Towards an Ontology to Represent Domain Knowledge of Attention Deficit Hyperactivity Disorder (ADHD): A Conceptual Model

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Abstract*—Attention deficit/hyperactivity disorder (ADHD) represents a highly heterogeneous and complex medical domain with numerous multidisciplinary research areas. Despite the rising number of research on the pathophysiology of ADHD, the available information in the ADHD domain is still scattered and disconnected. This research study mainly aims to develop a conceptual model of ADHD by applying knowledge engineering processes to structure the domain knowledge, elucidating key concepts and their interrelationships. The methodology for developing the conceptual model is derived from established practices in ontology construction. It adopts a hybrid approach, integrating principles from prominent methodologies such as Ontology Development 101, the Uschold and King methodology, and METHONTOLOGY. The proposed ADHD conceptual model links various aspects of ADHD including subtypes, symptoms, behaviors, diagnostic criteria, treatment, risk factors, comorbidities, and patient profile. Comprising eight top-level classes and highlighting 13 key relationships, it establishes connections between symptoms and recommended treatments, as well as symptoms and their diverse manifestations, risk factors, ADHD subtypes, and potential comorbidities. While the model captures a broad range of ADHD-related concepts, it has certain limitations. It does not extensively address genetic or neurobiological mechanisms, nor does it capture cultural and contextual variations in ADHD manifestations. These limitations highlight opportunities for future expansion, such as incorporating real-world data and diverse demographic contexts. Nevertheless, the model developed in this study is well-suited to serve as a cornerstone for constructing a comprehensive ADHD domain knowledge ontology. Ontologies play a crucial role as a layer for transferring knowledge and serve as a foundation for developing advanced systems, such as decision-support tools and expert systems, to enhance ADHD research and clinical practice.

Keywords*—Conceptual model; ontology; ADHD; knowledge engineering

I. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is the most prevalent behavioral disorder and the second most frequent chronic condition among children [1]. ADHD is a neurodevelopmental disorder characterized by a recurring pattern of inattention, hyperactivity, and impulsivity [2], [3]. The symptoms of inattention, hyperactivity and impulsivity include a wide range of behaviors such as difficulty completing tasks, difficulty following instructions, making careless mistakes, and being overly impulsive [3]. These symptoms of ADHD often have a direct negative impact on the individual's academic achievement, social relationships, self-esteem, and emotional functioning [2], [4]. ADHD was already a common condition in the past. However, it is becoming more common nowadays. Over the past two decades, there has been such a significant increase in rates of ADHD diagnoses that researchers describe it as a "dramatic change" that occurred between 1997 and 2016 [5], [6]. The global prevalence of ADHD is estimated at 2% to 7%, with an average of around 5% in school-aged children [7] and 2.5% to 5% in adults [8], [9].

In the last two decades, the field of ADHD has witnessed remarkable progress in research. Different studies often explore different aspects of ADHD. It incorporates multiple disciplines such as psychology (e.g. [10], [11]), neuroscience (e.g. [12], [13]), genetics (e.g. [9], [14]), epidemiology (e.g. [15], [16]), pharmacology (e.g. [17], [18]), and psychosocial and educational interventions (e.g. [19], [20]). Thus, ADHD research is quite diverse and multi-faceted. Bridging the gap between such different disciplines is particularly difficult due to this diversity.

Despite the rising number of studies on the pathophysiology of ADHD, the disorder remains a complex psychological condition that is challenging to characterize [21]. Many previous studies have repeatedly emphasized the complex and heterogeneous nature of ADHD [22]. This heterogeneity is reflected in its wide range of psychiatric comorbidities, diverse clinical profiles, patterns of neuropsychological impairment and developmental trajectories, and a broad spectrum of structural and functional brain abnormalities [22]. In addition to its complex nature, one of the significant challenges in the ADHD research field is the scattered and unstructured nature of the available information. ADHD knowledge is dispersed across various types of studies, making it difficult for researchers, clinicians, and caregivers to access and synthesize relevant insights effectively [23]. Thus, this research focuses on addressing two core problems: the complexity and heterogeneity of ADHD and the scattered, unstructured information in the domain.

As the research environment grows increasingly complex, it is crucial to establish methods that make the diverse output of ADHD studies more accessible and integrative [24]. Recently, there has been a striking rise in the use of biomedical ontologies as the preferred method for bridging different disciplinary gaps. They ensure wide access and exchange of information among researchers and professionals from different backgrounds and a wide range of disciplines [25], [26]. The remarkable success of

biomedical ontologies is due to their power to offer a comprehensive framework within which researchers can publish their new findings and physicians can conveniently access the studies that serve as the foundation for their diagnosis and treatment approaches.

Gruber [27] defined the computer science ontology in 1993 as " explicit specification of a conceptualization". This definition placed an emphasis on the conceptualization, which serves as the foundational phase influencing subsequent processes in ontology development. Conceptualization consumes the majority of the time dedicated to ontology construction. It commences with the knowledge acquisition phase, wherein a description of the domain ontology is formulated. Subsequently, the acquired knowledge is arranged and structured within a conceptual model [28]. Kabilan [29] defined the conceptual model as a theoretical representation of a segment of reality, outlining fundamental concepts and their interrelations. It captures all relevant knowledge in a given field, organizing it into a structured and unified framework. By doing so, a conceptual model serves as the foundation for integrating and harmonizing diverse and scattered information. This leads us to the central research question of this study: How to develop a conceptual model that offers a unified framework to integrate the heterogeneous and scattered knowledge in the ADHD domain?"

As we mentioned above, the ADHD domain, with its multifaceted nature and interdisciplinary scope, presents unique challenges in structuring and consolidating knowledge. Addressing the complexity and scattered nature of ADHD-related information requires a systematic approach to conceptualization, one that captures the domain's key components and their intricate interrelations. Recognizing this need, in this paper, we mainly aim to develop a conceptual model that describes the reality of the ADHD domain with its key concepts and relationships. The resulting conceptual model aims primarily to be a basis for building an ADHD domain knowledge ontology in order to provide a step towards reducing the knowledge gap in the field of ADHD.

The rest of this paper is organized as follows: Section II demonstrates the Related work, and the research methodology is detailed in section III. The findings of this research are explained in Section IV. The discussion is presented in Section V before concluding the work.

II. Related Work

Conceptual models have been widely used in the study of neurodevelopmental disorders to provide structured frameworks for understanding the relationships between symptoms, risk factors, functional impairments, and outcomes. These models are essential for integrating knowledge across disciplines, identifying intervention targets, and advancing clinical and research practices. They play a crucial role in organizing and integrating knowledge about complex disorders such as ADHD. However, within the field of ADHD, there is a notable paucity of comprehensive conceptual models that unify its various dimensions. Existing efforts often focus on isolated aspects, leaving gaps in understanding the disorder holistically. The following section highlights existing conceptual models in ADHD research and underscores the gaps this study aims to address.

Rapport et al. [30] introduced a conceptual model that highlights the underlying assumptions about what causes ADHD and how it is treated through behavioral and pharmacological approaches. The model suggests that biological factors, such as genetics or prenatal complications, lead to differences in how the brain's systems function. For example, changes in neurotransmitter systems like dopamine and norepinephrine are thought to be directly responsible for the main psychological features of ADHD, including cognitive and behavioral symptoms. The model also explains that other characteristics of ADHD, often called "associated features" in the DSM-IV (e.g., academic struggles, poor social skills, or family conflicts), are secondary effects caused by these core symptoms. For instance, a child's academic difficulties might result from their inability to pay attention or persist in tasks over time. Eventually, this model categorizes therapeutic interventions into pharmacological treatment, cognitive behavioral therapy (CBT), and skills training, correlating each type to be specifically directed to treat one aspect of the disorder: pharmacological treatment for biological factors, CBT for cognitive and behavioral symptoms (subtypes), and skills training for associated features.

Brod et al. [31] in their study focuses on understanding how ADHD symptoms and impairments impact the quality of life (QoL) in adults. The authors proposed a conceptual model based on data from experts, patients, and literature. The model identifies five areas of impact: work, daily activities, relationships, psychological well-being, and physical well-being, which are grouped into three key QoL domains—productivity, relationships, and health. The model highlights how ADHD symptoms interact synergistically, creating cascading impairment pathways that affect daily functioning. To operationalize the model, the Adult ADHD QoL Measure was developed, enabling clinicians to assess ADHD's impact on QoL and design more comprehensive, individualized treatment plans.

In the same context of ADHD, Dosreis & Myers [32] propose a conceptual model explaining how parents of children with ADHD recognize problems, seek medical evaluations, and decide to pursue treatment. Based on interviews with 48 parents, the model identifies three phases: (1) problem recognition, (2) motivation for evaluation, and (3) therapeutic intervention. Parental decisions are shaped by life circumstances (e.g., family changes, financial shifts), experiences at home, school, and within cultural/religious settings. The model distinguishes between family subgroups based on their help-seeking behaviors, offering insights for tailored, patient-centered interventions to enhance treatment delivery and family engagement.

In neurodevelopmental disorders fields such as autism spectrum disorder (ASD), dyslexia, and child psychopathology, numerous conceptual models have been developed to address the complexity and heterogeneity of these conditions. Alsobhi et al. [33] propose a conceptual model to support personalized learning experiences for students with dyslexia. The conceptual model links dyslexia types with assistive technologies and learning styles to create tailored educational materials. The

model includes key components such as Dyslexia Type, Assistive Technologies, and Learning Style, ensuring flexibility and adaptability. By aligning learning resources with student needs, the model provides a structured framework to enhance e-learning outcomes for dyslexic learners.

These studies illustrate the growing recognition of the importance of conceptual models in the field of neurodevelopmental disorders. They highlight the complexity of these conditions and the need for frameworks that integrate various factors. However, there remains a significant gap in developing comprehensive, unified models, which points to the need for continued research and further work to build more inclusive and practical models for understanding and addressing neurodevelopmental disorders such as ADHD.

III. METHODOLOGY

This paper embarks on a journey into the methodology employed for crafting not only a robust ontology but also the consequential development of an associated conceptual model. Recognizing the symbiotic relationship between these two endeavors, we acknowledge that the path toward a comprehensive ontology necessitates a deliberate and strategic approach in conceptualization. The conceptualization process produces the conceptual model which contributes to the ontology development process by enhancing clarity through its graphical representation, making it easier to understand and utilize. Additionally, the conceptual model promotes reusability, as it can be adapted into various ontology representation languages [28]. Consequently, our methodology for conceptual model development is basically derived from and informed by the proven techniques and practices established in the realm of ontology construction.

To develop the conceptual model proposed by the current study, a hybrid methodology of the most prominent ontology construction methodologies was adopted, drawing upon the foundational principles recommended by the Ontology Development 101 method [34], the Uschold and King methodology [35] and the METHONTOLOGY [36]. Specifically, the foundational framework presented by Uschold and King will be integrated through the iterative phases of the Ontology Development 101 method, complemented by the crucial conceptualization step outlined in METHONTOLOGY. The selection of this hybrid approach is grounded in its capacity to leverage the respective merits of each methodology. The Uschold and King methodology affords a clear and systematic framework for ontology development, facilitating the establishment of an initial ontology structure. Complementarily, the Ontology Development 101 method empowers us to incorporate finer-grained details and engage in iterative stages, thereby fostering the creation of a more thorough and comprehensive ontology. Furthermore, the integration of METHONTOLOGY augments our approach by harnessing the distinct benefits offered by its conceptualization step. This encourages a deep understanding of the domain and helps ensure that the conceptual model captures the semantics accurately, thereby enriching the overall development process of the ontology. Using these methodologies, the conceptual model is constructed following a set of prescribed guidelines and procedural steps: (1) Identify the domain, scope, and purpose, (2) Capture the knowledge and conceptualization by a set of iterative steps (Enumerate important terms in the domain, Define the classes, and define the properties (object and data properties), (3) Build the conceptual model). Fig. 1 illustrates the workflow of the methodology.

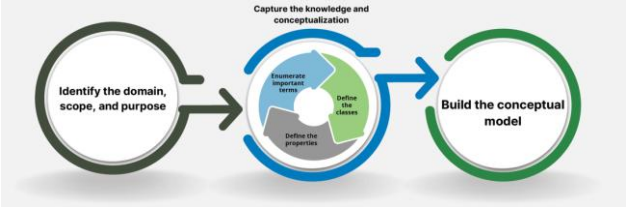

Fig. 1. The workflow of the conceptual model building methodology.

A. Identify the Domain, Scope, and Purpose

The foundational phase in constructing a robust conceptual model, and equally essential in ontology development, involves a meticulous exploration to identify the fundamental aspects that shape its essence. At the forefront of this endeavor is the imperative task of pinpointing the domain, determining the scope, and elucidating the purpose that the conceptual model aims to serve [34], [35]. This initial step serves as the compass, guiding the subsequent development process. Through a comprehensive examination of the domain's intricacies, a clear delineation of the model's boundaries, and a lucid definition of its overarching objectives, this step lays the groundwork for a conceptual model poised to effectively encapsulate and represent the targeted knowledge domain. Recognizing that this step is equally pivotal in constructing ontologies underscores its significance in fostering a seamless transition from conceptualization to formal knowledge representation. Table I illustrates the domain scope of the proposed conceptual model.

B. Capture the Knowledge and Conceptualization

1) Enumerate important terms in the domain: The starting point in Capturing the knowledge in a field is to write down a list of all relevant terms in the field. As outlined in the 101 method [34], the focus is on obtaining a comprehensive list of terms, regardless of any overlap between the concepts they represent, relations among the terms, or any properties that the concepts may possess. In the context of ADHD, essential terms include but are not limited to Symptoms, Inattention, Hyperactivity, Impulsivity, Subtypes (such as predominantly inattentive, predominantly hyperactive-impulsive, combined), Diagnostic criteria [43] (e.g., DSM-5 criteria), Treatment options (e.g., medication, behavioral therapy), Medication (e.g., stimulants, non-stimulants), Behavioral therapy, Risk factors, Genetics, Environmental factors, Comorbidities (e.g., anxiety disorders, depression), Executive dysfunction, Neurodevelopmental disorder, Neurobiology, Cognitive impairments, Academic performance ,Impairment in daily functioning. Subsequent steps in the knowledge capture process build upon this foundational list, often executed iteratively (as depicted in Fig. 1). From this list, the most significant terms are selected to represent the classes forming the conceptual model, with the remaining terms likely serving as subclasses or properties that provide detailed descriptions of these classes.

TABLE I. SCOPE, DOMAIN AND KNOWLEDGE SOURCE OF THE ADHD CONCEPTUAL MODEL

Domain	The domain of interest of this work is the ADHD domain
Date	2023 - 2024
Built By	Research student in Information Systems department at the Faculty of Computing and Information Technology – King Abdulaziz University
Purpose	• Knowledge Representation Blueprint: Acting as a blueprint, the conceptual model outlines key concepts, relationships, and entities crucial for accurate and comprehensive conceptualization and representation of the available knowledge in various aspects of ADHD. • Foundation for Ontology Construction: The conceptual model serves as the foundational framework upon which the subsequent ontology is constructed. • Defining Ontological Boundaries: By identifying the domain, scope, and purpose, the conceptual model aids in clearly defining the boundaries and parameters that subsequently shape the ontology. • Enhancing Ontological Consistency: It contributes to ensuring consistency and coherence in the ontology by presenting a conceptual framework that aligns with the nuances and intricacies of the targeted domain. • Facilitating Seamless Transition: The conceptual model facilitates a seamless transition from conceptualization to formal ontology construction, streamlining the overall knowledge modeling process.
Scope	The scope of the conceptual model is a manifestation of the domain knowledge encapsulated within the semantic model. Specifically, the ADHD domain conceptual model is finely tuned to address the intricacies of the ADHD domain. It covers aspects which include: ADHD types, symptoms, Diagnosis criteria and treatments, Comorbidities …
Source of Knowledge	• The Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, (DSM-5) [3] • The World Health Organization (WHO) Eleventh Revision of the International Classification of Diseases (ICD-11) [2] • The National Institutes of Health (NIH) [37] • The American Academy of Pediatrics (AAP) [38] • American Psychological Association (APA) [39] • Children and Adults with Attention-Deficit/Hyperactivity Disorder (CHADD) organization [40] • Centers for Disease Control and Prevention (CDC) [41] • Clinical Expert interview • The first researcher also reviewed various materials, including websites and academic papers, to gain comprehensive insights into the specified domain.

2) Define the classes: As we delve into constructing the conceptual model for the ADHD domain, a crucial initial step involves defining classes. The top-level classes of the ADHD conceptual model (illustrated in Table II) act as fundamental building blocks, representing key concepts and terms integral to the realm of ADHD. The process of defining classes not only brings clarity to our conceptual model but also lays the groundwork for developing an organized and thorough representation of ADHD, forming the basis for future ontology construction.

3) Define the properties: As outlined in study [34], properties serve as a form of association between concepts within the domain, describing relationships among individuals belonging to different classes. Typically, ontologies include ordered binary relations where one argument signifies the domain and the other represents the range. These relations are called Object properties which establish connections between individuals of the domain class and those of the range class. Object properties may possess corresponding inverse properties. For example, the properties treatedBy (s, t) and isTreatmentFor (t, s) that relate a symptom with a treatment are inverse properties. Additionally, properties may include cardinality constraints, specifying the number of relationships an individual can engage in for a given property. Table III provides an overview of the properties within the ADHD conceptual model, detailing their domain, range, inverse property (if applicable), and cardinality.

TABLE II. DESCRIPTION OF THE ADHD CONCEPTUAL MODEL MAIN CLASSES

Class	Description
Subtypes	Describes the three different subtypes of ADHD
Symptoms	A compilation of signs and symptoms endorsed by DSM-5, indicative of ADHD
Behaviors	A compilation of diverse expressions and behaviors exhibited by individuals, each representing varied manifestations falling under each specific symptom
Diagnostic Criteria	A compilation of diagnostic criteria outlined in DSM-5, officially endorsed for the identification and diagnosis of ADHD
Risk Factors	A list of genetic, environmental, and psychosocial factors that could potentially contribute to the manifestation of ADHD symptoms
comorbidities	Different common coexisting conditions or comorbidities frequently observed in individuals diagnosed with ADHD
Treatment	Different safe and effective treatments and management interventions suitable for individuals with ADHD throughout their lifespan
Patient profile	Personal medical history profile and information

TABLE III. ADHD CONCEPTUAL MODEL PROPERTIES

Property Name	Domain	Range	Cardinality	Inverse property
hasSymptoms	Subtypes	Symptoms	Multiple: a Subtype may have more than one Symptoms	hasSubtype
hasDiagnosticCriteria	Subtypes	Diagnostic Criteria	Multiple: a Subtype may have more than one Symptoms	-
hasBehviors	Symptoms	Behaviors	Multiple: a Symptom may have more than one Behaviors	hasRelatedSymptoms
hasDSM5Criteria	Symptoms	Diagnostic Criteria	Single: a Symptom relates to one DSM 5 Criteria	-
treatedBy	Symptoms	Treatment	Multiple: a Symptom may have more than one Treatments	isTreatmentFor
hasInfluenceOn	Risk Factors	Subtypes	Single: a risk factor may have an influence on the occurrence of one Subtype	influencedBy
hasInfluenceOn	Risk Factors	comorbidities	Multiple: a risk factor may have an influence on the occurrence of more than one comorbidity	-
hasSymptoms	Patient profile	Symptoms	Multiple: a patient may manifest more than one Symptoms	-
hasRiskFactors	Patient profile	Risk Factors	Multiple: a patient may have more than one Risk Factors	-

IV. ADHD CONCEPTUAL MODEL: UNVEILING THE INTERCONNECTED LANDSCAPE OF ADHD DOMAIN KNOWLEDGE

Fig. 2 illustrates the ADHD conceptual model that is meticulously crafted in an attempt to contribute to elucidate its multifaceted nature. This conceptual model serves as a guiding framework, delineating top-level classes alongside their corresponding properties and interrelationships. Each of these classes embodies a pivotal concept within the ADHD domain, encompassing a spectrum of subtypes, symptoms, behaviors, risk factors, comorbidities, treatment, and diagnostic criteria.

The relationships between these classes are not merely arbitrary connections but rather solid interconnections firmly grounded in evidence derived from reputable scientific research. Through a meticulous synthesis of findings from reliable sources, the conceptual model unveils the connections that exist between these fundamental concepts, serving as the initial blueprint for the ADHD domain knowledge ontology. As we navigate through this conceptual model, we embark on a journey toward a deeper understanding of ADHD, guided by the structured interplay of its constituent elements.

The 'Symptom' class is one of the most central concepts within the domain of ADHD, as underscored by its pervasive association with numerous concepts throughout the conceptual model. The relationship 'has_DSM5_criteria' between the symptom class and the diagnostic criteria class, elucidating the direct correlation between identified symptoms and the diagnostic standards delineated in DSM-5 [3]. This alignment with DSM-5 criteria, acknowledged as the authoritative reference for diagnostic guidelines worldwide, substantiates the reliability and validity of symptoms enumerated within the symptom class.

The 'Symptom' class further establishes a relationship with the 'Behavior' class through the designated relationship 'has_related_behaviors' and its corresponding inverse relationship 'has_related_symptoms'. While DSM-5 delineates diagnostic symptoms characteristic of ADHD, empirical evidence from numerous studies suggests that these symptoms may manifest diversely as behavioral patterns across different developmental stages—children, adolescents, and adults alike [35], [36], [37]. This interrelation serves to bridge each symptom outlined in DSM-5 with its varied behavioral manifestations across distinct age cohorts, thereby enhancing the diagnostic precision tailored to the nuanced needs of different age groups. Consequently, this alignment holds promise for refining the diagnostic process, rendering it more comprehensive and tailored to the developmental context of individuals presenting with ADHD symptoms.

Symptoms wield significant influence in subtype delineation within the disorder, thereby informing potential treatment modalities. Consequently, it is associated with the 'Subtypes' class through the relationship (has_subtype) and its inverse relationship (has_symptoms), as well as with the 'Treatments' class via another designated relationship (treated_by) and its corresponding inverse relationship (is a treatment for). This interconnection underscores the pivotal role of symptomatology not only in subtype classification but also in guiding treatment and interventions approaches. Such relational frameworks within the ontology facilitate a comprehensive understanding of the intricate interplay between symptoms, subtypes, and treatment strategies, thereby enriching the diagnostic and therapeutic landscape of ADHD management.

The relationship between the 'Risk Factors', 'Subtypes', and 'Comorbidities' classes within the ADHD ontology is illustrated in the conceptual model through relationships (has_influence_on) (a_risk_factor_for). Research, including the study by Freittag et al. [38], as well as numerous corroborating studies, have underscored the influential role of various risk factors in shaping both ADHD subtypes manifestations and comorbidities. By elucidating these relationships, the ontology contributes to the understanding of how risk factors contribute to the heterogeneity of ADHD presentation and the onset of comorbidities discussion.

In this paper, we propose a cohesive conceptual model that integrates various concepts of ADHD, including symptoms, subtypes, diagnostic criteria, treatment, risk factors, comorbidities, and patient profile. These concepts are related to each other through many relationships between them. This conceptual model aims to be the cornerstone for building an ontology of existing knowledge within the domain of ADHD.

A. Conceptual Models in the ADHD Field

The In the realm of ADHD, few works have delved into conceptualizing knowledge within a conceptual framework, while existing studies have made important contributions toward understanding various aspects of ADHD, the development of comprehensive conceptual models remains limited.

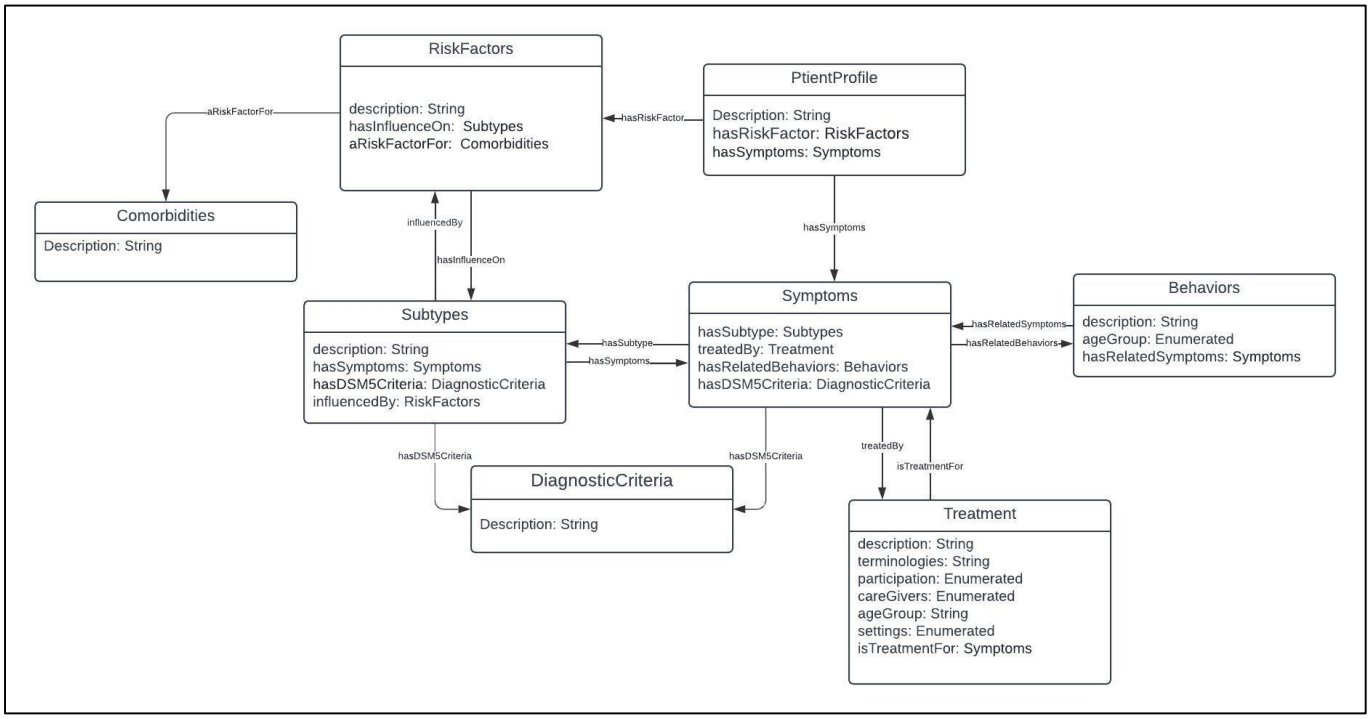

Fig. 2. ADHD conceptual model.

Such as symptoms, risk factors, or treatment pathways without integrating these elements into a unified framework. This highlights a clear need for a holistic approach that bridges these gaps, providing a more structured and interconnected representation of ADHD domain knowledge. The proposed work aims to address this gap by presenting a conceptual model that unifies these diverse components.

Unlike previous works in the field of ADHD, which focus solely on developing conceptual models, this research uniquely aims to transform a conceptual model into an ontology. Ontologies play a crucial role as a knowledge transfer layer, enabling the structured representation and integration of ADHD domain knowledge. By formalizing key concepts and relationships, an ontology serves as a foundation for building advanced systems such as decision-making systems and expert systems. These systems can enhance diagnosis, treatment planning, and research, ultimately improving outcomes for clinicians, researchers, and individuals with ADHD.

Building on the studies discussed in the "Related Work" section, the following section examines the similarities and differences between these studies and the current research, highlighting the unique contributions of this study. Rapport et al. [30] introduced a conceptual model focusing on the classification of therapeutic interventions for children with ADHD. However, given the disorder's inherent complexity and heterogeneity, such arbitrary classifications may not always prove effective. In the context of ADHD, several critical clinical considerations influence the selection of treatment strategies. These include factors such as the patient's age, the severity of ADHD symptoms [42], and the presence of comorbidities [46]. For instance, the (AAP) strongly advocates for behavioral therapy as the initial treatment approach for children aged 4-5 years, emphasizing the importance of evaluating its efficacy before considering pharmacological interventions [47]. In contrast to Rapport's model [30], the proposed ADHD conceptual model associates treatments primarily with symptoms. This association arises from the acknowledgment that there is no definitive cure for ADHD; rather, treatments focus on managing and alleviating the symptoms exhibited by individual patients [22], [48]. Additionally, it considers patient age through the "age group" property within the treatment class and addresses ADHD severity based on the number and type of symptoms exhibited by the patient.

Additionally, Brod et al. [31] introduced a conceptual model focused on assessing ADHD's impact on the quality of life among adults with the disorder. Central to their model is the interplay between ADHD symptoms and associated behaviors, including executive dysfunction. This reciprocal relationship underscores the intricate connection between symptoms and their outward manifestations, a principle mirrored in the findings of our proposed conceptual model (the relationship between Symptoms and behaviors classes). Both models highlight the complex dynamics between ADHD symptoms and their associted behaviors, emphasizing the multifaceted nature of the disorder's impact on individuals' lives. By recognizing this intricate relationship, our model aligns with Brod et al.'s [31] conceptual framework, contributing to a more comprehensive understanding of ADHD and its implications for quality of life.

B. Theoretical Implications on the Research Landscape in the ADHD Field

In advancing the theoretical conceptualization of ADHD, researchers have made significant strides through diverse studies. For instance, the review by Nigg et al. [49] underscores the importance of adopting a broader conceptualization of ADHD beyond the specific inattention and hyperactivity

symptoms. Instead, it raises the question of the possibility of inclusion of a wide spectrum of phenotypes that should be encompassed within the diagnostic framework of ADHD, such as emotion dysregulation and executive dysfunction. This perspective has been a focal point of numerous studies within the field, emphasizing the need for a comprehensive understanding of ADHD manifestations (e.g. [44]). The conceptual model presented in this paper directly addresses this imperative by integrating diverse viewpoints and establishing connections between symptoms delineated in the DSM-5 (Symptoms class) and the multifaceted array of phenotypes (Behaviors class), spanning functional and emotional dimensions.

Also, Faraone et al. [50] offers a comprehensive examination of ADHD, encompassing many of the core concepts of the disorder like diagnosis, treatment, and associated risk factors and comorbidities. Similarly, Drechsler et al. [51] delve into the current concepts, comorbidities and treatment in children and adolescents with ADHD. Additionally, Zayats & Neale [52] investigates how the genetic and neurobiological foundations [45] underpinnings on our conceptualization of ADHD, focusing specifically on two key aspects within the field: diagnosis and treatment. The present study, along with existing literature, reveals commonalities regarding fundamental concepts of ADHD, emphasizing the importance of understanding ADHD symptoms, subtypes, and their implications for diagnosis and treatment. Additionally, risk factors and comorbidities are recognized as significant contributors to the heterogeneity and complexity of ADHD presentations. Although these shared concepts provide a foundational conceptualizing of ADHD, they underscore the need for comprehensive models that can account for its multifaceted nature. While each of these works offers valuable contributions to the field, they often focus on specific aspects of ADHD in isolation. They frequently do not establish connections between different domain concepts, leading to a fragmented understanding of the disorder. The present research endeavors to bridge these conceptual gaps by proposing a comprehensive conceptual model that integrates multiple facets of ADHD. By elucidating the interconnectedness of these concepts, this research aims to provide a more holistic and cohesive framework for understanding ADHD. This fundamental difference in the theoretical implications of the present research and previous research in the field of ADHD emphasizes the importance of adopting an integrated approach to conceptualizing the disorder.

C. Practical Applications in the ADHD Field

In terms of contributing to practical applications in the field of ADHD, there are many knowledge-based systems that mainly rely on "background knowledge" as their input. For example, Göker & Tekedere [53] implemented an expert system that predicts ADHD during childhood, Silva et al. [54], Delavarian et al. [55] and Chu et al. [56] developed decision support systems with various goals serving the field. When data is collected specifically for each system individually the knowledge collected to develop these systems is exclusive to them and was not transferable to other systems, leaving future projects with no way of benefitting from what they had achieved. This means that any time a new system is created, it has to reinvent the wheel and go through the same process of collecting knowledge from scratch. Considering the complexity of ADHD domain knowledge and related sources that are of many sorts and sources, there is an increasing need for a unified knowledge base that provides easy access to information and the ability to share, transfer and reuse the knowledge. As previously mentioned, the primary objective of constructing this conceptual model is to serve as the foundational framework for the development of a comprehensive domain knowledge ontology pertaining to ADHD. It also plays a major role as a layer for transferring and reusing domain knowledge [57]. In general, the utilization of ontologies for knowledge structuring enables the creation of reusable and shareable knowledge that, once developed, can be used entirely or partially by anybody [58]. Therefore, building a conceptual model is frequently considered as the first step in formalizing and standardizing domain knowledge while building various systems.

V. CONCLUSION

In conclusion, this research has developed a comprehensive conceptual model that encapsulates the domain knowledge of ADHD, shedding light on its multifaceted nature and interrelationships between key concepts. By adopting a hybrid approach derived from established practices in ontology construction, the model effectively integrates principles from prominent methodologies. The resulting ADHD conceptual model delineates connections between various aspects of the disorder, including subtypes, symptoms, behaviors, diagnostic criteria, treatment options, risk factors, comorbidities, and patient profiles. Through its 8 top-level classes and 13 relationships, the model elucidates critical links between symptoms and treatments, symptom manifestations, risk factors and ADHD subtypes, and potential comorbidities. By bridging these domain concepts, the model contributes to a more holistic understanding of ADHD and serves as a foundational framework for constructing an ADHD domain knowledge ontology. This research thus plays a pivotal role in advancing knowledge within the field of ADHD and offers valuable insights for researchers, clinicians, and policymakers navigating the multidisciplinary landscape of ADHD research and practice.

Despite its contributions, this study has limitations that present opportunities for future research. While the model captures a broad range of ADHD-related concepts, it does not delve deeply into the genetic underpinnings or specific neurobiological mechanisms of the disorder, which are increasingly recognized as critical to understanding ADHD's etiology. Similarly, cultural and contextual variations in the manifestation, diagnosis, and treatment of ADHD remain underexplored, leaving gaps in how the disorder is understood and addressed across diverse populations. The model also relies predominantly on existing literature and expert consensus, potentially overlooking emerging research and patient perspectives, particularly those from underrepresented demographic groups.

Future work should address these limitations by incorporating real-world data, such as longitudinal studies and patient-reported outcomes, to validate and expand the model's applicability. Efforts to integrate genetic and neurobiological insights could enrich the conceptual framework, providing a

more comprehensive understanding of ADHD's mechanisms. Additionally, capturing cultural and contextual variations could make the model more globally relevant and inclusive. Expanding the scope to include emerging research trends and interdisciplinary perspectives will further enhance the model's utility in research and clinical practice.

The most critical next step is to use the resulting conceptual model as the foundation for constructing a comprehensive ontology for ADHD. This ontology would formalize the domain knowledge, enabling standardized representation, enhanced interoperability across systems, and the development of tools for diagnosis, treatment planning, and research. By advancing from conceptual modeling to ontology development, this work can catalyze significant progress in understanding and addressing ADHD, ultimately improving outcomes for individuals affected by this complex disorder.

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