_i = conditions

A_i = action if the condition is true

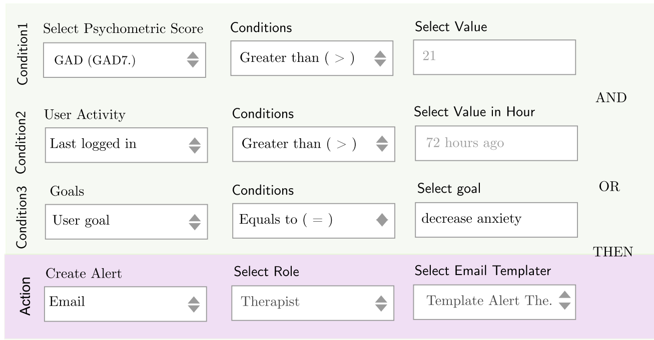

FIGURE 5. An example illustrating *rule based adaptation* where a therapist could create several alerts based on *psychometric tests score, user activity, goals and other* appropriate variables.

The quality of these rules and the quality of the performed adaptive actions are measured using several techniques [65] in the literature, including confidence value, rule weight, priority, check function [66], similarity degree, average fitness, case-based reasoning, system metrics and users' preferences [67]. Rule-based adaptation has advantages of readability, transparency, elegance, and they are easily modifiable [65]. According to the same survey, rule-based adaptation has been widely practiced in user interface adaptation [68], process adaptation [66], [69], workflow adaptation, content adaptation [70], software configuration adaptation, and feature adaptation [67]. We show an example of the rule-based adaptation in Figure 5, where an adaptive system sends a reminder (based on predefined email template) to a therapist if the following conditions are `True`:

1) (C_1) If the Psychometric score is GAD-7 for Generalized Anxiety Disorder and its value is greater 21 and,
2) (C_2) The user has not logged in to the system for more than 72 hours ($C_{2.1}$), or the user's goal is to decrease anxiety ($C_{2.2}$). The condition C_2 evaluates to `false` only if both $C_{2.1}$ and $C_{2.2}$ are `false`.

B. ADAPTATION THROUGH FEEDBACK LOOPS

Feedback loops are regarded as important aspects of self-adapting software systems. Brun *et al.* [71] argue feedback loops as essential for building self-adaptive software systems and for software evolution. A generic feedback loop contains four steps: collection, analysis, decision point, and action [72]. Several sensors based systems are utilized to collect data about the adaptive system's current state and context. The accumulated data are then transformed (cleaned, filtered, pruned, stored) for future referenced. The decision step then analyzes the data to infer trends and identify key patterns. Finally, based on the analysis results, a set of actions are decided that are executed using context actuators.

C. GOAL-DRIVEN ADAPTATION

In the goal-driven adaptation, the organizational and patient needs, in addition to their goals, are the main factors of adaptation. Heaven *et al.* [73] describes three-layer model controlling goal-driven adaptations- *goal management, change management and control*. The goal management layer

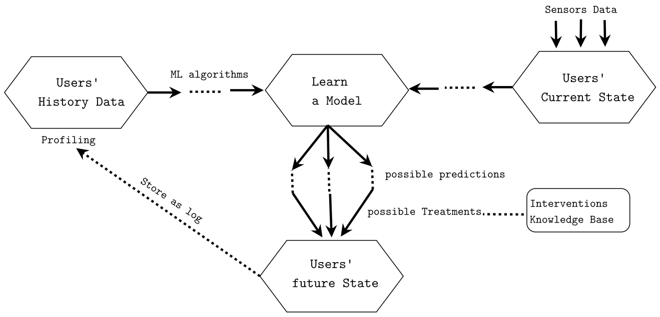

FIGURE 6. Adaptation based on predictive algorithms: Users' history data is fed to a suitable Machine Learning classifiers, and a model is trained. The users' current state (sensors data) is used as test data with the trained model to get possible predictions. Based on the prediction, a suitable treatment module can be used based on the pre-designed knowledge base.

handles the creation of a new set of goals or re-planning an existing set. The change management layer controls the adaptation among several tasks at hand based on the goals. Finally, the control layer is the level of execution of the selected configuration.

D. ADAPTATION THROUGH PREDICTIVE ALGORITHMS

The recent rapid growth in Artificial Intelligence (AI) has opened up unprecedented possibilities in analyzing and predicting diverse phenomena, including humanities, social and cognitive sciences, finances, healthcare, robotics, and other areas of natural sciences. Machine Learning (ML), a subset of Artificial Intelligence (AI), provides principled methodologies for the development of automatic, complex, objective algorithmic models for the analysis of multi-dimensional and multi-modal biological data. For instance, speech data that can be used in automated detection of mental health morbidities with the application of ML approaches. A study was done by Garcia-Ceja *et al.* [59] outlines several studies done about mental health monitoring system that uses sensors and machine learning. Similarly, ML-based algorithms have been used to predict user adherence to IDPT for depression and anxiety after myocardial infarction [74]. The use of ML-based predictive algorithms can be used to increase adaptation in IDPT systems, and the overall process is illustrated in Figure 6.

As depicted in Figure 1, the predictive algorithms are a type of adaptive strategy. These algorithms generally learn complex rules from the users' historical data. We store the patients' history data and feed these data to the predictive algorithms to obtain a trained model. Once we get a trained model, we input any user's current (sensor data) state to the trained model, which provides a set of possible predictions. Based on these predictions, we can get possible treatments based on the intervention knowledge base (KB). Here, we assume based on the domain expert knowledge (therapists), we can design a knowledge base. For example, Generalised Social Anxiety (GAD-7) [47] distinguishes three classes of anxiety based on symptom severity - mild, moderate, and severe. So, a typical KB would contain three different types of interventions for each category. When a user takes this intervention, we store their activities as a log file. We analyze this log file to create an understandable user profile. We refer to this process as user profiling.

VIII. DEVELOPING ADAPTIVE IDPT SYSTEM BASED ON PBA

In the previous sections, we have outlined several components of adaptive IDPT and covered several aspects of developing adaptive IDPT systems. In this Section, we provide an account of how to design and develop an adaptive IDPT system building on the PBA approach. PBA is well suited to complement the systems architecture and development approach because of it's focus on user needs. Hence, we map the development of an adaptive IDPT system to the PBA approach and present guidelines on how to develop an adaptive IDPT system based on user perspectives and needs. Here we utilize the design scaffolds available in PBA to provide insights into how to build user-friendly and relevant adaptive IDPT systems. The PBA proposes the development of digital health interventions in four distinct stages as depicted in Figure 7; (1) planning, (2) design, (3) development and evaluation of acceptability and feasibility, and (4) implementation and trialing [4]. PBA is a methodology for developing health and illness management interventions, inspired by user-centered design, that has the goal of providing as much value as possible to the end-user. Here, we explore how to supplement and expand the person-based approach with guidelines on how to develop an adaptive IDPT system.

A. PLANNING

During the planning phase, it is essential to define the problem domain, its scope, context, and main challenges of current problem-solving systems or techniques. Having understood the problem domain, we plan a new system and determine its objectives. We then perform CBA (Cost-Benefit-Analysis) of the proposed system, determine its SWOT (Strength, Weakness, Opportunities, and Threats) features, and finally perform feasibility analysis. The feasibility analysis should focus on different perspectives:

1) *Technical feasibility*: It is recommended to consult technical expertise to determine if the development of the proposed IDPT system is technically feasible.
2) *Economical feasibility*: Financial feasibility is an essential parameter to determine the level and complexity of the adaptive IDPT system.
3) *Legal and ethical feasibility*: The proposed system must abide by the legal requirements of the region and concerned stakeholders. It is relevant to know if the system meets within the legal and ethical constraints of the business, organization, and demography.
4) *Operational feasibility*: It is essential to identify if the proposed system solves the problem space that is originally identified.
5) *Behavioral feasibility*: It is important to take user attitude, behavior, or contextual consent towards

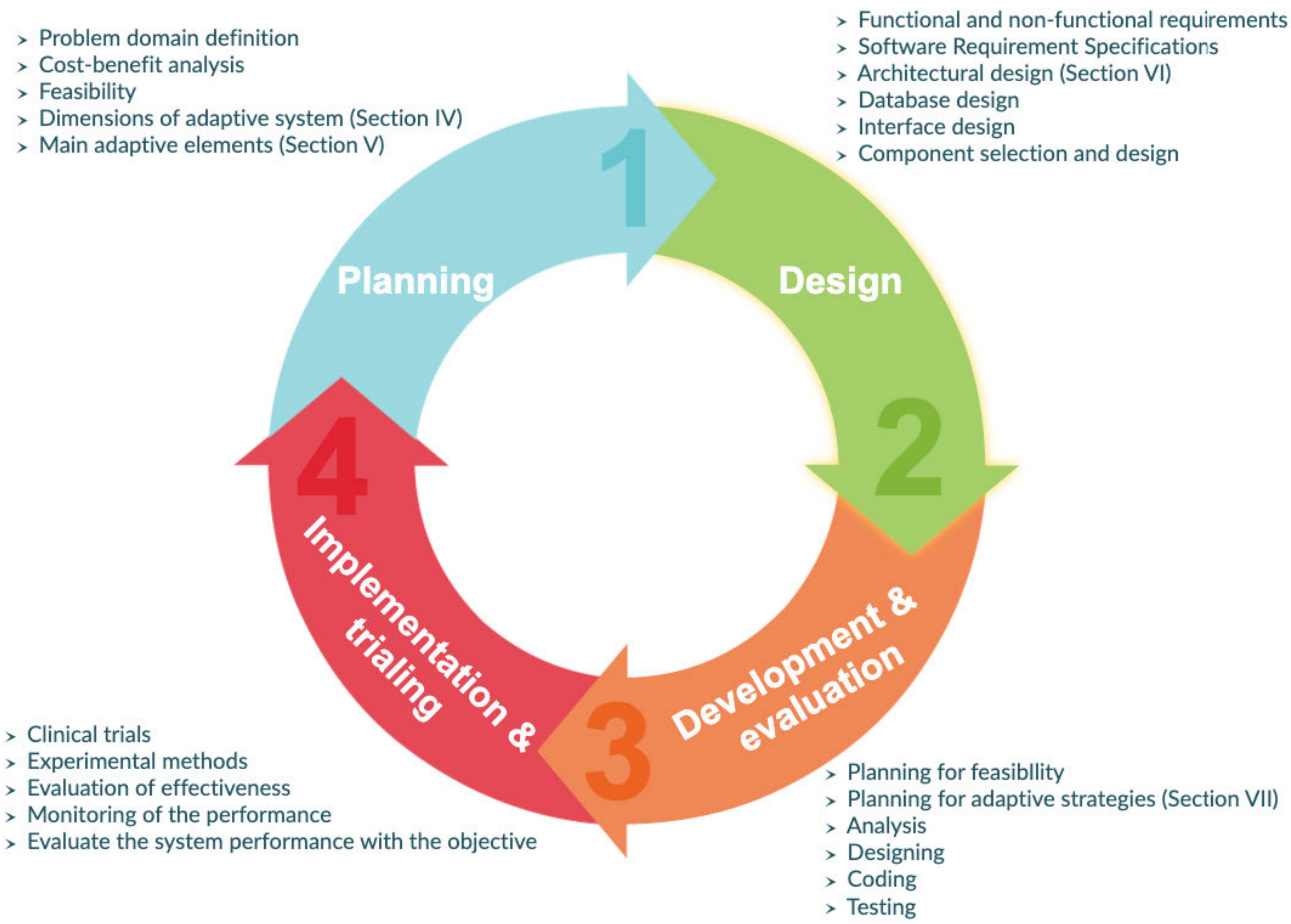

FIGURE 7. In this model, we compare the development of an adaptive IDPT system with the Person-Based Approach (PBA) and provide comprehensive guidelines about how to develop an adaptive IDPT system.

the development of the new system. As aforementioned, in Section I, there is currently a sub-optimal patient adherence towards IDPT programs. Hence, it is recommended to take user behavior and their need for the development of adaptive IDPT systems.

6) *Schedule feasibility*: It is essential to know if the adaptive IDPT system can be developed in the allowed time and within the offered resource and budget.

Moreover, we require to work on the design of the user interface and discuss the user interface choices such as multi-touch sensors, gesture-based, Augmented reality (AR) and Virtual Reality (VR) technologies, web-applications, smartwatches, and others. We need to comprehend available technologies and how these technologies assist with adaptation and discuss how users interact with these systems. The problem space needs to be articulated from the perspectives of both computer science and psychotherapy since each has different challenges to develop an adaptive IDPT system. In addition to usability and user experience goals, goals for adaptation are necessary to be considered to define the problem space thoroughly, which results in transferring the knowledge to design space. The main questions that we need to address during planning phases are listed below:

- What is the problem space we are addressing?
- What are the dimensions of the adaptive system?
- What are the main elements we want to adapt?

Theories, previous quantitative research evidence, systematic reviews, meta-analyses can provide insight into the intervention components and perspective of people who will use the intervention. The planning phase of PBA helps in exploring and analyzing the attitudes, understanding, needs, and situations of people who will be interacting with the systems. The exploratory analysis helps to disclose the dimensions of adaptiveness, the choice of user interfaces, and the main adaptive elements required in the intervention. The preference for user interfaces varies according to gender, cultural background, health literacy, or previous experiences. Hence, intervention developers need to consider purposefully sample a diverse range of users who differ in the characteristics to understand their actual needs. Understanding these needs helps to ensure that the researcher has all the insight into all relevant perspectives, allowing to server tailored intervention based on their needs.

B. DESIGN

During the design phase, we first need to define the requirements, evaluate the possible alternatives, and prioritize these requirements lists. Classifying these requirements into functional and non-functional requirements help to prioritize them.

1) *Functional requirements*: Functional requirements for adaptive IDPT systems include secure authentication and authorization; the ability for therapists to create interventions and adapt based on several adaptive strategies (see Section VII); adaptive dashboard for both therapists and patients; administrative functions; and audit tracking. Moreover, these requirement lists can differ based on legal and organizational aspects.
2) *Non-functional requirements*: Non-functional requirements includes product requirements (usability, dependability, efficiency requirements, interoperability requirements [75]), organizational requirements (development requirements, operational requirements), and external requirements (ethical, regulatory, and legislative requirements) [76].

Based on these requirements list, we need to create a Software Requirement Specification (SRS) [77]. In the design phase, we also need to create a design for the network, databases, user interfaces, and system interfaces. The designers transform the requirements from the SRS documents into the logical structure. These structures include:

1) *Architectural design*: In the architectural design, we identify the overall structure of the system (refer Subsection III-A), the main adaptive elements (refer Section V), their relationships, and their distribution.
2) *Database design*: Database design involves the creation of the system data structures and their relationships.
3) *Interface and interaction design*: Interface design requires the involvement of Interaction Design (IxD) experts to create interactive, precise, and unambiguous user interfaces. Interface design is also concerned with the specification of detail, including syntax and semantics of the services that are provided the user interface. Several structural diagrams can be used to model syntax of the interface, and the semantics of the interface may be defined by using constraint languages for example Object Constraint Language (OCL) [78].
4) *Component selection and design*: In this design, we need to search for reusable components. Since adaptive IDPT is mostly being developed as web or mobile-based apps, there is a large community of open-sourced and proprietary ingredients that helps in building rapid prototyping. Hence, instead of reinventing the well, we recommend identifying the usable components and utilize them for the creation of an IDPT system.

Lastly, we need to review the proposed design and ensure the final design adheres to SRS. The outcome of design phase is detailed *system architecture, database design, interface design,* and *component descriptions.*

C. DEVELOPMENT AND EVALUATION OF ACCEPTABILITY AND FEASIBILITY

In the development and evaluation phase, the developers transform the design specifications into source code, where several modules come together to perform an integrated system. This phase is also referred to as the *coding* phase and is the most prolonged phase of a development life cycle. It includes careful development planning, plan analysis, designing, actual coding, and testing.

- During the development planning phase, the development needs to decide appropriate programming languages, frameworks, databases, versioning systems, project management tools, and other tools required to develop the adaptive IDPT system. The process of selecting tools requires necessary feasibility analysis concerning business goals, available budgets, and schedules.
- The analysis involves making the detailed logical architecture of the applications, network, and database. An analyst decomposes the system into several parts called "Objects". Decomposition helps to identify reusable components increasing development efficiency and cost-effectiveness.
- The Designing phase is a creative step that involves making decisions about the system, for example which programming language to use, which database vendors to integrate, hardware, and network decisions.
- Coding is a mathematical approach that involves how logic operates. Coders follow specific styles, formats, and patterns to create the programs.
- Finally, the testing phase involves the verification and validation of the product. It consists of debugging by the programmers to ensure that the programs execute as intended. In addition to debugging, the product should need to go through the quality assurance (QA) process. QA involves acceptance testing that allows validating the software based on the original SRS. Acceptance testing involves several other forms of testing, including system testing (load testing, stress testing), integration testing, compatibility testing, user testing, and others [79].

D. IMPLEMENTATION AND TRIALING

In this stage, we apply the adaptive IDPT system into practical use - that is, clinical trials and experimental evaluations. Evaluation of problem space and user needs, usability, and user experience is an essential aspect of the development of digital tools that should be performed during development. When a stable and usable system is achieved, measuring and building evidence of the medical effects of the intervention is equally important. The development of online interventions requires a combination of the scientific traditions of computer science and medicine. In practice, the traditions have different conceptions of what can be taken as evidence, and how to construct it, and requires the evidencing to take place over different temporal phases. Corrections can be done in a pilot

TABLE 2. List of related studies attempting to adapt IDPT systems.

Reference	Year	Objective	Main findings
Brian *et al.* [57]	2005	Reviews the roles of considering IA designs for effective web-based interventions	Encourage adoption of a multidisciplinary perspective IA for presenting content of behavior change interventions.
Webb *et al.* [82]	2010	Investigate which characteristics of IDPT best promote health behavior change	a) IDPT incorporating more behavior change techniques (stress management, communication skills, problem-solving and others) have larger effects on outcomes. b) Additional communication with participants using SMS, email, messages increases adherence.
Christensen *et al.* [83]	2009	Review adherence with respect to IDPT and investigate the rates of dropouts and compliance in RCT for anxiety and depression	Main predictors of adherence include disease severity, treatment length, and chronicity. Very few studies examined the actual reasons for dropout.
Andersson *et al.* [18]	2019	Literature review arguing ICBT can be viewed as a vehicle for innovation	Detailed review in several directions including effectiveness of IDPT, implementation paradigm, predictors and future works.
Kelson *et al.* [84]	2019	Examine the therapeutic impact of Internet-delivered acceptance and commitment therapy(iACT) on all anxiety conditions.	Results indicate iACT to be efficacious and acceptable treatments.
Jokste *et al.* [65]	2017	A systematic review of rule-based adaptation to discover types of rules applied, application domains, and performance measures.	a) Results indicate widely adopted in medicine-related system, an adjustable system for people with disabilities and others. b) Categorized three forms of semantic rules: event-condition rules (if-else), association rules, and RuleML based behavior rules.
Karyotaki *et al.* [85]	2006	Examines the predictors of dropout in an individual patient data meta-analysis	a) Dropout can be predicted by several variables and is not randomly distributed. b) Understanding these variables can help to adapt IDPT to prevent dropout in identified groups at risk.
Rogers *et al.* [86]	2017	(a) discover the range of health-related topics that are addressed through Internet-delivered interventions, (b) generate a list of current websites used in the trials, and (c) identify gaps in the research that may have hindered dissemination.	Wide range of IDPT is available for health-related behavior. However, most of the IDPT found to be efficacious in RCT does not have a website for general use.
Brouwer *et al.* [87]	2011	Identify (a) which potentially exposure-promoting methods and strategies are used in existing IDPT, b) which objective measures are used to measure exposure to IDPT, c) which methods are associated with better exposure.	Feedback, interactive elements, and email/phone contact was mostly used methods and strategies to increase treatment outcomes. No clear conclusion is drawn due to the diversity of intervention methods used and inconsistency in reporting.
Pugatch *et al.* [50]	2018	Synthesize the existing literature on website information architecture and its effect on health outcomes, behavioral outcomes, and website engagement.	The authors only found three relevant papers. The first paper that investigated IA exclusively found that a tunnel IA improved site engagement and behavior knowledge, but it decreased users' perceived efficiency. The second and third papers found that a tailored site condition improved site usage, behavior knowledge, and some behavior outcomes.

trial where the developed adaptive IDPT system is accessed by users who test if an intervention is technically working, the presence of logical errors, and other functionalities by initial requirement specifications. The testing of adaptability in a clinical trial requires an evaluation of all potential configurations of adaptive components. To measure the medical outcomes and effects of adaptability requires a comparison of adaptive systems to non-adaptive systems. Additionally, adaptive aspects or elements of a system can be compared to non-adaptiveness or each other. Currently, Randomized Controlled Trials (RCTs) are not well matched to the pace of technology development, and there is a need for methodologies that can account for effects more rapidly [80]. One recent methodological approach that is aimed at meeting evidence demands from medicine, simultaneously to being relevant to methodological requirements from technology development is found in micro-randomized trials [81] Micro-RCTs aims to provide a data-based method for evaluating online interventions by providing an experimental design for use in testing the proximal effects of the newly developed treatments.

IX. RELATED WORKS

With the prevalence of mental health illness, on the one hand, the enhancement in ubiquitous computing on the other, several authors have attempted to adapt intervention in several ways with different objectives. Table 2 contains a list of similar studies done previously. The studies [50], [57] reviewed the roles of IA designs for effective web-based intervention. However, the studies are limited to IA and behavior changes. In particular, IA is just one of the characteristics of IDPT. Webb *et al.* [82] performed a systematic review to investigate which characteristics of IDPT best-promoted health behavior and reported IDPT that incorporated more behavior change techniques (stress management, communication skills, problem-solving and others) have more significant outcomes. However, it is still not sufficient to build an adaptive system only based on behavior change techniques, as several other dimensions (disease diversity, treatment length, chronicity) contribute to user adherence in the IDPT system [83].

Christensen *et al.* [83] performed a systematic review to investigate adherence to IDPT and the rates of dropouts for anxiety and depression. The study reports the main predictors of adherence are disease severity, treatment length, and chronicity. However, the study by Karyotaki *et al.* [85] reported that several variables could predict dropouts, and these variables are not randomly distributed. Understanding these variables can help to adapt IDPT and prevent dropouts in the identified groups as a risk. Adhering to this conclusion, we aim to present, in our study, several variables (adaptive dimensions) that affect adaptation.

Jokste and Grabis [65] conducted a systematic review of rule-based adaptation to discover types of rules, application domain, and performance measurement. The study by Brouwer *et al.* [87] attempts to identify which exposure-promoting methods and strategies are used in existing IDPT system and identify performance measures in the IDPT environment. The study reported that feedback, interactive elements, and email/phone contact were mostly used strategies. However, no clear conclusion was drawn due to the diversity of intervention methods used and inconsistency in reporting. While the study uses feedback, interactive elements, and email/phone contact as strategies, these are just the rule-based adaptation mechanism. Feedbacks, supports are the adaptive elements.

Rogers *et al.* [86] attempted to discover the range of health-related topics that are addressed through Internet-Delivered interventions and identify the gaps in the research that may have hindered dissemination. The study reported a wide range of IDPT systems is available for health-related intervention. However, most of the IDPT reported being efficacious in RCT trials does not have a website for general use. Hence, the internal architecture, adaptive elements, and strategies used remain unknown for the research community.

Andersson *et al.* [18] performed a systematic review arguing ICBT can be viewed as a vehicle for innovation and reported several directions, including the effectiveness of IDPT, implementation paradigm, and future works.

However, none of the studies reported a reference model of an adaptive IDPT system with its major components nor provided comprehensive guidelines on developing an adaptive IDPT system.

X. CONCLUSION

In this paper, we propose a model for adaptive IDPT based on classical control theory and discuss how the model can be used to represent an adaptive IDPT system. In addition to the model, we outline the core components of adaptive IDPT systems, the main adaptive elements, dimensions of adaptiveness, information architecture applied to adaptive systems and strategies used in the adaptation process. We also provide comprehensive guidelines on how to develop an adaptive IDPT system building on the Person-Based Approach. Patient adoption of and persistence with the IDPT intervention program is a prerequisite to successful outcomes of the therapy, which requires the combination of the perspectives of computer science and psychology/behaviour science when building the intervention. Here, we have proposed to combine a user-centered design approach with systems that adapt to patient behavior. Adaptive IDPT systems have the potential to offer personalized treatment to the far-reaching population with lesser use of resources, ensuring higher user adherence, reduced dropouts, and better treatment outcomes, and equally important: to achieve successful therapeutic outcomes for those affected.

In the future, we need tools, frameworks, architecture for an adaptive IDPT, and Domain-Specific Languages (DSL) for adaptive IDPT to facilitate the development of scalable, interoperable, and secure adaptive IDPT systems. We also need better dashboard tools that help therapists and other medical practitioners to comprehend the patients status better and adapt their interventions based on their engagement with the interventions. Thoroughly testing the adaptive IDPT system model and all the types of adaptive strategies have been kept as one of our project's immediate work.

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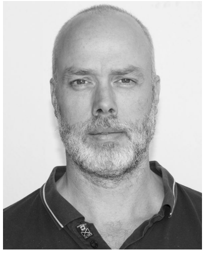

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PAPER **E**

SCIENTIFIC PAPER V

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Adaptation of IDPT system based on patient-authored text data using NLP

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***Abstract*—*Background:* Internet-Delivered Psychological Treatments (IDPT) system has the potential to provide evidence-based mental health treatments for a far-reaching population at a lower cost. However, most of the current IDPT systems are tunnel-based and does not adapt based on patients need. In this paper, we explore the possibility of applying Natural Language Processing (NLP) for personalizing the mental health intervention according to the patient's needs. *Objective:* The primary objective of this study is to present an adaptive strategy based on NLP techniques that analyses patient authored text data and extract depression symptoms based on clinically established assessment questionnaire, PHQ-9. *Method:* We propose a novel word-embeddings (Depression2Vec) to extract depression symptoms from the patient-authored text data and compare it with three state-of-the-art NLP techniques. We also present an adaptive IDPT system that personalizes treatments for mental health patients based on the proposed depression symptoms detection technique. *Result:* Our result indicates that the proposed *DepressionVec* performs mostly similar to *WordNet* but outperforms in same cases for extracting symptoms from patient authored text. *Conclusion:* While the extraction of symptoms from text is challenging, our proposed method can substantially extract depression symptoms from text data, which can be used to deliver personalized intervention.**

***Index Terms*—Internet-delivered interventions, NLP, tailored intervention, personalization, adaptive treatments**

I. Introduction

Internet-Delivered Psychological Treatments (IDPT) has the potential to increase accessibility and availability to evidence-based mental health treatments for a wider population using lower resources. However, despite extensive evidence that Internet Interventions can be effective means in mental health morbidities, most current IDPT systems are tunnel-based, inflexible, and non-interoperable. Lack of such adaptability results in higher dropouts and lower user adherence [1]. Hence, it is relevant to focus on the factors associated with enhancing user adaption towards such interventions. One of the ways to enhance user adaptation is by building adaptive IDPT systems that change its behavior according to several dimensions (user preferences, user needs, user-health symptoms, and others). In this study, we aim to build an adaptive IDPT system by extracting depression symptoms from patient-authored text using the Natural Language Processing (NLP) technique.

We envision two main motivations of extracting depression symptoms from the patient-authored text a) adaptation of IDPT based on known symptoms of any patient, b) understanding the degree of similarity with the depression symptoms. First, if we can extract symptoms from the patient-authored text, we can use this knowledge to provide tailored intervention for patients. We discuss this approach of adaptation in detail in Section IV. Second, the method to extract symptoms from the patient-authored text could help people appreciate the significance of their depression and realize they need to seek help. As outlined in [2], shyness, stigma, and embarrassment are the factors preventing people from getting treatments. In such a scenario, people tend to seek help using Internet technologies such as forums and blogs where people have the opportunity to talk about their feelings anonymously. However, due to such stigma related issues, people often do not recognize the severity of their depression. In such a case, the extraction of depression symptoms could help patients know about the seriousness of their illness and the urgency to look for professional help.

In this study, we answer the following questions: 1) How well patient-authored text data may be harnessed to capture the patient's depression symptoms? 2) How can we use the result to adapt intervention based on different dimensions? 3) What are the practical Natural Language Processing (NLP) techniques available to extract semantic similarity between authored text and actual symptoms? In this paper, we report two folds contributions:

1) We evaluated the state-of-the-art available NLP encoding libraries *Universal Sentence Encoder (USE)* [3], *Global Vector Representation (GloVe)* [4], *WordNet* [5] to extract symptoms from patient-authored text.
2) We propose *Depression2Vec*, an open set of depression word vectors/embedding that combines subword information from unlabeled online forums/websites. Inclined with this, we outline how the extracted symptoms from patient-authored texts can be used to adapt online intervention.

We discuss the methods, results, adaptive strategies and related works for adaptive IDPT system in the rest of the sections.

II. Methods

In this section, we explain four different methods that we used to extract the depression symptoms from the patient's authored text data. The diagnosis of psychological illness such as depression is complicated than it appears from the classification of ICD 10 definition [6]. One of the main reason for such complications is dynamicity of the symptoms between patients. Hence, psychiatrists during diagnosis listen for all the hints of symptoms as any patient outlines one's condition and queries to extract additional information. The psychiatrists often use standardized questionnaires like PHQ-9 [7] and other psychometric tests as the aid to elicit symptoms relatedness with the standard questionnaires. These questionnaires have a similar schema of detecting symptoms, determining the frequency of each symptom, calculating the score by summing the frequencies, and using a predefined threshold to classify the intensity of the illness. For example, PHQ-9 has nine distinct symptoms and based on the frequency of the symptoms, and it is possible to classify depression to be none, mild, moderate, and severe. We refer this approach as the *clinical symptom elicitation process (CSEP)*. We aim to automate the CSEP process by using the NLP technique to extract the depression symptoms from the text authored by the patients. Like the clinical process, we obtain the symptoms and their frequencies from the text and calculate the overall depression score. The underlying assumption is, the more symptoms terms we detect in the patient authored text, the higher is the likelihood that the patient suffers from depression. Figure 1 depicts the overall process of extracting PHQ-9 symptoms from the patient authored text data. We outline the steps involved in the symptoms extraction process:

A. Psychometric questionnaires (PQ)

We chose the PHQ-9 questionnaire as the standard to measure depression symptoms. However, one may use other types of questionnaires of other cases. The PHQ-9 is a nine item depression scale (see table 1 in supplement material VI in the appendix), which incorporates DSM-V[1]. Each symptom aims at eliciting the patient's condition in one dimension. In a standard CSEP, the psychiatrist extracts each symptom frequency by asking a question followed by frequency of observation in the form of options. Each question has the same options as follows: a) score 0: not at all, b) score 1: several days, c) score 2: more than half the days, and d) score 3: nearly every day. After all the questions are answered, the psychiatrist calculates the overall score based on the patient's answer. Finally, the overall score determines the depression level of the patient.

B. Seed term generation

The seed term generation technique is based on initially fed keywords extracted from the PHQ-9 questionnaire. The initially handpicked terms associated with each symptom and the seed generation algorithm is presented in the appendix. For each symptom in the PHQ-9 questionnaire, we handpick the most relevant keywords. For each word in each symptom, we use the WordNet to find synonyms. Then, for each synonym, we find associated hypernyms, hyponyms, and antonyms. If the method is using *Depression2Vec* then we chose the top five words for each symptom. Similarly, if the method is using *GloVe*, then we use only those words whose similarity is higher than 80%. The threshold for each method was empirically chosen to so that the results are relevant to the initial handpicked symptoms.

C. Preprocessing

Each symptom extraction method discussed in this paper compares the test sentences (patient authored text) with PHQ-9 symptoms (S1-S9) and finds a similarity score for each of these symptoms. To minimize outliers in the test sentences, we preprocess them using the algorithm provided as the supplement resource in the appendix. As shown in the algorithm, each test sentence goes through following preprocessing: 1) convert the test sentence into UTF-8 format to maintain encoding consistency, 2) transform it into a lower case, 3) strip any extra spaces around the sentences, 4) remove any symbols (#,, +, -, *, =, http, https) present in the sentence, 5) replace a short form of words with full formation. For example, *won't* is replaced by *will not*, *can't* is replaced by can not and so on.

D. Embeddings

In this section, we outline four different embedding methods that we used to extract symptoms.

1) Method 1 - Universal Sentence Encoder: The Universal Sentence Encoder (USE) [3], publicly distributed by Tensorflow-hub, is a pre-trained model that helps to encode text into high dimensional vectors. The USE comes in two different variations: a) Transformer encoder, and b) one trained with the deep averaging network (DAN). The two varieties have a trade-off of accuracy and computational resource requirement. While the one with a Transformer encoder has higher accuracy, it is computationally more intensive. The one with DAN encoding is computationally less expensive and with little lower accuracy. Here, we chose to go with the transformer encoder version to save computational resources.

2) Method 2 - WordNet: WordNet [5] is a machine-readable lexical database for English developed at Princeton University. The database consists of three separate databases, one for nouns, one for verbs, and one for adjectives and adverbs. These databases are grouped into sets of cognitive synonymous called synsets, each expressing a unique concept. Synsets are interlinked using conceptual-semantic and lexicon relations. A synset includes words. The words that go into a synset are synonymous.

3) Method 3: Global Vector Representation: The GloVe [4] is an unsupervised learning algorithm for getting vector representation for words. It takes a corpus of text as input and transforms each word in that corpus of text into a position in a high-dimensional space. It means that it places semantically similar words together. The pre-trained vectors are available for public use from the Standford official website [2].

[1]https://www.psychiatry.org/psychiatrists/practice/dsm

[2]http://nlp.stanford.edu/data/glove.6B.zip

2

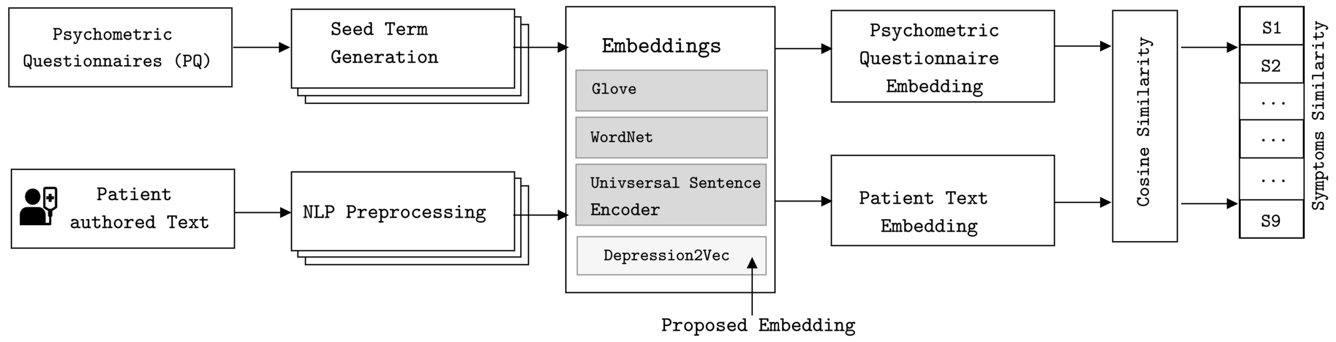

Fig. 1. Four different architectures for estimating PHQ-9 symptoms from the patient authored texts. Method 1: Universal Sentence Encoder, Method 2: using WordNet, Method 3: using GVR, and Method 4: Using *Depression2Vec*. Once we get the embeddings for both PHQ-9 questionnaire and patient-authored text, we use cosine similarity to compute the similarity between each symptom.

E. Method 4: Depression2Vec

One of the novelty of our work is the proposed technique Depression2Vec (*emotionally aware word sense embedding*) to predict the appropriate symptoms from the text authored by depressed person. There is an extensive literature in the NLP community available on emotion recognition. However, much less attention has been given on the representation of hybrid emotional knowledge (word embedding, sentence embedding, and word sense lexicon) and contextually-diverse embedding. Hence, in this method, we propose an embedding that incorporates contextually-diverse embedding that, in turn, combines depression lexicons as well as emotional knowledge by using the online forums texts.

In the emotion analysis, the text consists of many ordered words that represent different contexts. A vector space is used to project the text document *(set of words)* to different contexts. The context is used to identify how a learning model will process the words and sentences. The BoW *(bag of words)* model is used to learn about the sentence structure in the original text document. It is a method to model text into a numerical representation. The BoW model processes the text without considering the word order, semantic structure, and contexts. Therefore, the BoW model is not able to capture the complex semantic structure of the text in its processing. Another issue with BoW model is its high dimensions *(large feature space)* and sparsity *(a large number of distinct features)*.

1) Depression word vector embedding using emotional lexicon: Word embedding has been introduced to overcome the issues with the BoW model (see II-E). The word embedding uses unsupervised methods to embed any text (large corpus) into a vector space that represents the context (semantic meaning to a word). The state of art word embedding methods includes *the C and W model, the Skip-Gram Word2Vec model [5], the continuous bag-of-words (CBOW) model [8] and the GloVe model* [4]. The principle behind the word embedding method is the distributional vector hypothesis that *"You shall know a word by the company it keeps"* [9]. The statistical information *(i.e., co-occurrence frequencies)* of the words is used to embed many linguistics patterns and regularities in the vector space. The learnt model produces word vector space in which unique word in a corpus of texts is assigned to fixed-length corresponding vector, and similar contexts words in the training corpus are located in close proximity. The word distribution in the vector space and its feasibility has been confirmed in many experiments [9]. However, most existing word embedding algorithms produce domain-specific contextual preserved vector space [4], [9].

The learned vector representation from algorithms *(pre-trained model)* is not applicable for emotional analysis. The contextual knowledge (large corpus pre-trained word2vec models) are build using public sentiment lexicons *(Wikipedia texts)*, and sentiment knowledge *(Twitter data)* is derived by using the word sense in the context and co-occurrence frequency. For example, ***"happy"*** and ***"sad"*** can represent a similar emotional context, i.e., ***"feelings"***, but both words are representing different emotions and mental state. Therefore, it is incorrect to infer emotional information by using the large corpus pre-trained word embedding that uses word co-occurrence method.

The lexicon-based method shows promising results due to the existence of a high-quality emotional lexicon. A fine-grained emotional lexicon embedding can improve the accuracy in the classification of various symptoms. In order to overcome above-mentioned issue with word embedding, we proposed the contextually *(depression)* aware word embedding *(depression2Vec)* that uses the traditional word embedding model, i.e., skip-gram, and uses the domain-specific contextual knowledge to learn the complex meaning of a word. To generate the word embedding, a set of documents and emotional lexicons is given to the model. A corpus D, consisting of a set of texts, $D = \{d_1,\ d_2, \ldots, d_n\}$ and a vocabulary $V = \{v_1,\ v_2, \ldots, v_m\}$ are the unique terms extracted from D.

2) Prepossessing: The objective of this method is to find the semantically related word for each word in the corpus. However, most of the word in the text corpus does not infer opinion, so part of speech *(noun, verb, adverb, and adjective)* based reduction method is adopted. As mentioned in Algorithm 1, for each text document in the corpus, we perform text processing (explained in section II-C) and extracted part of speech. The $wordnet$ knowledge graph is used to extract synonyms, antonyms, hypernyms, and physical meaning for each extracted part of speech. Then, the obtained emotion set, $E = \{E_1, E_2, \ldots, E_K\}$ is added into the original process text to make a domain-specific contextual corpus. For each v_i, word representation is mapped from the trained $word2vec$ model, and then a set of word vectors is derived for the set V i.e. $T = \{T_1,\ T_2, \ldots, T_m\} \in \mathbb{R}^{mxd}$ where d is the word vector dimension and m is the size of the vocabulary. In this study, the skip-gram model is used for word embedding (depression2vec) training. The final word list for each text document in the corpus is used by the skip-gram model to learns word vector representation which gives the vector representations, $T_E = \{T_{E_1},\ T_{E_2}, \ldots, T_{E_K}\}$.

3) Construction of sentence embedding: The final text embedding is extracted by averaging over all the word vector in the text. The resultant text vectorization (depression2vec) is a joint learning of word sense and emotional knowledge in the same latent space. By using the trained word embedding (depression2vec), the input text is first converted into the word vector representation, and each nine symptoms from PHQ-9 questionnaire lexicons is also converted into the corresponding word vector representation.

TABLE I
ANNOTATION DONE BY TWO HUMANS A AND B SHOWING SYMPTOMS AND THEIR PRESENCE FREQUENCY IN THE TEST SENTENCES.

Symptom	Human A	Human B
1	37	13
2	82	92
3	17	13
4	39	2
5	6	3
6	30	25
7	11	3
8	3	0
9	24	23

F. Similarity

Given two vectors t representing vectors encoded from test sentence (patient authored text) and e representing any particular PHQ-9 symptom. We use cosine similarity for comparing the two vectors, which is defined as follows:

$$\cos(\mathbf{t}, \mathbf{e}) = \frac{\mathbf{te}}{\|\mathbf{t}\|\|\mathbf{e}\|} = \frac{\sum_{i=1}^{n} \mathbf{t}_i \mathbf{e}_i}{\sqrt{\sum_{i=1}^{n} (\mathbf{t}_i)^2} \sqrt{\sum_{i=1}^{n} (\mathbf{e}_i)^2}} \quad (1)$$

A high cosine value indicates that the patient authored text is closely related to the topic model associated with any particular PHQ-9 symptoms.

III. RESULTS

We used three different algorithms to compare with the proposed model. Our models produced a significantly higher agreement with annotated data. Out of 504 posts collected from online forums, websites, and social media, 100 posts were annotated by two humans. We used the Amazon Mechanical Turk to hire two human annotators who were familiar with PHQ-9 and clinical text assessment. We asked human annotators to rate the posts according to the PHQ-9 rating method, such that 0 indicated not depressed, 1 - mildly depressed, 2 moderately depressed, and 3 severely depressed. We converted this annotation into binary classification such that 0 indicates the absence of symptoms, and the other indicates the presence of the symptom. The depression annotation for test data is mentioned in Table I. Our primary hypothesis, as observed in this model, was *Depression2Vec* would generate precise embedding and results compared to state-of-the-art embeddings. We used the blind annotated test data and computed evaluation metrics (true positive rate, false-negative rate, accuracy, and f-measure) using all four methods. The results, as shown in Table II, indicate WordNet and Depression2Vec perform better compared to the other methods. However, the results show a drop in detection for the symptom five using WordNet. The proposed algorithm, Depression2Vec, significantly performs better for depression detection. In comparison with other symptoms, the WordNet and Depression2Vec showed similar accuracy. However, the results show no improvement with existing pre-trained models.

Algorithm 1: Algorithm to train Depression2Vec

```
input : Corpus
output: Trained embedding
foreach doc d ∈ corpus do
    d ← algorithm_1(d);
    foreach term t ∈ d do
        synonyms ← wordnet.synonyms(t);
        foreach synonym w ∈ synonyms do
            terms ← wordnet.hyperonym(w);
            terms ← wordnet.hyponym(w);
            terms ← wordnet.antonyms(w);
        end foreach
    end foreach
    vocabulary ← terms;
end foreach
Embedding ←
    word2vec_dep(vocabulary, corpus, window = 2);
return seed_terms
```

IV. ADAPTATION STRATEGY

The study [10] discusses several adaptive strategies, including rule-based adaptation, policy-based adaptation, goal-driven adaptation, and predictive-algorithm in IDPT systems. In this section, we illustrate the amalgamation of the predictive algorithm and rule-based techniques to adapt to psychological treatments. We use the same scenario for Internet-Delivered Psychological Treatment (IDPT), as outlined in the study [10]. As discussed in the paper, any psychological treatment system

TABLE II
DEPRESSION2VEC COMPARISON WITH DIFFERENT MODEL: *UE - Universal encoding, Glove - Global vector representation, WN - WordNET, Dep2VEC - Depression vector, TPR - True positive rate, FNR - False negative rate, ACC - Accuracy, Fscore - Fmeasure*

Symptoms	Methods	TPR	FNR	ACC	Fscore
1	UE	0.00	1.00	0.59	0.44
	Glove	0.00	1.00	0.59	0.44
	WN	1.00	0.00	1.00	**1.00**
	DP2Vec	0.98	0.02	0.99	**0.99**
2	UE	0.00	1.00	0.04	0.00
	Glove	0.00	1.00	0.04	0.00
	WN	1.00	0.00	1.00	**1.00**
	DP2Vec	0.97	0.03	0.97	**0.97**
3	UE	0.00	1.00	0.76	0.66
	Glove	0.00	1.00	0.76	0.66
	WN	1.00	0.00	1.00	**1.00**
	DP2Vec	0.92	0.08	0.98	**0.98**
4	UE	0.00	1.00	0.61	0.46
	Glove	0.00	1.00	0.61	0.46
	WN	1.00	0.00	1.00	**1.00**
	DP2Vec	0.95	0.05	0.98	**0.98**
5	UE	0.00	1.00	0.93	0.90
	Glove	0.00	1.00	0.93	0.90
	WN	0.43	0.57	0.96	**0.95**
	DP2Vec	0.86	0.14	0.99	**0.99**
6	UE	0.00	1.00	0.57	0.41
	Glove	0.00	1.00	0.57	0.41
	WN	1.00	0.00	1.00	**1.00**
	DP2Vec	0.98	0.02	0.99	**0.99**
7	UE	0.00	1.00	0.87	0.81
	Glove	0.00	1.00	0.87	0.81
	WN	1.00	0.00	1.00	**1.00**
	DP2Vec	0.92	0.08	0.99	**0.99**
8	UE	0.00	1.00	0.97	0.96
	Glove	0.00	1.00	0.97	0.96
	WN	1.00	0.00	1.00	**1.00**
	DP2Vec	1.00	0.00	1.00	**1.00**
9	UE	0.00	1.00	0.69	0.56
	Glove	0.00	1.00	0.69	0.56
	WN	1.00	0.00	1.00	**1.00**
	DP2Vec	0.94	0.06	0.98	**0.98**

has a case (such as depression, social anxiety, and others). Each case has one or more modules (eating disorder, concentration, sleeping disorder, and others). And each module has one or more tasks, educational materials, and exercise. The exercise can be computerized exercise (question answers, quiz, feedback) and physical activity (breathing exercise, walk). To illustrate adaptive strategies, we assume a case for depression with nine modules, each corresponding to symptoms used in the PHQ-9 questionnaire, $\forall s_i \in [S_1, S_2, \ldots, S_9], \exists m_i \in [M_1, M_2, \ldots, M_9]$ where each m_i is a module providing psycho-education about the corresponding symptom s_i in the PHQ-9 questionnaire.

Adapting the intervention modules and feedbacks

To adapt and personalized module to each individual, we first compute symptom similarity from the patient authored text. We feed the patient-authored text to the symptom extractor algorithm that we proposed in this paper and get a similarity score for every nine symptoms. Once we get the symptom similarity score, we can check against the *knowledge base.* We assume here that psychiatrists use their domain expertise to maintain a rule-based engine that shows which modules are relevant for what types of patients. For example, if a patient is showing a symptom of higher concentration problem, the patient should be offered to go through the concentration module and so on. A study by Bewick et al. reports feedbacks have thought to increase user adherence [11] for sixty-five percent of intervention participants. Personalizing such feedback based on their interaction with the IDPT system is required to improve user adherence [12]. Hence, based on the technique proposed in this paper, we can adapt both feedbacks and remainders. For instance, if the proposed model detects all the depressive symptoms in a patient text, the system can generate an automated alert to notify the therapist.

V. RELATED WORKS

Funk et al. [13] present a conceptual framework to apply NLP in digital health intervention to support the automated analysis of texts either authored by patients or the message exchanged between therapists and the patients. The study reports applying the framework to predict bing eating disorder and obtaining a result in an area under a curve between 0.57 to 0.72. However, the framework does now show how we can achieve adaptation in an IDTP environment. Moreover, the feature engineering process used in this study considers the inclusion of several features, including metadata, word usage, topic models, word embedding, parts of speech, sentiment analysis, and others. Unlike this, we use several word-embedding techniques and propose our word-embedding *Depression2Vec*. Yazdavar et al. [14] present a method to detect depressive symptoms, in line with the PHQ-9 questionnaire, from Twitter. The study uses a semi-supervised statistical model to evaluate how the duration of these symptoms and their expression on Twitter (in terms of word usage patterns and topic preferences) align with the medical findings reported via the PHQ-9. The authors use two different methods, Latent Dirichlet Allocation (LDA) [15] and a proposed semi-supervised topic modeling over time (ssToT). Several studies have highlighted that the topics learned by LDA are not granular level and concrete to capture depressive symptom [15], [16]. To empower LDA shortcomings, the authors add supervision to the LDA method by using the terms that are strongly related to the PHQ-9 symptoms as the seeds to the topic clusters and guide the model to aggregate semantically-related terms into the same cluster. Similar to this technique, we use a similar seed term generation method. The main difference between our seeding model and there is that we don't use any dictionary to retrieve synonyms. Instead, we use WordNet to extract not just synonyms but also hypernyms, hyponyms, antonyms. In addition to this, we apply a different threshold for selecting the words for different methods. Karmen et al. [17] (2015) used the NLP method to detect symptoms of depression from forum texts. While this work focused on keyword density to extract depressive symptoms, we concentrate on finding a more effective method to obtain depression symptom score based on four distinct ways.

VI. Discussion and conclusion

The application of NLP to clinical text to extract relevant information has been thriving in recent years. A recent systematic literature review by Dreisbacha [18] et al. in 2019, synthesize the literature on the usage of natural language processing and text mining to extract symptoms from patient-authored text data. We can see two crucial observations in the review. First, researchers attempt to obtain symptoms related to several healthcare conditions, including pain, fatigue, cognitive function, affective mood, digestive symptoms, and others. According to the review, a limited number of studies considered the extraction of mental health symptoms from patient authored text. Second, based on the review, none of the studies attempted to adapt the IDPT system based on symptom extraction. In this paper, we aim to fulfill this gap and use the knowledge of symptoms that the patients exhibit in the text authored by them, in the adaptation of IDPT.

We pursued an NLP approach to perform adaptation in IDPT system for two main reasons: a) IDPT deals with a huge amount of texts in the form of computerised exercises for psycho-education, b) NLP method can provide an elegant way to adapt the intervention on one hand and provide personalised feedback on the exercises. Several studies [1] have reported that lack of personalised feedback on their interventions were one of the main causes of high dropouts. Hence, in this paper, we present an NLP based adaptive strategies to adapt intervention based on the symptoms exhibited by the patients' through text data. In order to extract symptoms from such patient authored text data, we evaluate three different state-of-the are NLP techniques and propose our own. The results show that both the WordNet and the proposed embedding *Depression2Vec* captures depressive symptoms better than other methods. However, there are several challenges, as pointed by the study [19] associated with the detection of symptoms from text data. Outlining the complexities and challenges is beyond the scope of this paper and is kept as one of the immediate future work. In addition to this, other future work includes the application of the proposed algorithm and adaptive strategies in the clinical scenario to evaluate how well depressive symptoms are captured, and intervention is adapted.

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Appendix

Supplement resources can be obtained from the following link https://github.com/sureshHARDIYA/phd-resources/tree/master/Papers/AdaptationNLP

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PAPER F

SCIENTIFIC PAPER VI

- **Title:** A reference architecture for data-driven adaptive Internet-Delivered Psychological Treatment Systems
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A Reference Architecture for data-driven adaptive Internet-Delivered Psychological Treatment Systems

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Abstract—Internet-Delivered Psychological Treatment (IDPT) systems are software applications that offer psychological treatments through the Internet. Such IDPT systems have grown as one of the most commonly practised and widely researched forms of psychotherapy. Evidence shows that psychological treatments delivered by IDPT systems can be effective means in treating mental health morbidities. However, current IDPT systems often suffer from high dropout rates and low user adherence. The primary reasons are that the current IDPT systems are not flexible, adaptable, and personalized since they follow a fixed tunnel-based treatment architecture. Moreover, the current IDPT systems have poor interoperability and cause difficulties to reuse and share treatment materials. In addition to these, there are a lack of development and documentation standards, conceptual frameworks, and established (clinical) guidelines for such IDPT systems. As a result, several ad hoc forms of IDPT models exist. Developers and researchers tend to reinvent new versions of IDPT systems, making them more complex and less interoperable. In this paper, we address these problems by presenting a *Reference Architecture* (RA) that supports flexible user modelling and adaptive delivery of treatments. To evaluate the proposed RA, we developed an open-source framework based on the proposed reference architecture. The open-source framework aims to a) improve the development productivity and b) facilitate communication with domain experts. We followed Domain-Driven Design (DDD) to implement a prototype of the open-source framework and evaluate it using empirical (case study) and non-empirical approaches (SAAM method, expert evaluation, and software quality attributes). This paper presents an initial study, and the preliminary results show that the developers and the researchers can implement and tailor the proposed RA for multiple healthcare interventions.

Index Terms—Software architecture, adaptive system, IDPT system, healthcare systems, ICBT, adaptive strategies, personalized therapies, reference architecture

1 Introduction and Background

INTERNET-Delivered Psychological Treatment (IDPT) systems refer to software applications that offer psychological therapies or treatments through the Internet. In our work, we focus on treatments based on evidence-based psychological therapy [1]. *IDPT systems* borrow the core ideas from Learning Management Systems (LMS) and other Content Management Systems (CMS). However, IDPT systems are more inclined towards the healthcare domain and have a principal perspective to help the patient cope with their psychological problems. IDPT systems have two types of contents, psycho-educational materials and treatment exercises.

1.1 Problems with current IDPT system

1) Despite evidence that Internet Interventions can be effective means in mental health morbidities, most of current IDPT systems are tunnel-based, inflexible, and non-interoperable [2], [3], [4]. These restrictions cause a high dropout rate, less personalization, and hence low user adherence [3], [4].
2) IDPT systems targeting different psychological issues (such as depression, anxiety, bipolar disorder, schizophrenia, and others) have many similarities regarding psycho-educational materials, intervention structure, and assessment techniques. However, due to a lack of standard documentation, established frameworks, and clinical guidelines, several forms of IDPT models exist. As a result, developers and researchers tend to reinvent their versions of IDPT systems, making them more complex and less interoperable [5].

1.2 Objective

To address these issues associated with the current IDPT system, we conduct this study with the following objectives:

1) To create a reference architecture [6] of an *adaptive IDPT system*, that can personalize the treatments according to patients' need, and support adaptability, interoperability, reusability, scalability, security, and modifiability.
2) Based on the proposed reference architecture, create an *open-source* framework [7] that can be used to develop any adaptive IDPT system. The *open-source* framework is created to aim for a) improving the

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development productivity, b) facilitating communication with domain experts, and c) improving the quality of User Interfaces (UIs), user interaction and user experience.

1.3 The need for adaptive IDPTs

IDPTs have surfaced and grown as one of the most commonly practiced and widely researched forms of psychotherapy [8]. The evolution of IDPTs, coupled with the exponential growth of Internet access throughout the world, has the potential to reshape the landscape of mental healthcare. Despite the evolution in IDPT, several patients suffering from mental health issues are still untreated [9], [10]. Obstacles to receive treatment for mental health problems includes long waiting lists, limited access to therapy and psychiatric medications, perceived stigma of seeking help, and treatment costs [3], [10], [11]. IDPT systems have been proposed as one solution to bridge this treatment gap. IDPT removes several barriers over traditional face-to-face therapy that hinders the majority of patients from efficient psychiatric care [12]. The use of IDPT tools can enhance mental health in several ways: 1) IDPT can be available and accessible from anywhere with an Internet connection [13]; 2) the temporal aspects of access can be substantially improved; 3) the scalability of IDPT can drastically enhance the functional capacity of the care; 4) makes the treatment cost-effective for individuals who do not have insurance or can not afford the out-of-pocket fees for treatment, and 5) removes the discomfort and the stigma related issues associated with the face-to-face approaches [14].

Despite these shreds of evidence, most of the current IDPT systems are not adaptive and have poor interoperability. These restrictions cause a high dropout rate, less personalization, and hence low user adherence. Hence, there is a crucial need for an intervention system that can help to personalize treatments and increase user adherence. Current LMS and CMS are not designed to capture information of mental symptoms, and they do not monitor the treatment progress and relevant data. Moreover, they can not address the needs for personalization and interoperability. To solve these intrinsic requirements, we propose a new reference architecture and evaluate it by developing the open-source framework based on the RA. The proposed architecture relies on user profiling technique for personalization (see Figure 1) and ontological labelling for interoperability (see Figure 3).

1.4 How do we propose to increase adaptivity in IDPT system?

Figure 1 describes the interaction model of the proposed data-driven adaptive IDPT system. The patients interact with the *intervention system* (see Subsection 4.4), and a *analytics server* (see Subsection 4.3) stores those interactions. In our RA, analytics server refers to third parties or self-contained services that contains data stores to collect a large amount of data and provides data analytics services such as pattern matching, NLP service, Exploratory Data Analysis (EDA) service, ML/DL services and others. Based on the analysis of the logged data, a process referred to here as *user profiling* (see Subsection 5) maintains an up-to-date user model. The user model is used to provide an adaptive effect. An adaptive system behaves differently for different users. The decision on how the system should behave for any particular user is based on a user model. The user model is a detailed representation of an individual user's information associated with an adaptive system. The user preferences and needs are dynamic. Hence, it is essential to create, maintain, and update the user model. An adaptive system accumulates data in two distinct approaches to create and maintain an up-to-date user model: a) implicitly by observing user interactions and b) explicitly by requesting direct input from the user. This process is referred to as user *profiling*. The essence of the adaptation effect that a system can deliver depends on the nature of the user model's information. Hence, in this paper, we aim to present a framework based on user profiling to provide different adaptation effects.

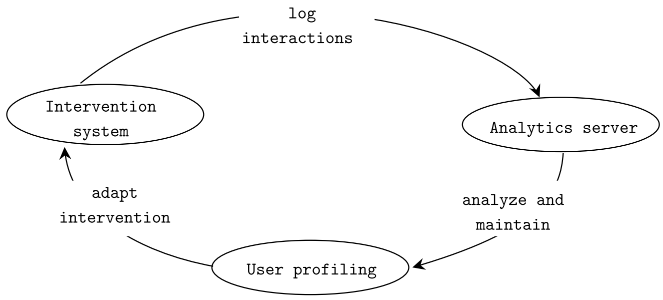

Fig. 1: The figure depicts our proposed model of a data-driven adaptive IDPT system. The patients interact with the intervention, and an analytics server captures those interactions. Based on the logged data analysis, a process referred to here as user profiling maintains an up-to-dated the user model to provide the adaptive effect.

1.5 Contributions

The contributions of this study are the following:

- We propose a reference architecture for an adaptive IDPT system that provides a different adaptation level based on user profiling. To the best of our knowledge, this is the pioneer and novel work to create, evaluate and publish RA in this domain.
- To evaluate the proposed architecture, we create an open-source framework that can be easily extended to several healthcare interventions. We envision to promote open-source development by creating a proof-of-concept prototype based on the proposed architecture.

2 Related Work

Grua et al. [15] presents a RA for personalized self-adaptive e-Health apps. The proposed RA is envisioned to personalize and self-adapt intervention and increase user engagement with AI application. The proposed RA uses Monitor-Analyze-Plan-Execute (MAPE) loop and is targeted primarily for mobile applications. Moreover, the RA follows a client-server architecture and assumes self-containing, fully flexible AI-enabled backend system. Such a self-containing backend is not scalable and flexible, especially for small scale healthcare providers. Healthcare providers specialize in their domain and dedicate services like AI, CMS, authentication and authorization to the third parties. For example, in Norway, the healthcare system relies on level 4 security system such as BankID [16] for authentication and authorization, AI service from Microsoft Azure or AWS. Not all the services are coupled into one self-containing system. In such a scenario, SOA architecture is suitable, like we provide in our RA. Unlike their RA, our RA focus on loosely coupled intervention system which incorporates, intervention authorizing services, user profiling services, adaption services and others.

WSO2 [17] presents a layered structure that targets scalability and security. The architecture is abstract and domain-independent on the one hand and lacks a specific mechanism to adapt intervention according to the patient's need. Wartena et al. [18] outline RA of a personal telehealth eco-system, referred to as continua. The proposed RA uses E2E architecture as design guidelines for supporting interoperability. Continua identifies Personal Area Network (PAN) devices for communication around a person, Local Area Network (LAN) devices for communication around a location, Wide Area Network (WAN) for communication around a home/office, Health Reporting Network (HRN) for communication around enterprise systems such as hospitals, telehealth service and others. Besides the report, how these devices can communicate using associated protocols that support interoperability. However, the architecture is a) abstract, b) doesn't address other software quality attributes beside interoperability and security, c) how one adapts intervention or personalize health services.

Rodriguez [19] presents a detailed RA regarding the Healthcare Supportive Homes, a particular type of Ambient Assisted Living (AAL) domain. The proposed RA provides detailed guidelines that can be used to achieve software quality attributes such as interoperability, reusability, security, safety, performance, and reliability. The study reports a detailed and stepwise recommendation for creating reusable RA. Similar to Continua, Hanke et al. [20] present universAAL reference model for establishing a cross-application platform for AAL. However, both the RA are specific to the AAL domain. Moreover, they fit into psychological perspective to adapt intervention according to patient's need. Mukhiya et al. [4] conducted a systematic literature review to identify adaptive elements (content, presentation, feedback message, assessment, activities, reminders, exercises and reports) of an IDPT system for a mental health disorder. The study concludes that most of the current IDPT system attempts to adapt feedback messages to patients from therapists. The study reports a lack of any open-source framework for creating adaptive IDPT system.

Researchers made attempts to theorize user profiling for adaptive web, personalization, and intelligence systems [21], [22], [23], [24]. Similar to the study [21], [24], we consider interest, knowledge, background, goals, individual tasks, and context as an essential user profile component. However, in addition to these, we have considered several other attributes, including temporal profile, lingual profile, user levels, and intervention profile. Furthermore, we have modeled these attributes in the proposed framework and illustrated how these attributes could facilitate psychological intervention's personalization.

3 Method

As a part of INTROMAT project[1], we envision developing an adaptive system to offer personalized and customized treatments for patients suffering from mental and neurological disorders. To satiate this goal, we started:

Evaluating state-of-the-art digital psychological treatments systems concerning current treatments requirements: We included usability and universal design principles to evaluate current IDPT systems and published our findings in this study [25]. Our findings indicate that despite the satisfactory treatment results and proven clinical effects, the systems, in general, have several issues regarding usability, universal design and outdated technology.

Collecting recommendations from research by doing a systematic literature review: We conducted a systematic literature [4] review a) to inspect and identify the main adaptive elements of an IDPT system, b) find its information architecture, and c) how adaptation influences the efficacy of IDPT on mental health treatments. The review suggests that adaptive IDPT has the potential to enhance intervention outcomes and increase user adherence. However, current IDPT systems are tunnel-based and do not offer personalized treatments according to the user needs. To comprehend how usability is being addressed and measured in mHealth intervention for mental health problems, we conducted a systematic literature review [26]. We published our findings from the perspective of computer science and Human-Computer Interaction (HCI) in this study [26]. Most studies described their methods as trials, gathered data from a small sample size, and carried out a summative evaluation using a single questionnaire, which indicates that usability evaluation was not the main focus.

Collaborating with domain experts and stakeholders to comprehend actual user needs: Technical domain experts included academicians and industry workers from software engineering, human-computer interaction, artificial intelligence and health informatics. Healthcare domain experts were personal from several mental and neurological disorder consultants. We followed the Domain-Driven Design (DDD) architectural style [27] to model and create the adaptive IDPT framework because these systems involve creating software programs that facilitate the delivery of psychological healthcare treatments over the Internet. Psychological treatments fall under the complex domain, and developing software systems requires thoughtful collaboration between domain experts and technical experts. When the domain is complex, it is a difficult task for designers and developers to build the software. In such a case, developers have to steep themselves into the domain to build up their business knowledge. However, most developers do not have much

1. https://intromat.no/

interest in learning about any specific domain in which they are working. In such use cases, the domain-driven design method comes to the rescue.

With the help of domain experts and technical team, we created the proposed RA. To evaluate the RA, we developed an open-source framework presented with this study. We have open-sourced the initial prototype under MIT License, where everyone is permissible to extend the framework without any consequences. The framework follows *Service-Oriented architecture* (SOA) for communication. The server-side of the framework follows the Backend for Frontend (BFF) architecture pattern. We follow the Test-Driven Development (TDD) [28] during the framework development. To evaluate the RA's and proposed open-source framework efficacy, we continuously extend the framework for several healthcare issues, perform RCT trials, conduct usability evaluation and enhance the system.

4 Reference Architecture

We use the term *reference architecture* [6] concerning the context and definitions provided by Cloutier et al. [6]. As suggested by this study, our proposed RA encompasses three essential questions, a) what (the intervention system and its components), b) why (to adapt and personalize the intervention to enhance user adherence and reduce dropouts), and c) how (by creating details user profiling and using AI, and other adaptive strategies to adapt intervention). One of the reasons for this study is to disseminate the proposed RA, the open-source framework and ideas for constructing adaptive web applications for healthcare treatments. To meet the objective of the study, we contextualized a web application at a high level without focusing on specific expertise. From this contextualization, we designed some models to comprehend the application behavior. Figure 2 provides reference architecture of the adaptive IDPT system. As the vision is a high level of abstraction, we eliminate constraints related to design, external stakeholders, and others from the model. The RA constitutes of four major components: *authorization server, mobile client, intervention system and analytics server.*

4.1 Authorization server

The authorization server [29] is an OpenID connect [30] compliant web server with an ability to authenticate patients and grant authorization access tokens. Moreover, the authorization server manages scopes and permission of the patients, introspects token, entails roles and permissions, audits log, assigns policy, and requests the intervention system. Our open-source framework includes standalone, authentication server. However, since the adaptive system follows SOA architecture, any third-party authentication server can be easily integrated with the framework. For example, in Norway, using BANKID [16] for authentication/authorization is common.

4.2 Mobile client

The mobile client is the host, where an adaptive intervention app (mHealth app) is installed. The mobile client app contains *third-party app data collector, network connectivity and utility service, intervention interface* and *sensor data manager*. The *third-party app data collector* is responsible for communication with third-party apps, healthcare apps and built-in healthcare apps to collect healthcare data. The *sensor data manager* collect sensors data from IoT devices. The *network connectivity and utility service* is responsible for sending these healthcare and sensors data to *data lake services* in the analytics server. The mobile client incorporates *intervention interfaces* that allows patients to interact with adapted intervention and communicate with therapists.

4.3 Analytics server

Conceptually, the analytics server has two parts: a) structural part of building a user profile and b)analytics method to feed information to profile. The analysis servers (see Figure 2) incorporate analytical software as a service (SaaS) Application Programming Interfaces (APIs). These services take the data as input, detect the patterns, and provide a detailed analysis. While there are several possibilities on the types of algorithms used for data analytics, in the adaptive IDPT context, we aim for the following core functionalities:

- *Data lake services* accumulate both sensors and intervention data.
- *Exploratory Data Analysis (EDA) services* help in data cleaning, data preparation, data exploration, and data visualization.
- *NLP services* help in building, evaluating and detecting patterns in the textual dataset. For example, when patients interact with an intervention, they write some texts as a part of computerized exercises. These texts exhibit keywords that express the current state or emotion of the patient. It is possible to send these texts directly to available Natural Language Processing (NLP) APIs such as Google NLP [2] and get the sentiment of the text, tone of the texts, and detect the presence of depression-related keywords [31]. In this study [31], we demonstrate how we can exploit the NLP technique to extract depression symptoms from the patient-authored text.
- *Pattern matching services* can reveal several associations, correlations and hidden patterns in the sensor and intervention data. For example, Sharma et al. [32] present a large-scale analysis of engagement patterns of 35 million posts on two popular online mental health platforms, talk life and Reddit. The study demonstrates that engagement patterns' proposed framework enables informative evaluations and analysis of online support platforms.
- *ML/DL based services* constitute Machine Learning (ML)/ Deep Learning (DL) algorithms. Data from sensors and intervention can be used to predict early dropout rates and personalize intervention. Once a model is developed, trained, and evaluated, domain experts, can evaluate it for approval. For example, Bremer et al. [33] outline use of ML techniques to predict dropout in insomnia intervention. Similarly, in the study [34], Nemesure et al. proposed an ML approach to predict the presence of Generalized Anxiety Disorder (GAD) and depressive disorder (MDD).

2. https://cloud.google.com/natural-language

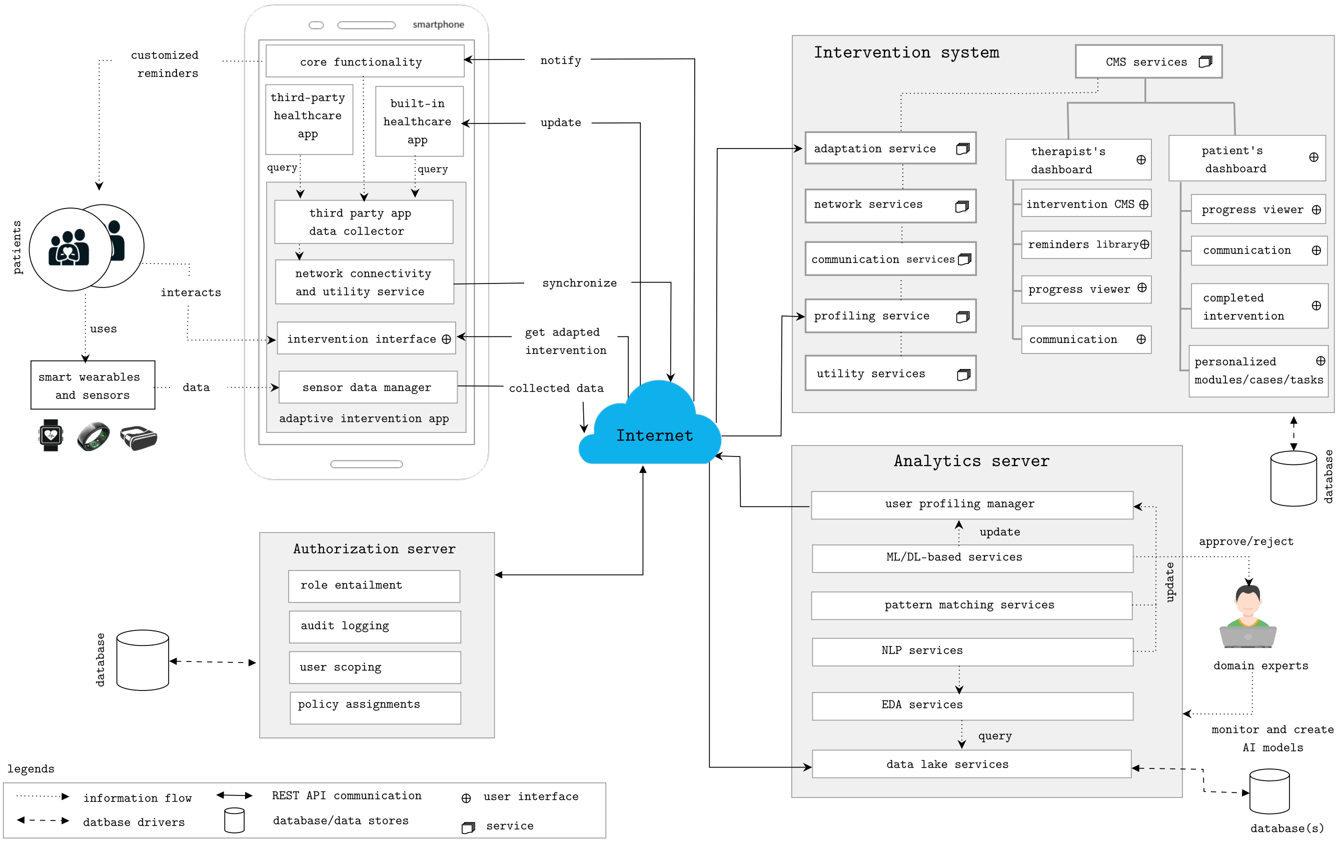

Fig. 2: Reference architecture of data-driven adaptive IDPT system

- *User profiling manager* is envisioned to use analysis and predictions done by NLP services, pattern matching services and ML/DL services to build a comprehensive profile for the patient.

4.4 Intervention system

The intervention system (see Figure 2) is one or more web-applications communicating by *Web Services* (WS) such as RESTFul API or GraphQL API. It constitutes several services. *CMS services* facilitate a therapist's dashboard (intervention creator, reminders library, progress viewer, communication channels) UI and patient's dashboard UI (progress viewer, communication channel, history, next/upcoming intervention modules, or tasks). *Adaptation services* provide a rule-based engine to build adaptation rules based on the user profile. *User profiling services* maintain such user profile. Similarly, *communication services* create a communication channel between patient and therapists. *Network* and *utility services* handle Internet connectivity logic and other utility-oriented tasks. One may separate these components and communicate using a micro-service architecture [35], but the intervention system components are monolithic for this open-source framework. Figure 3 depicts a conceptual model of an intervention. An intervention is a psychological treatment or therapy delivered through IDPT systems. An IDPT system refers to software that facilitates the creation, delivery and interaction with psychological therapy through the Internet. These mainly include web-applications, mobile applications, augmented reality, and virtual reality applications.

4.4.1 Components

An intervention generally consists of cases, modules, tasks, and taxonomies (labels). In this section, we explain these components, their underlying assumptions (see Table 1) and constraints. An example of intervention is included in the non-anonymous supplemental material submitted with this paper.

- **Cases**: Typically, IDPTs are targeting one or more cases such as Depression, Social Anxiety, Bipolar Disorder, ADHD, or other health issues. An example of *case* is shown in Figure 4.
- **Modules**: Each case contains one or more modules that focus on any particular dimension of the case. For example, for the depression case, there can be modules for, understanding and monitoring emotions, behavioral activation, identifying automatic thoughts, and others. One specific module can be part of one or many cases. The modules can have dependencies that specifies the ordering of the modules.
- **Tasks**: Each module, in turn, can include one or more tasks. A task can be learning materials (Informative task) or exercise (Interactive task). *Informative tasks* provide learning materials about mental health issues (cases), symptoms, use cases, and several ways

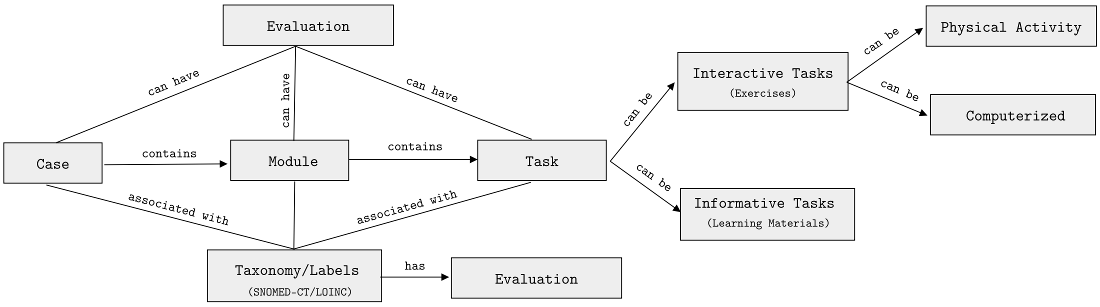

Fig. 3: The figure depicts the conceptual model of any intervention that is always associated with a case. A case contains one or more modules. Each module has one or more tasks that can be learning materials or exercises. An exercise can be physical activities or computerized.

```
CASE_EXAMPLE
├─title: Depression
├─taxonomy: Depression disorder
│  ├─SNOMEDCT: 160329001
│  └─LOINC: 45666-5
└─evaluation: psychometric tests
   ├─test1: PHQ9
   └─test2: MADRAS-S
```

Fig. 4: Example data structure of a case

to manage them. The main objective of such informative tasks is to provide psycho-education so that:

- patients and their families can learn about symptoms, causes, and treatment concepts
- patients can comprehend the self-help program and steps required to manage their illness
- patients can correlate their situations with others that has similar issues, which helps to ventilate their frustrations.

Such informative tasks are in the form of reading (text), listening (audio), graphics, presentations, and watching (video). In contrast to informative tasks, *interactive tasks* involve user interactions and often in the form of exercises and psychometric tests. The exercises can be *physical activities* or *computerized tasks*. Examples of physical activities include physical workouts and mindfulness exercises such as breathing exercises, walking certain distances, stretching, or physically performing any other activities. Examples of the computerized exercises involve filling in the blanks, answering (Q/A), multiple-choice questions (MCQ), and feedback. The feedback forms consists of using free text, rating systems, or multiple-choice questions. The minimal data structure of a task and its types are illustrated in Figure 5.

- **Taxonomy/Labels**: Each case, module, and tasks is associated with a label or taxonomy. Since, case, module and tasks forms hierarchical structure, these taxonomies provides ontological structure for adaptation.

```
TASK_DATA_STRUCTURE
├─ID: Integer
├─prerequisite: [{ID, score}]..ARRAY OF IDs
├─description: String
├─tags: [String]
├─points: Integer
├─completionRequired: Boolean
├─complexityLevel: Integer
├─nextTask: ID
├─type: String == TEXT
│  ├─isRead: Boolean
│  ├─totalReadTime: Integer
│  └─content: String
├─type: String == AUDIO
│  ├─isPlayed: Boolean
│  ├─audioLength: Integer
│  ├─playedLength: Integer
│  └─file: File
├─type: String == VIDEO
│  ├─isPlayed: Boolean
│  ├─videoLength: Integer
│  ├─watchedLength: Integer
│  └─file: File
├─type: String == EXERCISE
│  ├─type: [QUIZ,FEEDBACK,RATING]
│  ├─passingScore: Integer
│  └─owner: [ID]......BELONGS TO MODULE/TASK
├─taxonomy: [{key: value}]
└─evaluation: [{key: value}]
```

Fig. 5: Data structure of a task

4.4.2 Constraints

A task or a module can have one or more constraints. These constraints determine the states (see Subsection 4.4.3) of the task and the module. As illustrated in Figure 5, a task or a module can have the following constraints:

- *Prerequisite:* A list of tasks required to be complete before this task is active.
- *Next Task:* A task can have restrictive follow by selecting the next available task.
- *Completion Required:* It is a `Boolean` value that represents a user must complete the task if truthy.

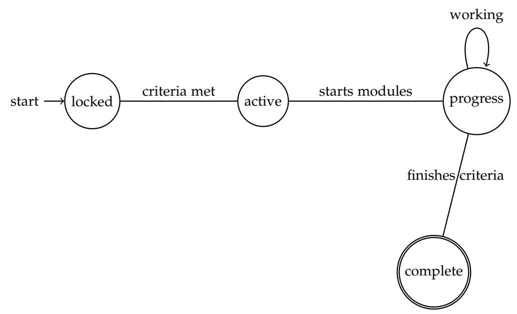

Fig. 6: States of an IDPT system

Components	Assumptions
Case	1. A case contains at least one module. 2. A case can have one or more evaluation criteria. 3. A case can have user inclusion and exclusion criteria.
Modules	1. A module contains at least one task. 2. One module can belong to one to many cases. 3. A module can depend on other modules. 4. A module can have one or more evaluation criteria.
Tasks	1. Task can have sub-tasks. 2. Each task can have an evaluation criteria. 3. The evaluation criteria of a task is the overall evaluation of the sub-tasks. 4. Tasks can have dependency but it can hot have its own dependency.

TABLE 1: Different assumptions that were considered when designing the open-source framework.

- A *passing score* on an exercise of type quiz determines whether an exercise is complete or not.

4.4.3 States of intervention component

All case, module, and the task can have four different states as depicted in Figure 6.

- *locked*: An entity is locked if its evaluation criteria is not fulfilled or a dependent entity not completed.
- *active*: An entity is active as soon as the evaluation criteria are matched or its dependent entity is completed.
- *progress*: An entity is in progress if the entity is active, but all the evaluation criteria have not been completed.
- *complete*: An active entity is marked complete if all its evaluation criteria are finished.

5 USER PROFILING

A profile is a description of an actor containing the necessary facts about the individual. In an adaptive IDPT context, a user profile (or user model) holds essential facts about the individual patient. The process of inferring unobserved data about users from observable data about them; that is, their actions or interactions are referred to as user profiling [36]. The primary motivation for building user profiling is that users differ in their preferences, interests, background, goals, cognitive skills, and other attributes. Discovering these differences is essential to presenting users with personalized or adapted services. In an adaptive IDPT system context, user profiling aims to provide the adaptation effect, that is, to behave differently for different users [21]. As aforementioned, we envision to apply user profiling as the fundamental basis for adaptation. Hence, we discuss user profiling in this section and discuss how we can use such profiling to adapt intervention in Section 6.1. It is essential to note that user profiling can be based on a distributed architecture. Hence, the data-driven adaptive system presented in Figure 1 follows the Service-oriented Architecture (SOA). An adaptive system tends to find the most relevant information to user interests and present the information in the right form so that the user may perceive its relevance. A user profile typically powers discovering such relevancy and its ranking. A user profile can contain several components (see Subsection 5.1) such as user interest, knowledge, background, goal, individual trait, and user context. An adaptive system can create and maintain the user profile explicitly and implicitly, and we discuss these data acquisition methods in Subsection 5.2. Table 2 summarizes the different aspects of a user profile, including the components of a user profile, the form of representation in a software, types of data stored in each of the components processes of obtaining data.

5.1 Components of a user profile

The content of user-profiles varies according to the system's domain and the software architect who designed the system. There are no specific standards that specify which components should be in a profile. Similar to the study [21], [24], we categorized the user profile content into the following components for our framework:

5.1.1 Interests

User interests affect their adherence to any software system. Hence, capturing user interests and attempting to personalize content based on their interests can be an effective means to boost user adherence. A software system can represent user interests in two ways:

- The weighted vector of keywords: For example, Letizia [37] uses TF-IDF (Term Frequency and Inverse Document Frequency) to model user interests. In the TF-IDF technique, each word's weight is computed by comparing the word frequency in a document against the word frequency in all the documents in the corpus.
- Topic hierarchies: A graph can express topic hierarchies where a node is a set of topic words representing a user's specific interest. These types of representations are essential when we want to model user interests as well as associated sub-topics.

5.1.2 Knowledge

The user's knowledge represents the understanding of the subject or the domain. The user's knowledge is a dynamic feature and hence increases or decreases over time. Therefore, a well adaptive system should recognize the user's current state of the knowledge and tailor the user model accordingly. A software system can represent the user's knowledge in two ways (see Table 2):

- *Scalar modeling:* A scalar modeling systems use quantitative scales (for example, 0 to 10) or qualitative scales (for example, excellent, very good, good, bad, poor, none). However, it is challenging to formulate

Attributes	Representations	Type of Data	Profiling
Interest	- weighted vector of keywords - topic hierarchies	news topics, web page topics, document topics, work-related topics, hobbies	implicit/explicit
Knowledge	- scalar modeling - overlay modeling	application domain	implicit
Background	- stereotype modeling	profession, job responsibilities, experience of work, specific view on the domain	explicit
Goal or tasks	- goal catalog approach	goal of the work, information need, learning goal	explicit
Individual trait	- mixed approaches	cognitive styles, personality traits, learning styles, demographic	implicit/explicit
Context	- set of name-value pairs	platform, location, physical environment, social context, affective state	implicit

TABLE 2: Different components of use profiling techniques. Column 1 represents the attributes, column 2 represents the most common representation, column 3 represents types of data and column 4 represents the profiling approach

scalar value for the knowledge of a user. Hence, scalar modeling suffers from low precision.

- *Overlay modeling:* In overlay modeling, the domain contains one or more sub-fragments. For each of the fragments, an overlay model stores the estimation of the user knowledge. The estimation can be binary (knows, does not know), qualitative (excellent, very good, good, bad, poor, none), or quantitative.

5.1.3 Background

The user's background constitutes information about the profession, job responsibilities, work experience, and specific view on the domain. The most common representation format for the user's background is stereotype modeling since detailed background information is not essential. In stereotype modeling, the domain expert distinguishes the most common categories of users according to their background information and adapt the content presented to the user category. The system can also differentiate users by their profession (student, medical personnel, teachers, etc.), which implies both knowledge and responsibilities. Several adaptive systems use background information to adapt content based on the background information of the user.

5.1.4 Goal

The user's goal represents the purpose the user desires to achieve from the system. The purpose can information needs, learning goals, or working of the applications (see Table 2). These user's goals are dynamic and change over time. Hence, it is essential to tailor intervention according to the current user's goal. The most common way to represent the user's goal is to use the goal catalog approach, where the system presents a pre-defined set of possible user goals. An adaptive system can recommend some pages to the user based on a pre-defined set of goals [21] or adapt the content selected page [38].

5.1.5 Individual traits

The user's traits include cognitive styles, personality traits, learning styles, or demographic data. Several researchers agree on the importance of individual traits and using them for adaptation. Individual traits are stable features of a user, and they do not change all or change over a long time and can be extracted through specially-designed psychological tests. While *cognitive styles, personality traits*, and *demographic data* are significantly discussed in the literature, *learning styles* are argued [39]. Various methods are used to extract a user's personality traits and cognitive styles and use them for adaptation.

5.1.6 Context

The prevalence of ubiquitous computing has attracted several researchers to the user's context, such as location, social context, physical environment, and affective state to tailor software systems. Most of the work on the user context is focused on user platforms. For example, most of the study attempts to adapt to make the system responsive [40] or tailoring the content based on hardware, available software, and bandwidth. The affective context includes the physiological context and mental context. The social context consists of the current user's social aspects, such as information about friends, neutrals, enemies, neighbors, co-workers, and relatives. The most common way to store user context is in the form of `key:value` pair.

5.2 Methods of collecting information for the user profile

As aforementioned, there are two ways to extract the information required for building a user profile: *either explicitly* or *implicitly*.

1) *Explicit information extraction:* A software system can extract the profile components such as background, goal, and interests explicitly, that is, by asking users through some user interfaces like forms or feedback. Generally, users are not willing to fill in long forms providing information about them, and hence they are optional. The information accumulated this way includes demographic data such as age, job, and hobbies.
2) *Implicit information extraction:* Explicit method of user information has several challenges, including a) users do not like to fill up long forms, b) users do not always tell the truth when made obligated to feel forms, and c) users who wish to fill-up the form willingly may not know how to express their interests in words. Observing the user interactions (time spent on the page, bookmarked pages, amount of scroll, content viewed, video watched, and others)

with a software system and logging these actions, we can obtain information about users through some machine learning or data mining techniques. A vital advantage of the implicit method is that we can log and analyze users' changing interests, preferences, habits, and goals over time. These logs can help in adapting content or presentation according to the correct context of the user.

6 Evaluation

Architectural evaluation assures that the architectural design decisions produced are the correct ones [41]. One of the RA evaluation aims is to analyze and verify that it addresses the problems we identified in the current IDPT systems. We chose both empirical (case study) and non-empirical (expert evaluation, scenario-based method) evaluation technique to analyze and verify the proposed RA and the open-source framework. Two relevant options for scenario-based evaluation are the software architecture analysis method (SAAM) [42] and the architecture tradeoff analysis method (ATAM) [43]. We chose to apply the SAAM method because we have proposed RA and qualitatively evaluate the RA. Moreover, SAAM is suitable to assess if or not the given RA satisfies a specific system's desired properties. Whereby ATAM is more suited to determine the tradeoff between architectural alternatives [43], done in the related section.

6.1 Scenario-based evaluation for adaptation support

The first of the SAAM method is to develop scenarios. This section presents how our proposed RA can perform different types of adaptation based on user profiling. These scenarios, along with the open-source framework's initial prototype, serve as scenarios for our evaluation process. The next step of SAAM is to describe the candidate RA, that is outlined in Section 4. After that, it is necessary to identify system quality attributes with the help of the developed scenario. Subsection 6.2 describe the identified software quality attributes extracted from our scenarios.

6.1.1 Content adaptation

Content adaptation may involve two sub-categories: a) content materials adaptation that involves deciding what content is the most relevant to the current user, and b) content presentation adaptation that involves determining how to present the selected content effectively to the current user.

Content materials adaptation: The main task here to identify the most relevant content for a given user in their context and how to organize those content. The user profile components such as *interests, preferences, background, knowledge*, and the *goals* can help to select the most relevant content for a given user. The literature mentions two different approaches for adapting the content, *page-variants*, and *fragment variants* [44]. Our RA supports both approaches for content adaptation. Moreover, with user profiling in place, we can perform *adaptation based on metadata*.

1) In the *page-variants approach*, different versions of each page are created using CMS service (see Figure 2). The chosen adaptive strategy [3] selects and presents the most suitable content to the user based on its current context and profile.
2) A page is divided into one or more fragments in the *fragment variants approach* where each fragment corresponds to a self-contained element such as text, audio, video, paragraph, picture, or presentations. In the case of an IDPT system, these fragments are authored by the domain experts. These fragments are selected and presented to the user based on an appropriate adaptive strategy. Currently, most of the IDPT system uses a rule-based adaptation mechanism to pre-define these fragments. However, once these fragments are pre-defined and labeled correctly, many pages can be automatically generated to cover a correspondingly large number of interaction contexts.
3) *Metadata/Taxonomy based adaptation*: As illustrated in Figure 5, the task can have several tags. These tags act as the list of controlled vocabulary sets, defining several dimensions of a text. For example, a text can provide psycho-education about different human emotions (*sad, happy, angry, disgust, sadness, joy, love, and surprise*). These controlled vocabularies can be abstracted to form taxonomy and ontology related to any particular illness (see Figure 7). For example, *joy* and *love* indicate positive emotions. Similarly, *anger*, *disgust*, *sadness*, and *fear* indicate negative emotions. While a user is reading a text about *disgust*, these taxonomies can help to recommend other tasks (audio, video, images, or activities) that exhibit similar labels as *anger, sadness*, or *fear* as they indicate negative emotions at a higher level. Moreover, *emotions* is associated with other mental health issues. Learning materials related to emotions for *depression case* can also be used for *social anxiety case.*

```
EMOTION_TAXONOMY
├─Positive
│  ├─joy
│  └─love
├─Negative
│  ├─anger
│  ├─disgust
│  ├─sadness
│  └─fear
└─Unexpected
   ├─fear
   └─surprise
```

Fig. 7: An example scenario of human emotion taxonomy

Content presentation adaptation: Let us assume that a Task can be represented in the following modalities: audio, video, slides and text. Here we assume, each format preserves the semantic meaning of the original format. An IDPT system can personalize content format based on user interests (see 5.1.1) and goals (see 5.1.4). An IDPT system can obtain user interests based on a) process mining technique, b) explicitly asking user, c) user interaction data, and d) other data mining techniques. Process mining can reveal which format

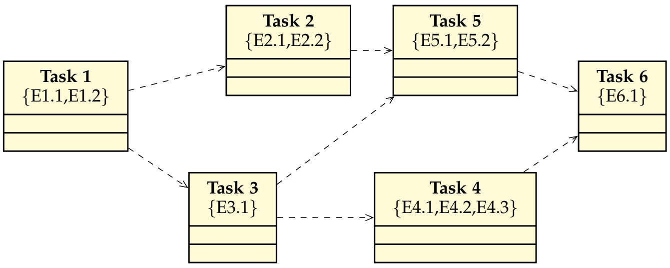

Fig. 8: An example of different tasks inside a module in an IDPT. Here, the dotted arrow denotes dependencies. For example, *Task 2* is dependent on *Task 1*. Such dependency indicates that a patient can not start *Task 2* before *Task 1*. Each task has one or more evaluation criteria denoted as *E.x*

.

Task	Evaluation	Completion	Notifications
Task 1	E1.1 E1.2	✓ ✓	• Task 1 completion alert & • [T2, T3] is active
Task 2	E2.1 E2.2	✓ ✓	• Task 2 completion alert
Task 3	E3.1	✓	• Task 3 completion alert & • [T4, T5] is active
...	...	...	...
Task 6	E6.1	✓	• Task 6 completion alert • Module 1 completion SMS.

TABLE 3: An example illustrating alert/notification adaptation.

of the content a particular user interacts the most. If a user spends more time watching videos, the system can present the next video format task. In addition to process mining, user interaction data can reveal the preferred content format by any particular user. These preferences and interests are stored in the user profile and hence used for content format adaptation.

6.1.2 Reminders/Alert/other notifications adaptation

Figure 8 illustrates an example of different tasks inside a module in a typical IDPT. As shown in the figure, *Task 2* and *Task 3* have *Task 1* as dependency. This dependency means a patient must finish *Task 1* before tasks 2 and 3 are active for them. Also, in order to finish Task 1, the patient must fulfill both evaluation criteria *E1.1* and E1.2. Once *Task 1* is completed, it is marked *complete* and *Task 2* and *Task 3* are *active*. In addition to that, the IDPT system schedules an automatic alert/notification for the patient with a personalized message indicating completion of the task and availability of the next tasks. As shown in Table 3, the process of customized alert/notifications can be adapted based on task status. The alert/notification adaptation scenario presented here is just an example and can be extended based on other criteria.

6.1.3 User-level adaptation

As depicted in Figure 5, each task has an evaluation (`points`) associated with it. Once a user completes the task, the user gets this point. The sum of points obtained from each task indicates the overall score of any user. An adaptive system can have a simple adaptive rule to activate or deactivate task based on the overall score. For example, if we know the total score of $T_{overall}$ of a user, we can activate or block the availability of the next task for that user. We can use a simple rule engine, for example, like the one given below, to activate or deactivate tasks:

$$T_{overall} \geqslant 0 \wedge T_{overall} \leqslant 40 \Rightarrow T_1$$
$$T_{overall} \geqslant 41 \wedge T_{overall} \leqslant 80 \Rightarrow T_2$$
$$T_{overall} \geqslant 81 \wedge T_{overall} \leqslant 120 \Rightarrow T_3$$

In above rules, T_i are list of tasks. In the above example, we assume the threshold score for each task can be decided empirically or determined by the therapists who designs the intervention.

6.2 Software quality metrics

As aforementioned, we envision to address the challenge of the high dropout and low user adherence in current IDPT system. Therefore, one primary software quality metrics based on ISO/IEC 25000 [45] is adaptability. Moreover, based on the current IDPT systems analysis, the recommendation from the literature review, and discussion from domain experts, our secondary software quality attributes requirements include scalability, interoperability, security, reusability, and modifiability. We have adopted the notational convention key words 'MUST,' 'MUST NOT,' 'REQUIRED,' 'SHALL,' 'SHALL NOT,' 'SHOULD,' 'SHOULD NOT,' 'RECOMMENDED,' 'MAY,' and 'OPTIONAL' in this section to describe these software quality attributes and its compliance in the proposed RA. These keywords are to be interpreted as described in RFC 2119 [46].

- *Adaptability:* We aim to adapt intervention according to user needs and requirements to enhance user engagement and increase adherence. To adapt intervention, we create a detailed user profile. Based on these profiles, we adapt to intervention. Subsection 6.1 provides several scenarios explaining how the proposed RA fulfils this need.
- *Scalability:* The entire data-driven adaptive system is based on SOA. The SOA enforces scalability by organizing services into several components communicating over a network. Each component of the architecture can be updated and evolved in terms of hardware and software independent of other components. For example, the IDPT intervention system server's data storage capacity can be increased or decreased without affecting the analytics server.
- *Interoperability*: Our framework supports taxonomic labelling. These are the basics of ontology. Based on these taxonomies, we can define several ontology codes such as `SNOMED-CT`, `LOINC` and others. Support for such taxonomies will allow us to gain interoperability. To enforce interoperability, we use `HL7 FHIR` as the underlying communication standard.
- *Reusability*: The proposed RA uses SOA that supports a great extent of reusability. For example, we can use the authorization server for handling authentication and authorization for several services. We can reuse the intervention for other healthcare treatments. Similarly, the analytics server is loosely coupled with the

RA and be reused for several different data analysis purposes.

- *Security:* The authorization mechanism MUST be TLS-secured [47] and should be improved using the contemporary practices mentioned in [47]. For the prototype, the authorization is incorporated inside the IDPT system but is subject to change as a separate SOA component, like an authorization server used [13]. In any case, the authorization SHOULD issue short-lived tokens and have a mechanism open to administrators and end-users to eliminate tokens in the case of a security conflict.
- *Modifiability:* Modifiability incorporates *evolvability, customizability, configurability*, and *extensibility* [13]. SOA-based architecture facilitates modifiability by allowing the manageable growth of systems [48]. These systems or components are independent of vendors, products, and technologies. This independence makes it easy for individual components to be managed and modified. For example, the analytics server in the architecture (described in Section 4) MAY update the machine learning libraries or create an additional service that consumes the data and performs business intelligence without affecting other components. Similarly, the authorization server MAY creates a customized interface for managing authorized clients, scopes, and permissions without broadcasting its development complexity, structure and patterns, and technological compliance with other components. However, the constituting components MUST follow a common standard for data storage and transmission.

6.3 Expert evaluation of open-source framework

As a part of the non-empirical evaluation, we conducted an expert review. A panel of 17 experts (developers and designers) were invited to review the system and its components. We invited the experts in the field, all of them working in the IT industry. The review team were presented the RA and the open-source framework. An interview followed up the review to determine their reaction towards the open-source framework and its components. We chose full-stack developers(n=10), front-end developers (n=3), back-end developers (n=5), and system architects (n=2) with more than five years of industrial experience. The evaluation aimed to inspect the open-source frameworks modifiability, extendability, scalability, security in authentication, reusability, and code readability. The reviewers were asked to rate evidence of these software qualities in the presented open-source framework. The result of the expert evaluation is tabulated in Table 4. As shown in the Table, experts evaluated the open-source framework to possess most of the above capabilities. In addition to these questions, we had open-ended questions for feedback, reviews and improvements. These feedback and reviews were considered for enhancement of the open-source framework.

6.4 Empirical evaluation - case study

In addition to non-empirical evaluation, we evaluated the framework with a small group of participants for the feasibility study for ADHD case, in INTROMAT project. Domain experts created an online intervention, and these participants were asked to interact with the intervention. The study's feasibility study and results are under review to be published as Randomized Control Trials (RCTs) here [50]. The feasibility study results show that the intervention system built on the top of the proposed RA can adapt the intervention, such as reminders/alerts adaptation, and content adaptation.

Questions	1	2	3	4	5	**Mean**	**SD**
Component modifiability	0	0	1	8	8	4.412	0.599
Framework extendability	0	0	4	5	8	4.235	0.807
System scalability	0	0	2	4	11	4.529	0.696
Security in Authentication	0	0	3	9	5	4.112	0.676
Component reusability	0	0	2	9	6	4.423	0.644
Code readability	0	0	2	11	4	4.118	0.582

TABLE 4: Expert evaluation results

7 Discussion and Future Work

One of essential question is, *why is reference architecture essential?* Our literature review reveals a lack of standard documentation, framework, and clinical guidelines on how the IDPT system should be developed. As a result, developers and researchers reinvent own version of the IDPT system, making it more complicated, less interoperable, and lacking common foundation. Defining RA is a well-recognized method to tackle these challenges. Martinez et al. [51] mention that RA increases development speed reduces operational expenses, and improves software system quality. Similarly, several other studies [6], [52] outlines the benefits of RA as it provides a template solution for a specific domain.

In the healthcare context, researchers, developers and industrial partners have published RA. So, one might argue, *why is the proposed RA better? And how does it solve the identified problems?* To the best of our understanding, no RA have been reported in the psychological domain. Some related RA published has been compared in the related work (see Section 2). Furthermore, we provide a detailed architecture of the intervention system and is the part of RA. The intervention system allows the creation and designing of interventions that can be used for several use cases. Hence, both researchers and software developers can use the open-source framework or extend the framework to match their use cases. Angelov et al. [49] present a detailed framework for the analysis and design of RA. To reduce threats to validity, we used this framework [49] to analyse the proposed RA and create contextual Table 5. We identified two problems in the current IDPT systems: a) they lack adaptiveness and b) they are complex and less interoperable due to the lack of open-source standards. Section 6.1 outlines several scenarios on how the proposed RA addresses adaptiveness. And we made both RA and intervention systems the open-source framework to attract researchers and developers to use it rather than re-inventing from scratch.

7.1 Future work

The promising objective of this open-source framework is to adapt intervention based on user needs and pref-

Context	Where will it be used?	Healthcare providers, hospitals, health clinics that provides digital intervention.
	Who defines it?	Collaboration between psychological domain experts, software engineers, IT industry partners and HCI experts.
	When is it defined?	With a high prevalence of mental or neurological disorders in Norway and around the world, INTROMAT project aims to provide adaptive interventions for people suffering from mental health issues
Goals	Why is it defined?	To adapt the intervention to reduce current higher dropout and increase user adherence.
Design	What is described?	Components that are working together to form a data-driven adaptive system.
	How is it represented?	We used a semi-formal representation of RA and described each component in detail.

TABLE 5: Analysis of proposed RA with respect to framework presented by Angelov et al. [49]

erences. However, RA requires continuous evolution and refactoring. And so does our open-source framework for intervention system. Our immediate future work involves: a) usability and performance evaluation of the Content Management System (CMS) for therapists and patients' user interface; b) evaluation of adaptive strategies and their implications on user adherence using effective Randomized Control Trial (RCT) methods; c) maintenance and evaluation of user-interfaces using user interface experts; d) building and supporting analytics server endpoints for adaptation. There are several potential research directions for future research with this open-source framework, including automatic structuring of modules and tasks inside a case, taxonomic or ontological-based adaptation, interoperability, and support for better user interactions, for example, adaptive conversational agents.

8 Conclusion

To the best of our knowledge, this is the first study to create a reference architecture and an open-source framework for the adaptive IDPT system. The proposed RA uses user profiling model to adapt, and personalized intervention based on the user needs. Moreover, based on the proposed RA, we created an open-source framework for adaptive IDPT system. We followed the DDD architectural style and TDD software development process to create the open-source framework prototype. We evaluated it using empirical (case study) and non-empirical approaches (SAAM method, expert evaluation and software quality matrices). This paper presents an initial study, and preliminary evaluation results show that the developers and the researchers can extend the proposed RA for multiple healthcare interventions. Our immediate future work involves extending and evaluating the framework for usability, performance, and other adaptive capabilities.

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PAPER G

SCIENTIFIC PAPER VII

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An HL7 FHIR and GraphQL approach for interoperability between heterogeneous Electronic Health Record systems

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Abstract

Heterogeneities in data representation and care processes create interoperability complexity among Electronic Health Record systems (EHRs). We can resolve such data and process level heterogeneities by following consistent healthcare standards like Clinical Document Architecture (CDA), OpenEHR, and HL7 FHIR. However, these standards also differ at the structural and implementation level, making interoperability more complex. Hence, there is a need to investigate mechanisms that can resolve data level heterogeneity to achieve semantic data interoperability between heterogeneous systems. As a solution to this, we offer an architecture that utilizes a resource server based on GraphQL and HL7 FHIR that establishes communication between two heterogeneous EHRs. This paper describes how the proposed architecture is implemented to achieve interoperability between two heterogeneous EHRs, HL7 FHIR and OpenMRS. The presented approach establishes secure communication between the EHRs and provides accurate mappings that enable timely health information exchange between EHRs.

Keywords

authorization server, health information exchange, HL7 FHIR, interoperability, OpenMRS, resource server

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Introduction

Interoperability is acknowledged as an essential factor for the success of HIS. We can achieve interoperability by using uniform standards, outlining the meaning of the information being exchanged.[1] CDA, openEHR,[2] and HL7 FHIR are the common standards for Health Information Exchange (HIE).[1] As shown by the literature study,[1,3–6] HL7 FHIR has received interests by both industry and academia. Hence, we chose to use HL7 FHIR in our system. HL7 FHIR supports REST architecture and SOA for information exchange. However, it inherits the RESTful approach's inflexibility and complexity, such as over-fetching and under fetching.[1] In over-fetching, a REST endpoint provides more data than required. The latter, under-fetching, does not return all the data necessary. In these situations, an application has to make an additional request to fetch all the required data. This addition request is referred to as n+1 request. To reduce the problems mentioned above, Facebook proposed GraphQL[7] query language in 2012. After GraphQL's public release in 2015, companies from diverse areas, including technology (GitHub, GitLab), entertainment (Netflix), marketplace (Airbnb), travel (KLM), finance (PayPal), and others, added GraphQL to their development stack. Consequently, there is a rise of architectures, design patterns, development paradigm, experimentation, and frameworks to leverage the benefits of GraphQL and support interoperability. A notable characteristic of these architectures and studies is, the communication between systems (for simplicity, consider two systems) mainly fall in one of the following scenarios:

1. *Scenario 1*: A single EHR system that follows a client-server architecture and has several end-users (For example, an independent clinical EHR system).
2. *Scenario 2*: Both EHR systems follow the same health standard (For example, organization A follows HL7 FHIR version R4, and organization B follows HL7 FHIR version R4).
3. *Scenario 3*: EHR systems follow the same standards but different versions (For example, organization A follows HL7 FHIR V3, and organization B follows HL7 version R4).
4. *Scenario 4*: EHR systems follow different health standards (For example, organization A follows OpenMRS, and organization B follows HL7 FHIR).

Most of the existing studies concentrate on the problem associated with scenario 1 and 2 from different perspectives. Interoperability can be achieved when one or more EHR systems follow the same healthcare standard (as in scenario 1 and 2). However, it becomes challenging when EHR systems[6] differ in healthcare standards (scenario 3 and 4). As a solution to scenario 3 and 4 problems, we propose the exploitation of GraphQL-based architecture to achieve interoperability among the heterogeneous system. This paper presents a GraphQL based architecture for interoperability among several EHR systems following different healthcare standards. To justify our approach, we developed a prototype where we communicate between OpenMRS and HL7 FHIR server. Furthermore, our investigations are accompanied by a non-empirical evaluation based on software quality metrics ISO/IEC 25000.[8]

The study's primary aim is to: (a) establish technical interoperability between two different EHR systems following different healthcare standards, HL7 FHIR and OpenMRS, (b) report architecture for exploiting GraphQL for achieving communication between distinct EHR systems. We report the following novel contribution in this paper: (a) We outline the architecture for exploiting GraphQL to achieve interoperability between EHR systems following different healthcare standards, and (b) We present an open-source GraphQL powered resource server using the recent version of HL7 FHIR.

Background and motivation

The term *interoperability* has a subjective interpretation based on people context and experience.[9] We use the term in context to the definition provided by the IEEE 1990 as:

> *Interoperability is achieved when two or more systems or the systems' components can interchange data/information and utilise the data/information being interchanged. (IEEE 1990)*[10].

The definition incorporates both the *technical interoperability*, that is, the interchange of information and *semantic interoperability*, which is the ability to utilize the information being interchanged. In addition to this technical and semantic interoperability, Tolk et al. proposed seven interoperability layers, including no interoperability, technical interoperability, syntactic interoperability, semantic interoperability, pragmatic interoperability, dynamic interoperability, and finally, conceptual interoperability.[11] Gibbons et al.[12] introduced *clinical interoperability*, which refers to the actual usage of information in the clinical process workflow. In this study, we mainly focus on achieving technical interoperability (by following `HL7 FHIR` and `GraphQL`) and semantic interoperability (by following common healthcare IT standards `SNOMED CT,` and `LOINC`).

Why do we need common healthcare IT standards for interoperability?

Healthcare IT Standards are a set of agreed-upon representations of data and methods for communication between Healthcare Information Systems (HIS). These standards incorporate agreement for communication among HIS. Such agreement includes: (a) mechanisms for enforcing secured communication, (b) structure of format of data structure, (c) definitions of common terminologies, (d) description and architecture of the communication protocols, and (e) comprehensive documentation. Examples of such Healthcare IT standards include `HL7 FHIR` and `OpenEHR`. We need such healthcare IT standards for the following reasons:

- *Lack of regulator*: There is no one to regulate with power to ensure healthcare deployment happen systematically. Consequently, a custom version of EHR systems and healthcare standards are followed. The obstacle with these custom standards is not that there are so diverse to pick from, but we have failed to adopt the currently available ones.[13]
- *Complex standards*: The available standards have been complicated and expensive to implement, which lead to the development of `HL7 FHIR`.
- *Volume of data*: There are massive events in the healthcare ecosystem, including patient admission, prognosis, pre-assessment, diagnosis, monitoring, follow up and others. These events show the characteristics of big data. Hence, it requires proper attention to be processed, stored, and accessed.
- *Interfacing with other EHRs*: The number of API links required to connect `n` EHR systems increments according to the formula[13]:

$$Number\ of\ \ API\ interfaces = \frac{n\,(n-1)}{2} = \binom{N}{2}$$

Hence, connecting only two EHRs require a single API interface. Linking 5 EHR systems would require ten distinct API interfaces and connecting hundred nodes needs 4950 interfaces.[13] Such growth in connecting different EHRs is referred to as the combinatorial explosion.

- *Translation*: Interoperability at the root level transfers data/information from system A (sender) to B (receiver). If both sender and receiver adhere to the same standard, no translation is required. However, EHR systems have been used before these standards came into existence. Many of these EHR systems are wrapped in health providers protected firewall and follow traditional or custom standards. In order to communicate with the external EHR systems, the sender data has to translate to the format understood by receiver and vice versa. `HL7 FHIR` provides such a common standard to avoid such translation.

REST versus GraphQL

Both REST and `GraphQL` are the framework for developing *Web Services (WS)*. Traditionally, there are two WS-protocols: *SOAP*[14] and *REST*.[15] The SOAP protocol requires specification of all available methods, including input and out data structures in a schema. In contrast, the REST uses information encoded in the `URL` and `HTTP` method to describe the service interface. The main disadvantage of SOAP is seen in its complexity and the overhead imposed through the explicit schema.[4] REST, on the other hand, is more lightweight and relies on the developer discipline. `GraphQL` is an alternative approach to WS, developed by Facebook. Every server interface using `GraphQL` has to define its underlying domain model in a schema representing a graph. Such a definition is given a textual *Schema Definition Language* (SDL). As aforementioned, `GraphQL` improves the problems[1] associated with the REST approach.

HL7 FHIR versus OpenEHR

Readers must note that OpenMRS is an EHR system, whereas OpenEHR is a healthcare IT standards. `HL7 FHIR` is one of the popular healthcare standards created for web standards like `XML, JSON, HTTP`, and `OAuth`. The standard incorporates a modular set of components referred to as Resources such as Patient, Observation, Careflow, Organization, and others. `HL7 FHIR` supports a coding system that is defined by `SNOMED-CT, LOINC, RxNorm, ICD 10` family, and others.[16] `HL7 FHIR` supports RESTful communication and SOA architecture. OpenEHR[17] is an alternative to `HL7 FHIR` that uses over 300 more complex Archetypes created to yield a maximal number of data items.

Related works

There is not much work done to establish interoperability between heterogeneous system. However, to support interoperability, the OpenMRS community are developing an `HL7 FHIR` module that can utilize `HL7 FHIR` resources and communicate with the OpenMRS.[18] However, the FHIR modules are not complete and do not support all the `HL7 FHIR` resources yet. Consequently, there is a need to build a method to communicate between OpenMRS and other EHR systems. In the study done by Kasthurirathne et al.,[18] the authors introduce the FHIR module recently developed for OpenMRS to show how the newly developed endpoints can be used to communicate with `HL7 FHIR` based resource server. Gavrilov et al.[19] presents a design of a healthcare warehouse to achieve technical and organizational interoperability. Similar to our proposed architecture, their framework communicates over SOA. However, unlike their study, we present open-source RS based on `HL7 FHIR` and present architecture to establish communication between two or more EHR systems following a completely different healthcare standard.

In the study by Mukhiya et al.,[1] the authors proposed architecture for communicating between EHR systems following the same standard. Besides, we presented an empirical evaluation of the use of the REST approach with GraphQL endpoints. The result indicated that GraphQL-based endpoints has better performance, offers scalability, and are economical compared to REST. This paper extends experimentation of the work by Mukhiya et al.[1] Unlike their study, we aim to establish communication between two heterogeneous EHRs.

Solution

This section outlines the architecture of the proposed system for establishing communication between heterogeneous EHR systems. An obvious question would be, *"why do we need to communicate between OpenMRS and HL7 FHIR resource server?"* The answer is a continuous evolution. All the current EHR records are in the OpenMRS server, and we envision supporting interoperability by using HL7 FHIR resource server as most of the healthcare systems are adopting HL7 FHIR.[1,3,4] As aforementioned, the lack of regulation gives healthcare providers the freedom to choose their EHR system based on their technical, economic, legal, operational, and system feasibility study. So, the need for such inter EHR system communication is a common problem. Hence, in this architecture, we maintain the existing system (OpenMRS) and establish communication with the HL7 FHIR Resource server. HL7 FHIR Resource server is also responsible for sharing endpoint with other EHR systems in case of external provider communication.

Architecture

The multi-level model illustrated in Figure 1 outlines the communication between OpenMRS and Resource server based on HL7 FHIR. The top left block in Figure 1 represents an RS based on HL7 FHIR, which consists of GraphQL endpoint guarded by Authorizations Server. Each HL7 FHIR resources (like *Patient, Encounter, Observation*, and others) have their associated service and strategic resolvers for intercepting the valid requests and translating the resources from OpenMRS format to HL7 FHIR format. The top right block in Figure 1 represents an instance of the Resource server.

The bottom blocks of Figure 1 represents OpenMRS layers and its instance. As aforementioned, OpenMRS has a built-in Authorization server. The GraphQL endpoint captures any requests made to the Resource Server. The Authorization Server guards the endpoint for authentication and authorization purposes. The valid requests are then forwarded to associated Resource services. For example, for a valid request to write patient resource (POST HTTP request), PatientService captures the requests and forwards to PatientStrategyResolver which translates the requests body (patients attributes) from OpenMRS to HL7 FHIR format. The translated format is then used by request to communicate with the database service.

Experimental setup

This section explains the main components of the recommended architecture, as depicted in Figure 2. In addition, we outline how these components communicate with each other.

1. *OpenMRS server*: OpenMRS[17] is an open-source, configurable EHR system programmed in Java, JavaScript and several open-source components including MySQL, Apache Tomcat, Hibernate, and others. It represents data in XML and XML Forms format and uses a relational database with SQL. The architecture of OpenMRS is presented in Seebregts et al.[20] for the interested readers.

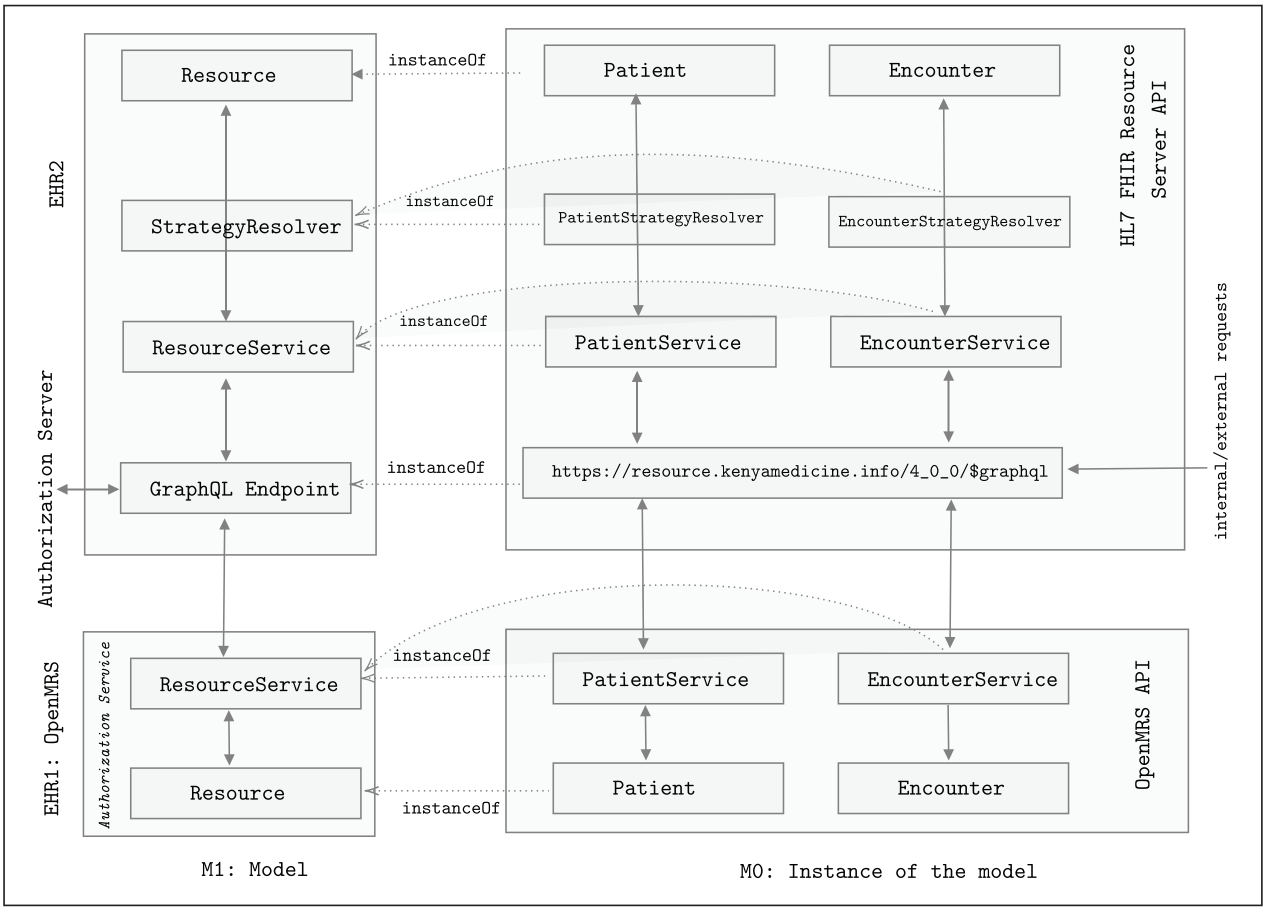

Figure 1. Multi-level model illustrating communication between OpenMRS API and HL7 FHIR Resource server.

2. *Resource Server*: It is a web server complying with `HL7 FHIR` healthcare standard and can communicate using REST API. The communication is established when an authorization Server grants a valid `access tokens`. In SOA, terms, a resource server is a service provider.[21] The available open-sourced resource servers are REST-based, and some non-open sourced are proprietary to the best of our knowledge. We intend to leverage the benefit of `GraphQL` based approach, and hence we initiated an open-source resource server powered by `HL7 FHIR` and `GraphQL`. The resource server is available for use under MIT license. The GitHub links for downloading the source code for all the components are given in supplementary resources.
3. *Authorization Server*: The authorization server is a web server based on `OpenID connect`[22] and has a function to authenticate and authorize users. Besides, it is responsible for managing the clients' scope, permission, and introspect token for its validity. Our prototype consists of a standalone authorization server; however, any the architecture is compatible with any third-party authorization server provided they are based on `OpenID connect` and can grant valid `access tokens`.
4. *FHIR patient app*: FHIR patient app can be mobile-application or web application that assist in data interchange between wearable sensors and resource server. Moreover, we can utilize such a patient app to create a user interface for the patient to provide information or accumulate information. In SOA, both mobile and web application corresponds to the service requester/consumer components.[21] In our implementation, the FHIR patient

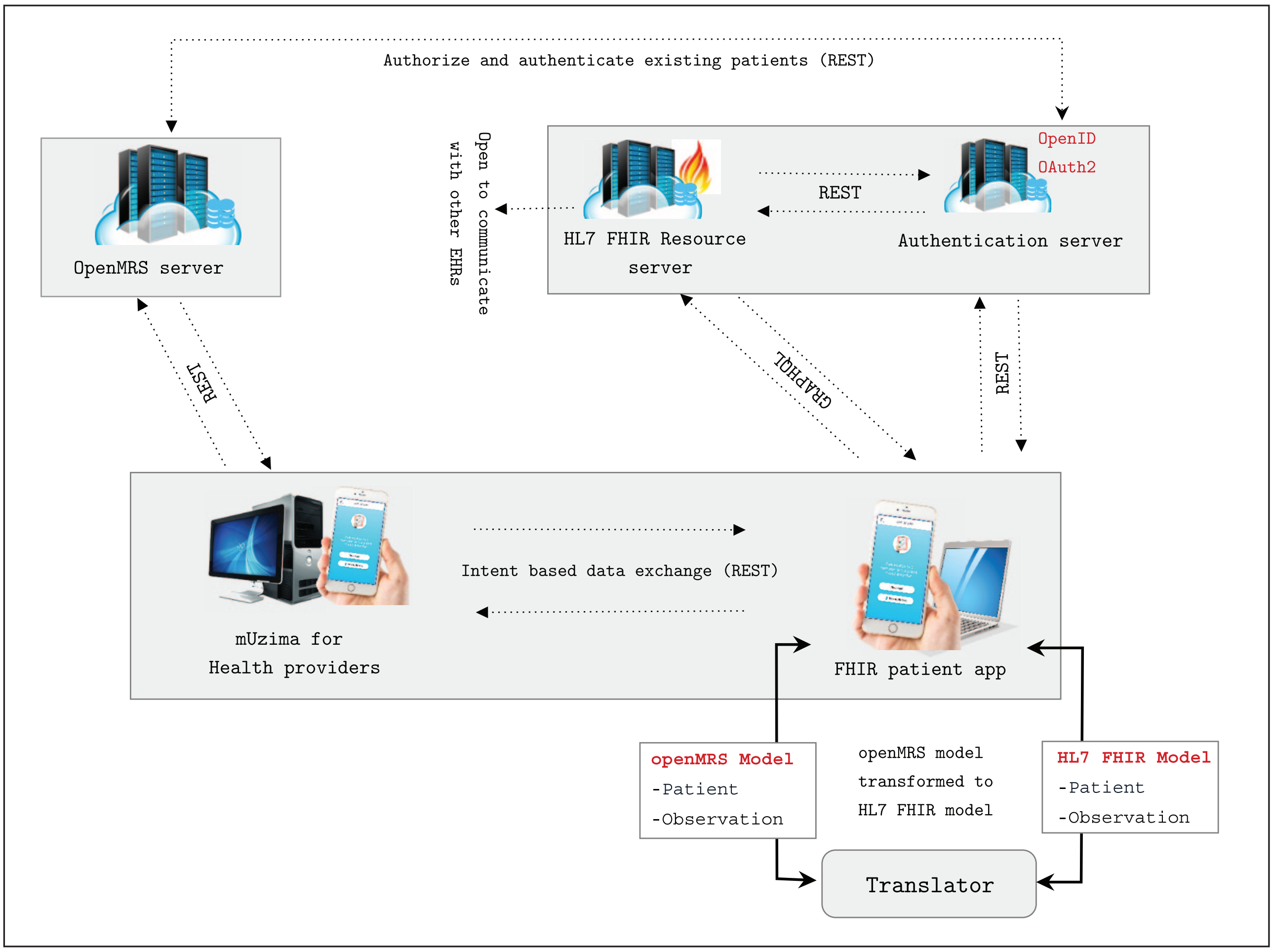

Figure 2. Our set up establishing communication between OpenMRS and resource server based on HL7 FHIR and GraphQL.

application uses a middleman service to translate OpenMRS entities to `HL7 FHIR` entities and vice versa. We can delegate such translation to a separate service similar to the broker-architecture pattern.[23] However, we chose to implement a middleman service for translation inside the FHIR patient mobile application for the initial prototype.

5. *mUzima for health providers*: mUzima for health providers[24] is a client that presents interfaces authentication, and authorization to the healthcare provider. The muZima health provider application provides abilities to create resources such as patients, observations, clinical process, and others for their users and present them in a dashboard, associated with their progress, and activities.[25]

Communication flow

In our architecture, there are two types of communication: (a) between OpenMRS server and `HL7 FHIR` Resource server, (b) among `HL7 FHIR` Resource server, authentication server, and FHIR patient app.

Communication among `HL7 FHIR` Resource server (RS), authentication server, and FHIR patient app: The communication among `HL7 FHIR` Resource server, authorization server and FHIR client follow the same workflow as mentioned in the study.[21] This communication follows contextless handshaking recommended by SMART on FHIR[26] and involves the following steps:

1. The FHIR patient app makes conformance `HTTP` request call to the RS.
2. The RS responds back by providing valid conformance endpoints (for example,/token,/authorize, /manage).
3. The FHIR patient app attempts to authenticate by sending valid scopes, headers, and payloads to the authorization server.
4. Once the FHIR patient app is successfully authenticated with the Authorization server; they are redirected back to the app. In this process, the FHIR patient app receives an `Access Token`, a long string of characters that serve as credentials in the next step.
5. The FHIR patient app then creates a request to the RS with access tokens provided by the Authorization Server. An example of the `HTTP` request is shown below (for readability purpose, the token has been shortened):

```
GET/Observation?subject=Patient/987654

Accept: application/fhir+json

Authorization: Bearer

eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9.eyJpZCI6
```

6. The RS makes token introspection to verify the users' scope, grants and permissions. The request is only successful, if the user requesting the information has valid access, grant types and more importantly, correct access token. The following is an example request made by an `HL7 FHIR` Resourcer server to an Authorization Server. Note the header `Authorization` whose value is the string `Bearer` followed by the `Access Token`.

```
POST/oauth/token/introspect

Accept: application/json

Content-Type: application/x-www-form-urlencoded

Authorization: Bearer ImlhdCI6MTYwMDcwMDczOX0.e95nuufbE7lBrWkpRrNuJu
PAsW5

token=eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9.eyJpZCI6
```

7. Provided the request has valid payloads; the authorization server returns with scopes, permissions, token type and token expiration. It throws an exception, otherwise. The following is an example response made by an Authorization Server that indicates the user has been approved for `observation` read scope, the expiration date of the access token, and other meta information.


```
{

"active": true,

"scope": "observation/*.read online_access openid profile",

"client_id": "growth-chart",

"token_type": "Bearer",

"exp": 1316269159,
```

```
"iat": 1316269109,

"iss": "https://auths.kenyamedicine.info"
```

8. With valid scope and permission, the RS performs a DB query.
9. Assuming DB has been configured, and correctly connected, it returns with asked resources.
10. Finally, the RS sends the requested resources to the FHIR patient app.

Communication between OpenMRS server and HL7 FHIR Resource server: OpenMRS comes with an inbuilt authorization server. The mUzima for health provider application[24] communicates with the OpenMRS server via a REST interface and the inbuilt authorization server. Here is a point to note: OpenMRS server comes with REST communication and suffers from the challenges mentioned earlier. To overcome such challenges, we envision moving toward the `GraphQL` approach, and therefore this architecture is used. To comprehend the communication between these components, let us say a patient needs to create an observation resource in the `HL7 FHIR` Resource server. In such a case, there are two actions:

1. A patient data model in the OpenMRS and `HL7 FHIR` is not the same. There can be the following situations: (a) some attributes present in the OpenMRS data model is not present in the `HL7 FHIR` Resource server and vice versa, (b) different naming for the same attributes, (c) different data types and structure for the same attributes. To solve this situation, we introduced translator service inside the FHIR patient app that translates one model to another.
2. Once the patient is validated, the observation resources need to be created in the FHIR Resource server.

The Authorization Server authenticates the FHIR patient app, making a REST call to the OpenMRS authentication service to check the patient details. If the patient is valid, the authorization server returns the requested resources to the FHIR patient app. The app then sends requests to mUzima for the Health provider app for the patient detail and gets the patient details back as the response. The patient model returned by the mUzima health provider app has the OpenMRS patient model and is translated to `HL7 FHIR` by the translator service inside the FHIR patient app. The translated data is then sent to the `HL7 FHIR` RS with the valid access token. With a valid access token, the `HL7 FHIR` resource server saves the patient information inside its database. Once the patient information is successfully saved into the `HL7 FHIR` Resource server, the following action is to create the observation resources. The observation information is encoded into the `HL7 FHIR` format. The request is made to the RS using the flow mentioned in the previous section, that is, contextless handshaking recommended by SMART on FHIR.[26]

Experiment results

The primary artifact of this paper is the software architecture model, which envisions establish communication between the OpenMRS server and the Resource Server. To evaluate the architecture, we conducted an experiment where we sent several queries to read, write, update, and delete (CRUD) `HL7 FHIR` resources. This section presents 11 queries (Q1, Q2), each indicating two types of communications: (a) C1: Query by the mobile client to the RS and (b) C2: Query by the mobile client to the OpenMRS server. We executed each query 10 times and recorded the response time and response size of the request. The reported response time and size are the average values

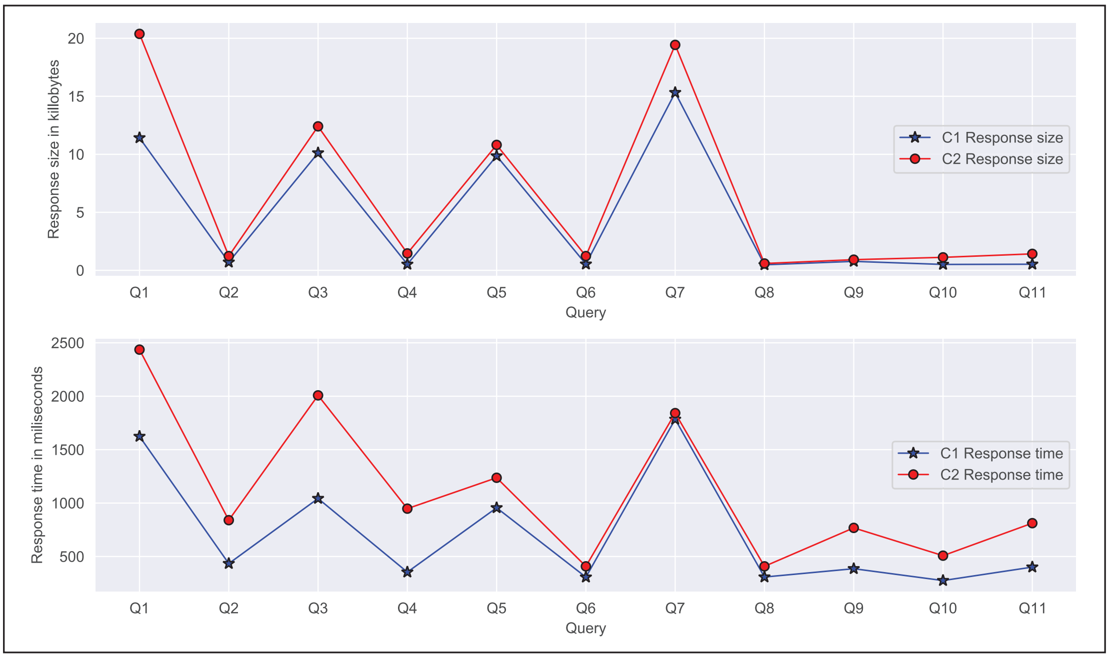

Figure 3. The figure compares the response size (top) and response time in millisecond (bottom) with 11 different queries for two communications, C1: query by the mobile client to the resource server, C2: query by the mobile client to the OpenMRS server.

Table 1. The table outlines the expected and actual response for each of the queries. Resources: HL7 FHIR resource, [resources]: array of resources, resource: response in object format.

Query	Description	Expected response	Actual response
Q1, Q3, Q5, Q7	Read all resources	Status code: 200 Response body: [resources] content-type: JSON	Status code: 200 Response body: [resources] content-type: JSON
Q2, Q4, Q6, Q8	Read one resource	Status code: 200 Response body: {resource} content-type: JSON	Status code: 200 Response body: {resource} content-type: JSON
Q9, Q10	Create and update a resource	Status code: 200 Response body: {resource} content-type: JSON	Status code: 200 Response body: {resource} content-type: JSON
Q11	Delete a resource	Status code: 200 Response body: {id} content-type: JSON	Status code: 200 Response body: {id} content-type: JSON

taken for each request (see Figure 3). The expected response and the actual response from each of these queries are outlined in Table 1. To keep the experiment result homogeneous, we hosted all the servers locally on Asus Predator Triton 500 with 32 GB of RAM, 1 TB SSD drive, 2070 RTX GPU, and Ubuntu 20.14.

Apart from the communication mentioned earlier (C1, C2), we executed `HTTP` requests to read resource from OpenMRS and write to the RS (C3). Thus, this communication involved two phases (a) query to read resource (Q2, Q4, Q6, and Q8) and (b) query to write the resource. Finally, we evaluated the communication to be successful by manually checking if the database of the RS. It is imperative to note that `HTTP` requests are subjected to network bandwidth, connectivity, and server

Table 2. The table presents an interoperability scenario between HL7 FHIR-based Resource Server (RS) and OpenMRS. Here, the FHIR patient app attempts to get Observation resource from OpenMRS and write to HL7 FHIR based RS.

Scenario	Interoperability scenario
Source of stimulus	FHIR patient app
Artifact	OpenMRS, HL7 FHIR Resource server, Authorization server, mUzima for providers, and FHIR patient app communicating over SOA.
Environment	Read Observation resource from OpenMRS and write to HL7 FHIR Resource server
Response	FHIR patient app gets valid token, sends requests to OpenMRS, OpenMRS sends valid resources to FHIR patient app, it sends write requests to HL7 FHIR RS, RS writes the observation in its database.
Response measure	Valid requests and responses

execution. Hence, one must expect to get different response time and response size on their set-up. Furthermore, this paper aims to advocate the feasibility of communication between heterogeneous EHR systems rather than performance measures.

Evaluation

We performed a non-empirical evaluation by comparing the software quality metrics of our prototype based on ISO/IEC 25000 and expert evaluation discussed in the next section. In addition to this, we share our experience regarding the maturity of `HL7 FHIR` and challenges faced during the study.

Software quality metrics

Following are the lists of software quality metrics, based on ISO/IEC 25000 standards, associated with our prototype.

1. *Interoperability*: To enforce interoperability, we use `HL7 FHIR` as the underlying communication standard. Since our principal aim is to establish interoperability between heterogeneous EHRs, we used scenario-based evaluation as recommended by the SAAM.[27] The result of the scenario-based evaluation is presented in Table 2.
2. *Security*: Both our authorization server and the `HL7 FHIR` RS communicate over `TLS`[28] and follow the contemporary practices as mentioned in the study.[21,26,28] As per the `TLS` community's recommendation, the authorization server generates the short-lived access tokens and provides a way to revoke access tokens when security conflict is noticed.
3. *Modifiability*: Several studies outline that SOA-based architecture[21,29] supports the modifiability. In SOA, the components are not dependent on vendors, technologies, brands, or underlying technological stack. Consequently, we can modify individual components without affecting others. For example, in our case, we can upgrade the database of OpenMRS without affecting the database of `HL7 FHIR` RS.
4. *Reusability*: The proposed architecture uses SOA that supports a great extent of reusability. For example, we can use the authorization server for handling authentication and authorization for several services. Besides, any third-party authorization server can communicate with the resource server, as long as they meet communication protocol standards.

5. *Scalability*: Since our architecture is based on SOA; scalability comes as in inherent attributes. The modular architecture makes it easy to scale each module if required. For example, we can increase RS's storage capacity when there are more resources to store, query, update, or delete.

Expert evaluation

The code for all the components of the prototype has been evaluated by seven developers (front-end and back-end) to verify their agreement under ISO/IEC 25000[8] software product quality requirements, and presence of anti-patterns.[30] The review team were presented the RA and the open-source framework. An interview followed up the review to determine their reaction toward the architecture, interoperability communication, and components. In addition to these questions, we had open-ended questions for feedback, reviews, and improvements. We used these feedbacks and thoughts to the enhancement of the architecture and prototype.

Discussion

Maturity of HL7 FHIR implementation: Interoperability is complex due difference in standards and representsion.[31] However, it is essential for the successful realization of healthcare. Interoperability using `HL7 FHIR` is adopted speedily. It is evident when Apple company, which is considered vital in the mobile industry, declared to adopt FHIR in iOS devices.[32] Similarly, powerful companies like Amazon, Google, Microsoft, Salesforce, IBM, and Oracle signed a joint pledge in August 2018 to support true health data interoperability by using standards like `HL7 FHIR`.[33] While `HL7 FHIR` is open-source,[34] specifications for `HL7 FHIR` are open, keeps 80/20 rule, is suitable for mobile apps and abides by the standard, well-known web technologies with specific challenges. This section addresses some of the challenges we discovered during this study.

- *Essence of rigorous validation and testing*: Interoperability with `HL7 FHIR` is in its nascent stage and hence not all EHR systems are compatible with it. Therefore, the implementer must guarantee that the evaluation tools (functional testing, platform testing, conformance testing, load and performance testing) work as specified in the `HL7 FHIR` specification.
- *Data conformance challenges*: One of the prevalent issues during the study was data matching. Data in EHR may not be the same structure and data types. For example, the `patient` data model in OpenMRS is different from `HL7 FHIR` patient model. Such mismatch scenario is common in vendor-specific EHR systems and hence makes interoperability practically challenging. Patients are the core user of any EHR systems, and patient matching could be challenging if there is a mismatch in either structure, representation, or data types. For example, a small error in the social security number (SSN), such as a dash, spelling mistake, can cause a problem.[32]
- *HL7 FHIR standards are not backwards compatible*: `HL7 FHIR` relies on 80/20 rules meaning that resources defined by `HL7 FHIR` cover 80% of the data elements used in existing EHR systems. The outstanding 20% are exceptional use cases that can be dealt with as `HL7 FHIR` extensions. Extensions are supplementary resources designed at specific companies to include data not handled by the core `HL7 FHIR` profiles. Consequently, it provides various ways for implementors to achieve identical action. Such a difference in implementation backfires when `HL7 FHIR` practitioners extend `HL7 FHIR` differently.[32]
- *FHIR does not address infrastructure*: Current healthcare solutions need to be secured and reliable. To achieve such security and reliability, it needs to follow the current infrastructure

system backed up by cloud service, Kubernetes platform, and other IAAS features. HL7 FHIR does not address these infrastructure questions. Furthermore, HL7 FHIR is not meant to address the security issue; hence, one must build HIPPA technical safeguards[35] themselves.

Limitations

The presented prototype and architecture do not address issues related to patient privacy. They do not evaluate the security to set up communication between heterogeneous EHR systems for gradual migration from OpenMRS to HL7 FHIR resource server. HL7 FHIR does not address issues associated with security and privacy. However, it provides guidelines to support Oauth2.0 and OpenID Connect for authentication. In addition to this, we do not evaluate the usability perspective of the user interface. After successful qualitative communication between the system, the prototype requires design evaluation and usability evaluation. Nevertheless, even with these restrictions, this study's proposed architecture, prototype, and communication approach will significantly benefit the healthcare industry and research communities to obtain interoperability in EHR systems following different healthcare standards.

Conclusion

We architectured and developed a system to communicate between OpenMRS and Resource server based on HL7 FHIR. This paper sought to demonstrate how the proposed architecture could be generalized to establish communication between one or more heterogeneous healthcare systems. The proposed approach can grow or keep communication alive between legacy healthcare systems. As a validation of the proposed architecture, we blended OpenMRS with a Resource server based on HL7 FHIR and GraphQL, thereby illustrating interoperability between heterogeneous healthcare systems. This study's architectural communication paves the way for innumerable attractive novel opportunities and a notable architectural mindset innovation. Nonetheless, the lessons uncovered by this study will help the OpenMRS research community by familiarizing them with how to allow the OpenMRS healthcare standard to evolve to achieve better interoperability.

Abbreviations

CDA Clinical Document Architecture
EHR Electronic Health Record
FHIR Fast Healthcare Interoperability Resources
HIS Healthcare Information Systems
HTTP Hypertext Transfer Protocol
IAAS Infrastructure-as-a-service
ICD International Classification of Diseases
JSON JavaScript Object Notation
REST Representational State Transfer
RS Resource Server
SAAM Software Architecture Analysis Method
SOA Service-oriented Architecture
SOAP Simple Object Access Protocol
SQL Structured Query Language
TLS Transport Layer Security
URL Uniform Resource Locator
XML Extensible Markup Language

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Supplementary materials

The following links contains source codes for all the components used in the experimental setup, and are open-sourced under MIT license. https://github.com/sureshHARDIYA/phd-resources/tree/master/Papers/SAGE

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List of Figures

List of Tables