Open Journal of Civil Engineering, 2022, 12, 492-523
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

Integrating Universal Design Standards and Building Information Modeling at the Conceptual Design Stage of Buildings

Vafa Rostamiasl, Ahmad Jrade

Department of Civil Engineering, University of Ottawa, Ottawa, ON, Canada
Email: vrost064@uottawa.ca, ajrade@uottawa.ca

How to cite this paper: Rostamiasl, V. and Jrade, A. (2022) Integrating Universal Design Standards and Building Information Modeling at the Conceptual Design Stage of Buildings *Open Journal of Civil Engineering*, **12**, 492-523.
https://doi.org/10.4236/ojce.2022.124028

Received: October 15, 2022
Accepted: December 24, 2022
Published: December 27, 2022

Abstract

A projection of the Canadian population shows that in 2024 one in five Canadians will be over 65 years old. This shift forces designers to consider the entire lifetime of occupants during the design of new buildings. Universal Design (UD), which is a design that accommodates all people to the greatest extent possible and aging in place design that is deeply rooted in the principles of UD, aim to house people irrespective of their age, ability, and chronic health conditions. Building Information Modeling (BIM) significantly helps advance the development of the Architecture, Engineering, and Construction (AEC) industry in a more collaborative and automated way. Integrating BIM and UD allows designers to incorporate UD standards easily and efficiently at the conceptual design stage of buildings by using the functionalities and capabilities of BIM tools. Therefore, this study presents the development of an automated computer model to facilitate the adoption of UD standards and processes. The novelty highlighted in this model resides in the creation of an automated method that employs a newly created plug-in and databases to assist designers to incorporate UD standards at the conceptual stage in a timely and cost-effective manner. Furthermore, the study introduces the methodology consisting of collecting, categorizing, and storing data from various universal design and accessible design guidelines in the developed databases and developing new plug-ins in BIM tool to link the developed databases in order to automate the process of retrieving necessary information and components to help designers and owners select optimal design alternatives based on their predefined criteria.

Keywords

Building Information Modeling (BIM), Universal Design, Accessible Design, Aging in Place, Computer Integration and Automation

1. Introduction

In 2015, Statistics Canada revealed that 16.9% of Canadians were aged 65 years or older, out of which 2.2% were aged 85 years or older, which represented a 20.0% increase in the age of that group since 2011. Thereafter, a projection of the Canadian population showed that the number of persons aged 65 years and older will continue to increase to reach 20.1% of the whole population in 2024 [1]. Generally, aging relates to increased chronic health issues and functional disabilities. A recent report by Globe Newswire [2] uncovered trends related to aging and its impact on seniors' housing aspirations, expectations, and realities across Canada. The report showed that 86% of Canadian seniors want to live in their homes for as long as possible rather than go to long-term care facilities. On the other hand, in 2021, the Government of Ontario [3] reported that between April 2020 and April 2021, the number of Canadian seniors who died due to Covid-19 in Ontario's long-term care facilities reached 3785 cases (3772 residents and 13 staff). As a result, adopting the concept of aging in place becomes of top priority and high importance. Therefore, more design strategies should be considered to overcome the issue of aging in place [4]. Universal Design philosophy is inspired by the social responsibility of using the built environment with no distinction. This philosophy led to a systematic development of the design guidelines for architectural and urban projects to render the accessibility of the built environment to all [5]. It aims to simplify the life of people regardless of their age, size, or ability to achieve an inclusive society where every person has equal opportunities to participate, whether young, senior, disabled, or non-disabled [6]. Thus, the term accessibility, which is one of the critical factors for aging in place, is used for that purpose. Andersson [7] stated that architecture and gerontology are two fields of research that closely need to be explored to be prepared for senior citizens in an aging society. Design for aging aims to accommodate the rapid increase in the senior population and to promote innovative design solutions to create desired physical and service environments facilitating a sustainable aging process [8]. An age-friendly design needs to be accessible for older people with varying needs and abilities to promote their physical activities and to reduce the risk of many health and medical problems of particular concern to elderly Canadians [9]. There is growing evidence that physical activity prevents or delays cognitive impairment and improves sleep [10]. "Aging in place means having access to health services and social supports for elderlies who need to live safely and independently in their homes or their community for as long as they wish and are able" [11]. To enable aging-in-place, environmental barriers must be removed, including indoor physical modifications and accommodations to enhance the accessibility and usability of the home environment, increase safety, and reduce difficulties in activities' performance [12]. Physical modifications involve installing ramps in staircases and safety bars in bathrooms, making premises more accessible and useable [13]. Liu and Lapane [14] stated that environmental modifications in a residential building, such as street-level entrance, railings, automatic doors, bathroom and kitchen modifications and elevator or lift, could potentially influence an individual's ability to perform basic tasks necessary for daily functioning. Building Information Modeling (BIM) is a concept used in the AEC industry all over the lifecycle of a project, from design and documentation passing through the construction stage to operation [15]. BIM has significant benefits related to the rich project information, geometry, materials properties, and the building process through the project's life cycle [16]. The increased use of BIM in the construction industry provides a unique opportunity for integrating Universal Design principles into buildings' model as a fundamental strength of the interoperability of BIM tools to other programs. Coupling BIM and UD have the potential to produce high-performance and universally designed facilities. Applying UD guidelines to the built environment at the early design stage would facilitate the creation of homes based on owners' needs. It would be adequate throughout their lifespan despite the changes in their circumstances or abilities [17]. While existing studies such as [17] and [18] proposed models to incorporate universal design standards at the conceptual design stage, these studies are limited to creating design families and integrating them into BIM tools based only on the National Building Codes of Canada. The authors were not able to find literature about an integrated/automated model that has the capability of combining various standards and guidelines in a single model that couples universal design and accessible design standards with Building Information Modeling to help designers apply them at the conceptual design stage. This study adequately incorporates various universal design and accessible design standards and guidelines to enhance the design for aging in place and help designers have instant access to such type of data as well as newly created design families that are compatible with those standards and guidelines through an automated model. This paper presents the development of an automated model that integrates Building Information Modeling with Universal Design (UD) and Accessible Design (AD) standards at the conceptual design stage of proposed buildings. The said integration will systematically incorporate Universal Design Standards into BIM environment by developing a database that stores those standards and links it to BIM tools. The database stores newly created and modified families of architectural components that comply with the different Universal Design (UD) and Accessible Design (AD) guidelines. That database is integrated with BIM tool by using the tool's API and by creating an innovative plug-in, which is developed for that purpose. This integration would facilitate the process of retrieving universal design families while producing the design of new buildings under UD/AD standards. Therefore, the main objective of this study is to develop an automated computer model that integrates BIM and UD/AD standards to help designers incorporate those standards into the design of buildings at the conceptual stage to accommodate Canadians despite of their age and health conditions and to help inhabitants age in place; hence when aged, they will not be forced to move out to long-term care facilities. The proposed model will provide designers with instant access to information related to the desired standards and guidelines, and it will automatically check the associated design elements to find the ones that do not comply with the selected guidelines.

2. Literature Review

2.1. Universal Design and Accessible Design

Universal Design (UD) hypothesis is to design products or environments that can be used by people of different ages and abilities without adaptation. This theory is widely growing, and it has been expanded towards the scope of inclusive design, which extends the definition of UD by counting inhabitants who have been excluded by the rapid change of technology, particularly the aging population [19]. The main objective of UD is to provide inclusivity and prohibit exclusivity [20]. The term universal design was first defined by the US in 1985 as a design approach that incorporates products and building features to the greatest extent possible that everyone can use [21]. Globally, different terminologies have been used to guide to the terms of UD, such as Universal Access (Universally Accessible), Accessible Design, Adaptable Design, Barrier-Free Design, Design for All, Inclusive Design, User Sensitive Inclusive Design, Cooperative Design and User-Oriented Design. Some of those terms imply different ideas, while others have the same meaning [6]. Iwarsson and Ståhl [21] described accessibility as a term for all parameters that influence human's functioning in the living environment. The accessible environment must match the abilities of a single individual or a group of individuals. They describe usability as a measure of the effectiveness, efficiency, and satisfaction with which specified users can achieve established goals in a particular environment. Accessibility and usability concepts group people into abled and disabled individuals, which result in segregation, but universal design considers the whole population as one single group of individuals that represents diverse characteristics and abilities [21]. Design for all is another term more frequently used in Europe and is defined as the design for human diversity, social inclusion, and equality [22].

Persson *et al.* [23] stated that the most cited explanations of the universal design concept consist of the following seven principles: Equitable Use; Flexibility in Use; Simple and Intuitive Use; Perceptible Information; Tolerance for Error; Low Physical Effort; and Size and Space for Approach and Use, which provide a framework for designers to foresee the benefits of the design for all users with or without disabilities. Carr *et al.* [24] provided examples to better conceive those principles. For instance, automatic sliding doors at the entrance of a public building meet at least 6 of those principles. They provide equal access for individuals with diverse abilities and needs (Principles 1 and 2). They are straightforward and intuitive to use (Principle 3). Since they are using sensors to detect the presence of a person within a range, they require no physical effort to operate (Principle 6). These sensors also ensure that the sliding door will remain open for as long as the person stays within the sensor's range, which minimizes the risk of injury (Principle 5). Finally, automatic sliding doors usually are more expansive than typical swinging doors, making them easier to maneuver through the doorway for people using ambulatory aids such as canes, walkers, scooters, wheelchairs, crutches, etc. (Principle 7).

2.2. Building Codes

Building code provides the mandatory minimum technical specifications for the built environment, while the given comments and suggestions are to have a higher standard for designers [25]. Improving accessibility is attained through the enactment of new legislation and the development of new policies or modifying the existing standards and policies [26]. Accessibility standards have been in place for many years in Canada; they intend to create equitable, barrier-free access to communities, workplaces, and services for people with disabilities. Nationally, few provinces and cities have either adopted the national standards or implemented their own standards. The province of Ontario was one of the first jurisdictions in the world to enact the Accessibility for Ontarians with Disabilities Act (AODA) in 2005, which sets specific enforceable goals for accessibility while Manitoba and Nova Scotia were next in 2013 and 2017, respectively. The proposed Accessibility Act in British Columbia (B.C.) is currently under review after its first reading was completed in 2019, as illustrated in **Figure 1** [26]. However, the authors noticed that the accessibility legislation has just been passed by B.C.'s government. In recent times, the Accessible Canada Act (ACA) passed through legislation to create communities, workplaces, and services that enable all persons, including persons with disabilities, to fully participate in society without barriers. The different legislations forced many cities and provinces to adopt the accessibility standards; however, that adaptation varies from one province to another and from one city to another [26]. The National Building Code of Canada (NBCC) was introducing the accessibility requirements since 1965 when accessibility was mentioned for the first time as a Supplement to the National Building Code entitled "Building Standards for the Handicapped" [18]. Provincial and territorial governments have the authority to pass legislation that regulates buildings' design and construction within their jurisdictions. That legislation may adopt the National Building Code (NBC) without any changes or with some necessary modifications to make it suits the local needs [27]. Many Canadian provinces and cities provide guidelines for accessibility requirements and guidelines based on the National Building Code of Canada, either as it is published or after modifying it based on their business needs.

The Canadian Human Rights Commission [25] published a study entitled "International Best Practices in Universal Design," in which they claimed that

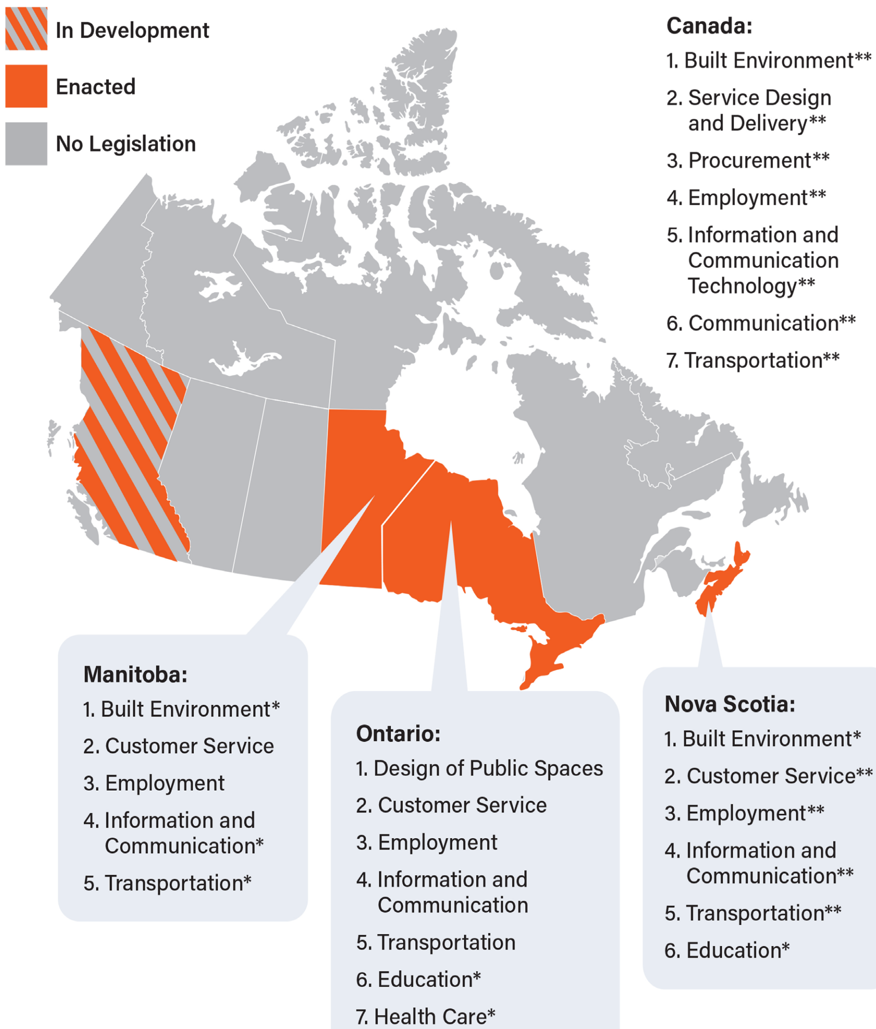

Figure 1. Provinces with accessibility legislation [26].

only half of the countries around the world have developed and included accessibility criteria in their building codes and standards. Some countries have well-developed technical specifications, while others are still working on including accessibility criteria in their building codes. The study compared the Canadian B651-M95 Barrier-Free Design Standard and the National Building Code of Canada with other codes and standards used in different countries around the world, such as the UK, US, Japan, Australia, Nordic countries, and Fiji, to determine the optimum practices based on UD principles by providing and comparing accessibility codes and standards for different design elements in a tabulated format and then to determine the best practice for the selected elements. The result of the study described UD's best practice as being the affordable building practices and procedures that comply with UD principles and that meet the needs of the broadest range of people [25]. Nwadike & Wilkinson [28] listed several challenges when using building codes and standards, such as: Poor understanding of building code compliance documents; Lack of qualified technical staff on the part of the building codes; and inadequate training for code users. Soliman-Junior *et al.* [29] believe that regulatory requirements might be subjective because they rely on designers' interpretation and creativity. On the other hand, with the demographic shifts and growth in the aging population, expectations for using universal design standards and accessibility design standards have increased significantly in recent years. Moreover, the COVID-19 pandemic has accelerated the need to provide inclusively designed homes for all. Therefore, several researchers, such as Soliman-Junior *et al.* [29], recommend automation to help designers access and use the standards and codes and to provide them with the necessary information whenever it is needed.

2.3. Building Information Modeling

Building Information Modelling (BIM) is defined as the process of generating, storing, managing, exchanging, and sharing building information in an interoperable and reusable way. It represents the process of developing and using a computer-generated model to simulate the planning, design, construction, and operation of a facility [30]. Ding *et al.* [31] defined BIM as a digital representation of a facility's physical and functional characteristics. It is a shared source of knowledge and information about a facility forming a reliable basis for decisions during its lifecycle, from earliest conception to demolition. Wu *et al.* [32] described BIM as a novel approach in the AEC industry that is implemented in a data center, which integrates geometric and functional information during the lifecycle of a building that is presented in a visualized 3D model. BIM supports solid spatial cognition by revealing most design issues early during the design stage. Antwi-Afari *et al.* [33] considered that BIM has received considerable attention from academia and industry because of its latent potential and capability to achieve performance improvement in the architecture, engineering, construction, and owner-operated (AECO) sector. It is a dynamic, rapidly changing and expanding system that can revolutionize the construction industry. Automation in the modeling process, improving the accuracy of construction documents, enhancing the communication among parties during the design and reducing the field coordination problems are the most critical factors that lead to BIM adoption in a project [34]. Abanda *et al.* [35] emphasized that the common feature in all the provided definitions of BIM is its process, which is facilitated and driven by people through its tools that consists of the three following dimensions that need to be incorporated when adopting BIM approach: process; technology; and people. Zhang *et al.* [36] stated that by rapidly increasing the elderly population, housing issues are the main barrier to implementing aging in place strategy and encouraging people to age in their residences. Although many studies have contributed to age-friendly cities and communities, few studies had the focus on measuring age-friendly housing. Numerous data are required to assess the age-friendly housing and to offer enough tangible actions or recommendations for planners and policymakers. Digital techniques such as BIM tools are utilized to facilitate the data collection and to accelerate the assessment in actual projects. BIM techniques are widely applied in different types of assessment for housing. Even though age-friendly housing is complicated, and its evaluation is a time-consuming process, utilizing BIM would significantly optimize the traditional assessment flow by integrating multi-sources of data. Integrating Universal Design (UD) with Building Information Modeling is an efficient way to monitor the compliance of buildings' design with the UD guidelines. BIM model is a virtual representation of the facility's physical and functional characteristics in a digital format, which provides detailed and reliable information for decisions during the facility's life cycle. BIM has the potential to share a platform API that provides users with a chance to integrate external applications [37]. Therefore, accessibility requirements can be integrated into BIM during the design of a project at the conceptual stage and thereafter during the construction phase. Coupling BIM and UD has the capability to produce high-performance and universally designed facilities.

2.4. Overview of the Existing Studies

Although there are substantial studies that used BIM during the various phases of a project, but limited research work was conducted about the integration of BIM and UD. Jrade and Valdez [18] described the methodology used to develop and implement a model that incorporates a database management system, which stores detailed information about architectural components and elements that are used to execute universal design based on the inhabitant's requirements and needs. They created a database storing newly developed design families based on the National Building Codes of Canada, and they linked it to BIM tool (Autodesk Revit©) at the conceptual design stage. Jrade and Jalaei [17] presented a methodology to develop and implement an integrated model that links BIM with energy analysis and LCA tools to execute sustainable universal design at the conceptual stage for Canadian houses. Their model evaluates and compares the life cycle cost and benefits of conventional and sustainable universal houses.

However, one of the limitations of the above-mentioned studies is in creating UD families based only on the National Building Code of Canada (NBCC) and then incorporating them into the design, while the described model in this paper provides the designers with the option to have full access to various universal design and accessible design standards and guidelines including the NBCC also in addition to multiple guidelines and standards collected from other countries in an attempt to increase the efficiency and variety of the information needed for the design of universal buildings regardless of their locations. Furthermore, the model has the ability to automatically check the design elements and compare them with the selected standard or guideline to make sure they meet their requirements. Several studies implemented in the past by Cheng J. and Das M. [38]; Choi J. and KIM I. [39]; Kincelova, *et al.* [40]; Patlakas *et al.* [41]; Narayanswamy *et al.* [42]; Häußler *et al.* [43]; Khattra *et al.* [44] focused on integrating BIM and building codes or standards in different areas such as architecture, structures or green buildings. However, their emphasis was mainly on automating building code compliance checking within a BIM environment by using different ways and methods, such as IFC or gbXML file format, Dynamo visual programming, C# programming and BIM tool Application programming interface (API), MATLAB computing environment and rule-based checking engines or commercial software such as Solibri Model Checker (SMC). However, the current study is not limited to building code compliance checking. Yet, it uses various standards and guidelines related to both universal design and accessible design and integrates them into BIM tool by using its API and C# programming. One of the functions of the proposed model is its capacity to check and compare the design items with the various sources simultaneously, mainly in the form of the design items' dimensions. Another innovation of the presented model is its ability to help designers retrieve detailed information concerning the selected design elements in the form of dimensions, colour, and texture in addition to other descriptive information and to access the original associated documents of the selected standard instantly while doing the design. Alsayyar and Jrade [4] proposed a methodology to integrate BIM with Sustainable Universal Design (SUD) principles and requirements through a Visual Basic interface (VB.NET) to evaluate the benefits and costs of adopting such type of design for buildings over their anticipated life. Türkyılmaz E. [45] stated that accessible design is critical to the social integration of disabled people by improving their quality of life. Design's decisions that comply with the inhabitants' needs can create a more compatible and high-quality living space. Furthermore, they stated that conventional methods of design are currently used, while their results are not compatible with the accessibility regulations. BIM is an excellent option to control and evaluate the accessibility criteria. Therefore, they proposed a BIM-based analyzing method that integrates BIM tool with a model checker software to compare the designed model with a set of accessibility rules, which were generated from the Turkish accessibility standards to analyze the living spaces based on the standards, then to generate a report to show whether the design is compatible with the standards or not and to list the incompatible items.

Thus, this paper describes the design and development of an automated model that integrates BIM and Universal Design standards and accessibility guidelines through an extensive database, which is linked to BIM tool. The model would help owners and designers do the design of universal and accessible buildings at the conceptual stage. Guidelines from several Canadian provinces and major cities were collected, evaluated, and stored in a database developed for that purpose and linked to the model to help designers incorporate universal/accessible design standards while doing the design of buildings regardless of their location in an easy and efficient way. In addition, different related guidelines from other countries, such as the United States, were collected and stored in that database to increase the efficiency and variety of the data for designing universal buildings that are outside Canada. It is worth mentioning that only publicly available documents, including accessibility legislation, standards, or guidelines, were included in this study. This process is fully automated and achieved via a newly developed plug-in by using and modifying the API's of BIM tool.

3. Development Methodology

The development of the integrated model requires an instant and automatic access to the necessary data in the form of design families to simplify the creation of facilities that comply with the universal design standards and to help designers and owners select an optimal design based on their defined criteria. Generally, a computer model should meet three requirements known as flexibility, transparency, and functionality in order to help designers incorporate universal design standards and guidelines while creating the design of homes to accommodate inhabitants so they would age in them. The functionality requirement is to help designers have quick access to all the data and design families that are compatible with the different universal design and accessible design standards and guidelines. Whereas the transparency requirement is to aid designers identify and understand the reliability, suitability and relationships between the data used in the model. Where flexibility is to have the model easily manageable during its implementation, operation, and maintenance by enabling designers to add and modify the stored data in a user-friendly way, in addition to automation, which gives designers instant access to the data and the newly created design families in a computerized way. Moreover, the model meets the automation requirements by having the capability to automatically check and compare the design elements based on the selected standards or guidelines to ensure they comply with their requirements. To achieve the main objective of this study, which is the development of an automated computer model to facilitate the adoption of universal design and accessible design standards and guidelines at the conceptual design stage of building projects, the required data and information for the proposed integrated model were collected from different sources, such as the literature, published standards and guidelines, and governmental agencies. The integration process flow, as shown in **Figure 2**, consists of three phases in order to achieve the integration of UD, AD and BIM: A Knowledge and family Database development phase; A Data interaction environment phase; and A BIM 3D model design phase. The first phase consists of developing two databases, the first is a knowledge database and the second is a design families database to store the newly created design families and the collected information and data, which are related to universal design and accessible design guidelines in an attempt to simplify the process of designing universal and accessible buildings at the conceptual stage. The second phase focuses on developing new plug-ins to be inherited into BIM tool (*i.e.*, Autodesk Revit©) by using the tool's API. The plug-ins will be used to link the developed databases in phase

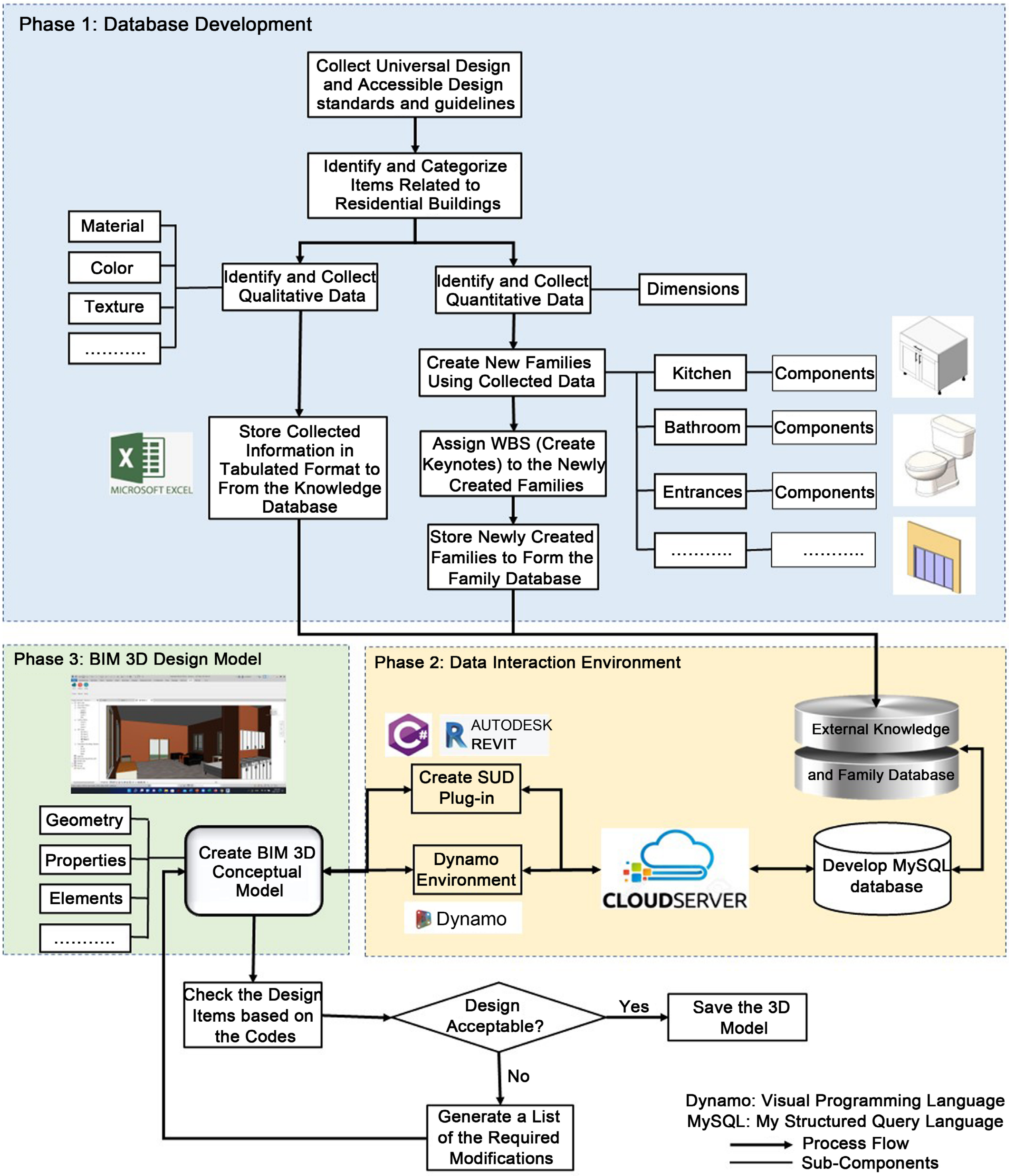

Figure 2. BIM-UD integration process flow.

1 with BIM tool to facilitate the selection of new design families and the retrieval of the associated data and information. This integration will systematically incorporate Universal Design Standards into BIM environment at the conceptual design stage. It will facilitate the process of retrieving universal families of archi-

tectural components by incorporating the UD standards into the design. The third phase focuses on designing and creating a 3D BIM design model by using the databases and newly created plug-ins developed in phases 1 and 2, respectively. The design is based on pre-defined criteria set by owners to incorporate UD standards to achieve the best practical scenario to meet inhabitants' requirements and expectations.

Phase 1: Database Development

This phase consists of developing two major databases: a standard database, and a design families database. To accomplish the standard database, data from universal design and accessible design guidelines are collected and stored in it and categorized into four different levels. The first is at the national level, such as the National Building Code of Canada (NBCC) and CAN/CSA B-651-18 Accessible design for the built environment. The second is at the provincial/territorial level, such as Barrier-Free Design Guide, Alberta, and Building Design Guide-Barrier-Free Design, Government of Saskatchewan. The third is at the municipal level, such as Accessibility Design Standards, City of Ottawa and Facility Accessibility Design Standards, City of Mississauga, while the fourth is at the international level, such as American National Standards Institute (ANSI). However, in this database, the collected data is divided into quantitative data and qualitative data. The qualitative data consists of all the descriptive information related to the objects and components used in the 3D model, such as components' colour, texture, type, and associated materials. In contrast, the quantitative data comprises numerical information, mainly in the form of dimensions extracted from the guidelines. Data is stored in a series of tables forming the Knowledge Database that holds over seventeen guidelines collected from various sources, as displayed in Table 1. Unique abbreviations are created to identify the guidelines in an effort to simplify recalling and storing them, as shown in Table 1. Some guidelines have their own abbreviation, such as NBCC, CMHC and ANSI. The Families Database is formed to store newly created and/or modified design families, which are already inherited in BIM tool (*i.e.*, Autodesk Revit©) based on the stored information and data in the knowledge database. Those design families have either the Revit Families (RFA) or the Revit projects (RVT) file formats and are stored in the corresponding database.

The data and information used in this study are collected, grouped, and stored based on two sets the Residential dwellings Data and Families (Indoor Items), as shown in Table 2, and the Public Area Data and Families (Outdoor Items), as represented in Table 3. Those tables clearly state the type of data related to any item stored in the knowledge database or the design families' database by placing an asterisk (*) beside the item. All the stated guidelines were examined and evaluated in order to collect all the relevant data. The evaluation showed that some indoor or outdoor items were not covered in all the guidelines; therefore, all the data covered by each specific guideline are listed in Table 4 and Table 5. Under the guideline's name, an asterisk (*) is inserted, which indicates that the item is

Table 1. Various guidelines stored in the standard database.

Level	Standards Database	
	Accessible Design Guidelines	**Universal Design Guidelines**
Level 1: national level	National Building Code of Canada (NBCC) CAN/CSA B-651-18 Accessible design for the built environment (CAN/CSA)	Canada Mortgage and Housing Corporation (CMHC)
Level 2: provincial/ territorial level	Barrier-Free Design Guide Alberta (BFDGA) Barrier-Free Design Guideline, Yukon (BFDGY) Barrier-Free Design Saskatchewan (BFDS)	
Level 3: municipal level	Accessible Design Guideline, City of Toronto (ADGT) Facility Accessibility Design Standards, City of Mississauga (FADSM) Ottawa Accessibility Design Standards (OADS) Facility Accessibility Design Standards, London, Canada (FADSL) Barrier-Free Design Guideline, City of Hamilton (BFDGH)	Universal Design Handbook, Calgary (UDHC)
Level 4: International level	American National Standards Institute (ANSI) Fair Housing Act Design Manual, USA (FHADM) Uniform Federal Accessibility Standards (USA) (UFAS)	The Centre for Excellence in Universal Design, Ireland NDA (CNUD) Universal Design by Selwyn Goldsmith (UDSG)

fully covered by the guideline, while "N/A" implies that the item is not covered, and "limited" means that the item is partially covered, and its associated data or information is limited. The significant contribution of the developed database residents in enhancing the functionality and capability of BIM tools at the conceptual design stage to help designers incorporate Universal Design standards and Accessible Design guidelines easily while designing proposed buildings. The aim of developing a separate database of families is to load them every time BIM tool (*i.e.*, Autodesk Revit©) opens and to access them via the newly created plug-in. This makes the created families instantly accessible when they are needed during the design process. The developed databases in this phase can be easily updated whenever new or modified versions of the standards and guidelines are released. These accurate standards and guidelines are published by the federal or provincial governments, who are trustful sources. However, the version and the year of publication are indicated in the original documents, which are instantly accessible by the designers through the model. While currently updating those documents is done manually, the authors are working on making that update automatic.

Phase 2: Data Interaction Environment

This phase focuses on developing new plug-ins in BIM's tool (*i.e.*, Autodesk Revit©) by using its API and C# programming language to link the developed databases in phase 1 to it in order to facilitate the selection of new design families and the retrieval of their associated data and information while creating 3D

Table 2. Residential dwellings data and families (indoor items).

Indoor Item	Subset	Knowledge Database	Family Database
Kitchen	Kitchen Size, Layout (Flexibility…), Minimal Effort (Low Physical Effort), Adaptability, Ease of Cleaning (Finishing material, …), Safety, Ease of Use, Furniture Size	*	
	Elements and Furniture (Counters, Cupboards, Drawers and Pantries, Sink, Oven, Microwaves, Refrigerators and Freezers, Highlights in furniture design (Equitable Use, Flexibility in Use, Simple and Intuitive, Perceptible Information, …)		*
Bathroom	Size, Layout, Framing, Adaptability, Ease of Cleaning (interior Finishes), Safety (Finishing and Grab bars)	*	
	Sanitary Facilities (Water Closets, Showers, Bathtubs, Toilets, Showers, Toilets, Vanities, Lavatories) Elements and Furniture (Drawers and Storage, Grab Bars, Lighting, Switches and Controls, Towel Dryers), Doors (Size, Opening Side, Lock System, Threshold Height…)		*
Restroom (WC)	Standard Size, Layout (Doorway, …)	*	
	Sanitary Facilities (Water Closets, Grab Bars, Lavatories, Automatic Flush Controls), Washroom amenities (hand dryers, paper towel dispensers, soap dispensers, waste bins, mirrors, changing stations and tables), Door (Size, Opening Side, Lock System, Threshold Height, …)		*
Bedroom	Standard Size, Layout (Doorway, Closet, and …)	*	
	Furniture (Bed, Closet), Door Size and Location, Window (Easy to Operate, …)		*
Living Room	Size, Layout, Framing, Adaptability	*	
	Furniture, Door (Size and Location, lock System, Opening Side, Doorway), Window (Easy to Operate)		*
Elevator	Elevator Cabin Size, Elevator Door (Location and Type), button and Signage Requirements, Visible and Audible Indicator	*	
	Door, Cabin, Keypad (button and Signage)		*
Parking	Design and Layout (Safe & Clear Path of Travel, Close to Mail Entrance), Parking Location and distance to the elevator and exit Route & Size, Signage and Pavement Markings, Flooring Materials	*	
	Signs (International Symbols), Lighting, …		*
Stair	Ground and Floor Surfaces, Guards and Handrails, Tactile Walking Surface Indicators, Design Features, Treads and Risers, Nosing	*	
	Attachments (handrail & barrier), Nosing and Risers Type, …		*
Ramp	Ground and Floor Surfaces, Guards and Handrails, Tactile Walking Surface Indicators, Lighting, Running Slope, Cross-Slope, Edge Protection, Clear width, Landing size	*	
	Attachment (handrail & barrier)		*

Continued

Entrance Area	Size & Layout (Free Path of Travel, Suitable for Wheelchair traffic), Clear of Wind and Snow Proper Drainage, Floor and wall finishing Materials (Door Mats), Control System	*	
	Door, Control System Device		*
Door & Gate	Size and Dimension (Opening Side, Lock System, Threshold Height…), Layout (Path and Doorway…)	*	
	Doors, Attachments (lock System& Right or Left Opening, Handel, Fastening Device)		*
Window	Size and Dimension	*	
	windows, Attachments (lock System & Opening System, Easy to Operate)		*
Guards and Barrier	Size (Height, Railing or Solid Type, …)	*	
	Railing or Solid Type Model		*
Turnstile, Gate Area	Size, Layout, Wall and Floor material (Technical Information)	*	
	Attachments (handrail & barrier)		*
Grills & Gratings	material (Technical Information)	*	
	Opening Size Limit, Installation Details		*
floor	material (Technical Information)	*	
	Finishes, Grating & cover, Installation Details		*
Wall	material (Technical Information)	*	
	Opening, Attachments (sign, lighting, …)		*
Ceiling	material (Technical Information)	*	
	Installation Details, Attachments (detector, sprinkler, lighting, …)		*

design models of proposed buildings. Autodesk provides powerful APIs (Application Programming Interface) and SDKs (Software Development Kits) that allow users to customize and alter the used tool based on their needs. At first, designers need to access the various universal design standards and associated families by using the created plug-in before starting the design process. Then after, they can view, download, share and print the associated documents of the selected standards easily and instantly. Microsoft Excel© and MySQL© are used to create the knowledge database, while C# and Dynamo visual programming are used to automate the process of transferring the data. The variation of the relational database servers depends on how the information is stored and how users can access that information concurrently. In general, databases are either remote databases, such as Structured Query Language (SQL) that reside on separate machine/machines or local databases, such as MS Access, that reside on a local drive or network. Local databases are tied to a fixed location, such as a device or a local network. In contrast, remote databases and cloud servers are available and accessible via the internet by any PC or mobile device from any location.

Table 3. Public area data and families (outdoor items).

Outdoor Item	Subset	Knowledge Database	Family Database
Exterior Path, Access & Free Path of Travel	Width of Exterior Walks-Doorway Clear Width Exit Device-Clear Space at Sides of Doors-Threshold Height (Dimension & Size)	*	
	Attachments (handrail & barrier, Access control)		*
Passenger Loading Zone	Design and Layout, Relationship to Accessible Routes, Tactile Walking Surface Indicators (Floor Surface), Sign Location, Curb Ramps and Depressed Curbs, Lighting, Dimension & Size	*	
Parking	Design and Layout, Parking Location and distance to elevator and exit Route, Dimension & Size, Signage and Pavement Markings, Additional Considerations-On-Street Parking	*	
Ramp	Ground and Floor Surfaces, Guards and Handrails, Tactile Walking Surface Indicators, Lighting, Running Slope, Cross-Slope, Edge Protection, Clear width, Landing size	*	
	Handrails and Guards		*
Stairs	Ground and Floor Surfaces, Guards and Handrails, Tactile Walking Surface Indicators, Design Features, Treads and Risers, Nosing	*	
	Handrails and Railing		*
Elevator & Lift	Elevator Cabin Size, Elevator Door Requirements, Lift Platform Size, button and Signage Requirements	*	
	Door, Cabin, button, and Signage		*
Water Closet Stalls (WC)	Design and Layout, Door and Furniture Requirements (Threshold Height, Door Pull Location and Detail, Grab Bars, …)	*	
	Furniture and Door		*
Rest Area	Ground and Floor Surfaces, Seating, Tables and Work Surfaces, Lighting, Design, and Placement, clear floor space	*	
	Furniture		*
Public Transit Area	Design and Layout, Signage and Wayfinding, Controls and Operating Mechanisms, Ground and Floor Surfaces, Tactile Walking Surface Indicators, Elevating Devices…	*	
	Elevating Devices, Shelters, Street Furniture, and Equipment		*
Inclusive Play Area	Key Design Considerations, Entry and Exit Points, Accessible Routes, Play space Ground Surface (Material)	*	
	Elevated Play Components and other Furniture		*
Refuge Area	Design and Layout, Accessibility, emergency electrical power and Lighting, fire safety, identify and designated signage	*	
	Signage, Lighting, …		*
Public Space Furniture	Service and Payment Counter, Signage and Wayfinding, Lighting, Benches and Seats, Public Telephones, Waterspout…		*

Table 4. Covered items in different guidelines (indoor items).

Indoor Item	Qualitative Data	Quantitative Data	CMHC	UDHC	UDSG	UFAS	OADS	BFDS	FHADM	FADSL	BFDGH	FADSM	ADGT	CNUD
Kitchen	*		*	limited	N/A	N/A	*	N/A	*	limited	limited	limited	limited	*
		*	*	limited	limited	limited	*	N/A	*	*	limited	*	limited	*
Bathroom	*		*	N/A	*	N/A	limited	limited	*	limited	*	*	limited	*
		*	*	N/A	limited	*	limited	limited	*	*	limited	*	limited	*
Restroom (WC)	*		*	limited	*	*	*	*	*	limited	*	*	limited	*
		*	*	limited	*	*	*	*	*	*	*	*	limited	*
Bedroom	*		limited	limited	limited	N/A	N/A	N/A	N/A	N/A	limited	N/A	limited	N/A
		*	N/A	limited	limited	N/A	N/A	N/A	N/A	N/A	limited	N/A	limited	N/A
Living Room	*		limited	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		*	N/A	N/A	limited	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Elevator	*		N/A	N/A	*	*	*	N/A	N/A	*	*	*	*	*
		*	N/A	N/A	*	*	*	N/A	N/A	*	*	*	*	*
Parking	*		N/A	limited	*	limited	*	N/A	N/A	*	*	*	*	*
		*	N/A	N/A	limited	limited	*	N/A	N/A	*	*	*	*	*
Stair	*		N/A	limited	limited	limited	*	N/A	N/A	limited	*	*	*	*
		*	N/A	*	*	*	*	N/A	N/A	*	*	*	*	*
Ramp	*		N/A	limited	*	limited	*	*	N/A	*	*	*	*	*
		*	N/A	*	*	*	*	limited	N/A	*	*	*	*	*
Entrance Area	*		limited	*	*	limited	*	*	*	limited	*	*	*	*
		*	N/A	*	*	limited	*	*	limited	limited	*	*	*	*
Door & Gate	*		N/A	*	*	limited	*	*	*	*	*	*	*	*
		*	N/A	*	*	limited	*	*	limited	*	*	*	*	*
Window	*		N/A	N/A	limited	N/A	limited	N/A	N/A	limited	limited	limited	*	*
		*	N/A	N/A	limited	N/A	limited	N/A	N/A	N/A	N/A	limited	*	*
Guards & Barrier	*		N/A	*	limited	limited	*	limited	N/A	*	*	limited	limited	*
		*	N/A	*	limited	limited	*	limited	N/A	*	*	limited	*	*
Turnstile, Gate Area	*		N/A	limited	limited	limited	*	N/A	N/A	limited	limited	*	N/A	*
		*	N/A	*	*	*	*	N/A	N/A	limited	limited	*	limited	*
Grills & Gratings	*		N/A	limited	N/A	N/A	*	N/A	N/A	limited	*	*	*	N/A
		*	N/A	limited	N/A	N/A	*	*	N/A	limited	*	*	*	*
floor	*		N/A	N/A	N/A	N/A	limited	N/A	limited	N/A	limited	*	N/A	*
		*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	limited	*	N/A	*
Wall	*		N/A	N/A	N/A	N/A	N/A	N/A	limited	N/A	N/A	limited	N/A	limited
		*	N/A	N/A	N/A	N/A	N/A	N/A	limited	N/A	limited	limited	limited	limited
Ceiling	*		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Continued

BFDGA	ANSI	BFDGY	CAN/CSA	NBCC
*	*	limited	*	limited
*	*	limited	*	limited
*	*	*	*	*
*	*	*	*	*
*	*	limited	*	*
*	limited	limited	*	*
N/A	N/A	N/A	*	N/A
N/A	N/A	N/A	*	N/A
N/A	N/A	N/A	*	N/A
N/A	N/A	N/A	*	N/A
*	*	limited	*	limited
*	*	limited	*	limited
*	limited	*	*	*
*	limited	*	*	*
limited	limited	*	*	*
*	*	*	*	*
limited	*	*	*	*
*	*	*	*	*
*	*	*	*	*
*	*	limited	*	limited
*	limited	*	*	*
*	limited	*	*	*
limited	N/A	N/A	*	N/A
*	N/A	N/A	*	N/A
limited	N/A	limited	*	limited
limited	N/A	limited	*	limited
N/A	N/A	limited	limited	limited
N/A	N/A	limited	limited	limited
*	N/A	N/A	*	N/A
*	N/A	N/A	*	N/A
N/A	N/A	limited	*	limited
N/A	N/A	N/A	*	N/A
N/A	N/A	N/A	limited	N/A
limited	limited	N/A	limited	N/A
N/A	N/A	N/A	limited	N/A
N/A	N/A	N/A	limited	N/A

Therefore, in this study, MySQL and a cloud server are used to allow designers instantly access the created databases. For that purpose, different tables are created in MySQL after making Microsoft Excel tables in the knowledge database. Data is automatically transferred from MS Excel tables to MySQL through a set of rules coded by C#. Next, SQL Server is linked to a cloud server to facilitate accessing the created databases while the cloud server is connected to the created plug-in in BIM tool. All the connections between MySQL, cloud server, and the plug-in in BIM tools are automated and coded by C#. Furthermore, other data in the form of design families and original documents (guidelines) were separately stored in the cloud server. The newly created plug-in connects directly to the cloud server to recall those design families and original guidelines whenever they are needed, while Dynamo was used to connect the plug-in with the cloud server and to retrieve the necessary data stored in the MySQL, such as dimensions and descriptive data, and then provide them to the designer while using the plug-in. Also, the developed model automatically checks the design elements and compares them with the selected standards or guidelines to verify that they meet their requirements. This is achieved when the newly created plug-in reads the families' properties, which are used in the 3D design created in BIM tool, such as their width, height, length, etc., to make sure they are compatible with the data stored in the cloud server, which are specific to the guideline selected by the designer. In case of any discrepancies, the plug-in highlights the elements that do not comply with the selected guideline and proposes the correct data of those elements related to the selected guideline. The created plug-in has the ability to convert the units of measurements used in BIM tool to match the units of the stored data in the cloud server in an automatic manner that was coded by using C# programming language.

Phase 3: BIM 3D Design Model

In this phase, the 3D BIM design model of the proposed building is created in

Table 5. Covered items in different guidelines (outdoor items).

Outdoor Item	Qualitative Data	Quantitative Data	CMHC	UDHC	UDSG	UFAS	OADS	BFDS	FHADM	FADSL	BFDGH	FADSM	ADGT
Exterior Path, Access & free path of travel	*		limited	limited	limited	*	*	*	*	*	*	*	*
		*	N/A	limited	limited	limited	*	*	*	*	*	*	*
Passenger Loading Zone	*		N/A	limited	N/A	limited	limited	limited	*	*	limited	limited	limited
Parking	*		N/A	limited	limited	*	N/A	N/A	N/A	*	*	*	*
Ramp	*		N/A	limited	*	*	*	*	N/A	*	*	*	*
		*	N/A	*	limited	*	*	*	N/A	*	*	*	*
Stairs	*		N/A	limited	*	*	*	N/A	N/A	*	*	*	*
		*	N/A	*	limited	*	*	N/A	N/A	*	*	*	*
Elevator & Lift	*		N/A	limited	*	*	*	N/A	N/A	limited	*	*	limited
		*	N/A	N/A	*	*	*	N/A	N/A	limited	*	*	limited
Water Closet Stalls (WC)	*		N/A	limited	*	*	*	*	*	*	limited	*	*
		*	N/A	limited	*	*	*	*	*	*	*	*	limited
Rest Area	*		N/A	limited	N/A	limited	*	N/A	N/A	*	limited	*	*
		*	N/A	limited	N/A	limited	*	N/A	N/A	*	limited	*	*
Public Transit Area	*		N/A	limited	N/A	N/A	*	N/A	limited	limited	limited	limited	limited
		*	N/A	N/A	N/A	N/A	*	N/A	limited	limited	limited	limited	limited
Inclusive Play Area	*		N/A	N/A	N/A	N/A	*	N/A	N/A	N/A	limited	limited	limited
		*	N/A	N/A	N/A	N/A	*	N/A	N/A	N/A	limited	limited	limited
Refuge Area	*		N/A	limited	N/A	limited	*	N/A	N/A	limited	limited	limited	*
		*	N/A	limited	N/A	limited	limited	N/A	N/A	limited	limited	limited	*
Public Space Furniture		*	N/A	N/A	N/A	limited	limited	limited	N/A	limited	limited	*	*

Continued

CNUD	BFDGA	ANSI	BFDGY	CAN/CSA	NBCC
*	*	*	limited	*	limited
*	*	limited	limited	*	limited
*	limited	N/A	N/A	*	N/A
*	limited	limited	*	*	*
*	limited	*	*	*	*
*	*	*	*	*	*
*	limited	*	*	*	*
*	*	*	*	*	*
*	limited	*	limited	*	limited
*	limited	*	limited	*	limited
*	*	*	*	*	*
*	*	limited	*	*	*
N/A	N/A	N/A	N/A	*	limited
N/A	N/A	N/A	N/A	*	limited
N/A	N/A	limited	N/A	*	N/A
N/A	N/A	limited	N/A	*	N/A
N/A	N/A	N/A	N/A	limited	N/A
N/A	N/A	N/A	N/A	limited	N/A
limited	*	limited	N/A	*	N/A
N/A	*	limited	N/A	*	N/A
Limited	limited	limited	limited	*	limited

BIM tool. That step is achieved by using the newly created families and their associated components, which are automatically loaded and used via the developed plug-in. Designers would be able to select and retrieve the compatible guidelines from the Universal Design standard or Accessible design standard stored in the databases of phase 1. Once a guideline and its component(s) are selected during the design process, all the related design families are automatically loaded and placed in the same location where the general families of BIM tool (*i.e.*, Autodesk Revit©) are positioned to facilitate their use in the design model. In that stage, the cloud server will have a two-way interaction with the newly created plug-in in BIM tool to help importing and exporting the data from and to the database. Dynamo visual programming connects the database to BIM tool so that any modification in the design is automatically executed whenever is needed. Once the design is complete, the developed plug-in will check all the design components based on the selected standard and guideline. If the design is acceptable, it will be saved; otherwise, a list of required modifications will be generated and used to modify the design accordingly.

Although the model is somehow fully automated, adequate notes have been provided in each section to enhance its transparency and useability. In such a case, designers can effectively use the model and gain full knowledge of its performance. It is worth mentioning that this study is ongoing, where it incorporates four major databases: 1) Universal Design Database; 2) Conventional Design Database; 3) Sustainable Design Database; and 4) Sustainable Universal Design Database; however, this paper focuses on the Universal Design Database in addition to its Accessible Design sub-category.

4. Model Implementation and Testing

To test the developed model and to examine its performance and capabilities, a single-floor residential building located in Ottawa, Ontario, Canada, is used. Autodesk Revit© is selected as BIM tool to create the building's 3D design model with all its components such as walls, doors, windows, floor, stairs, cabinets, and railings and their associated geometry. To create the 3D design model of the proposed building, the families stored in the external database are retrieved through the created plug-in, which is named SUD, in Autodesk Revit©. SUD helps designers select and incorporate the appropriate standard and guidelines from the database. After making the selection, designers must choose the next step from different options, such as reading the related documents; comparing the different standards and guidelines; checking the created components based on the selected guideline; and using the associated design families to implement the selected standard into the building's 3D design model. Once the designer clicks the SUD plug-in, as shown in Figure 3, a form appears with a list of options allowing designers to access the other sections. The most important option in that form is the Standard option, so as once picked, the designer is given access to the information related to the selected design standard. Upon selecting the Universal Design standard, the designer must choose either the Universal Design standards or the Accessible Design standards, as illustrated in Figure 3.

Once a selection is made, a new screen opens, as shown in Figure 4, for the designer to choosea specific guideline, then a category, indoor or outdoor, and

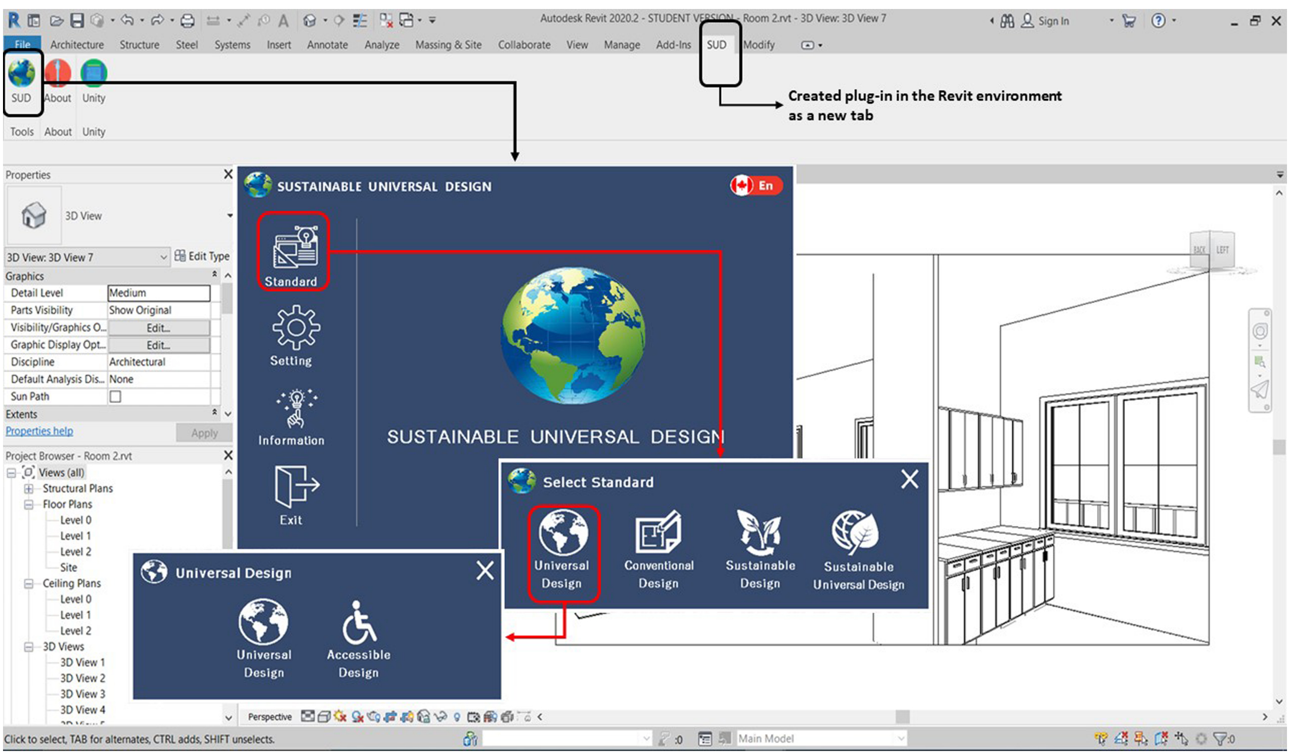

Figure 3. Snapshot of the created plug-in and the 3D design model.

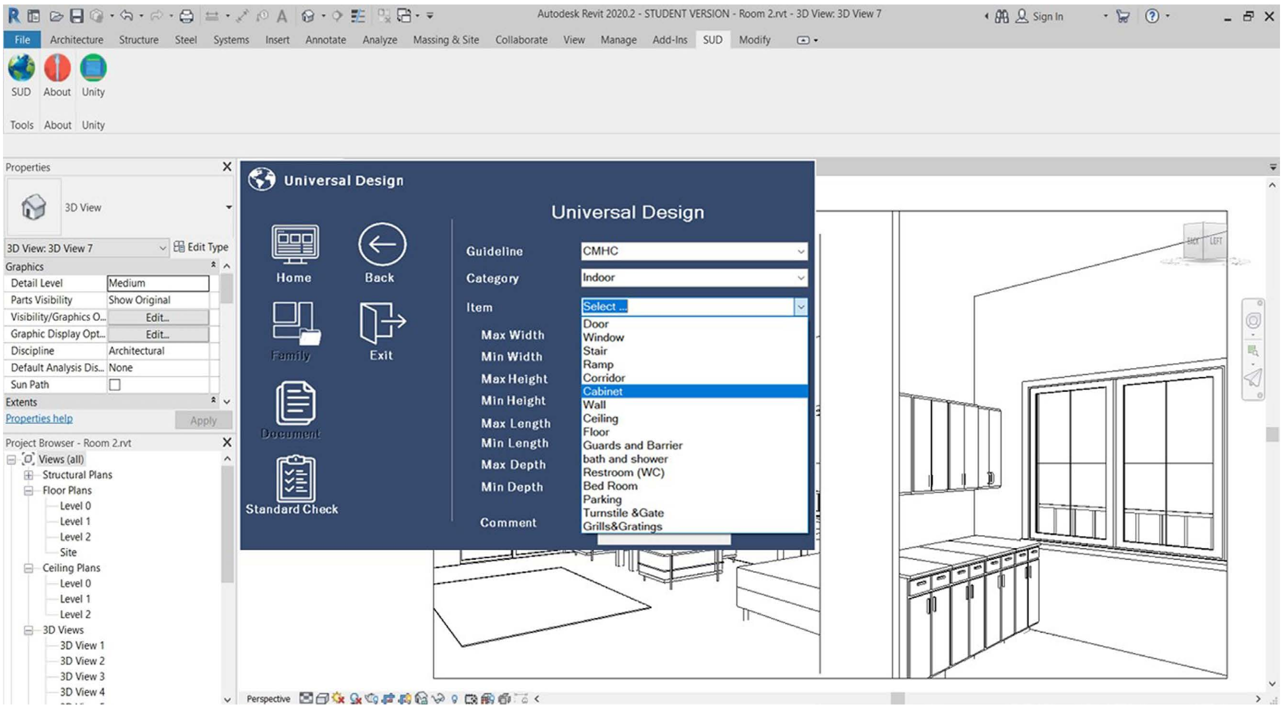

Figure 4. Access all the items listed in **Table 2** and **Table 3** via the created plug-in.

after that, select the items that are needed for the 3D design model. An efficient numeric coding system is used to symbolize the relationships between the stored data in the databases and to simplify the retrieval of the necessary information. These codes are unique for each item in the form of five-digit keynote codes. They represent the division, subdivision, elements, and materials' names.

Next, the designer will have access to additional information about the selected item(s) in the form of numerical data, such as the item's dimensions, and descriptive data in the form of comments retrieved from the knowledge database. **Figure 5** shows an example of a selected cabinet and its related data. Such data helps the designer to anticipate the item's requirements and ensure that they meet the occupants' needs. Having instant access to this type of data is vital since it reduces the possibility of making errors and significantly saves time. Once the Document button is clicked, that designer gains access to both the original documents of the selected guideline and the specific item, as shown in **Figure 6**. Furthermore, the designer can view, read, share, save, and print those documents. As soon as the "Family" button is clicked, the families' database is activated, as shown in **Figure 7**, then the families related to the selected item are automatically placed in the library of Autodesk Revit© to be used in the proposed project. The flexibility of the model, besides being user-friendly, resides in the ability of managing and modifying the associated databases in an easy and simple way. In addition to the abilities that were mentioned above, which include selecting standards and guidelines, retrieving related data and design families for design elements instantly, having access to the original documents, etc., clearly demonstrate the functionality requirement of the described model.

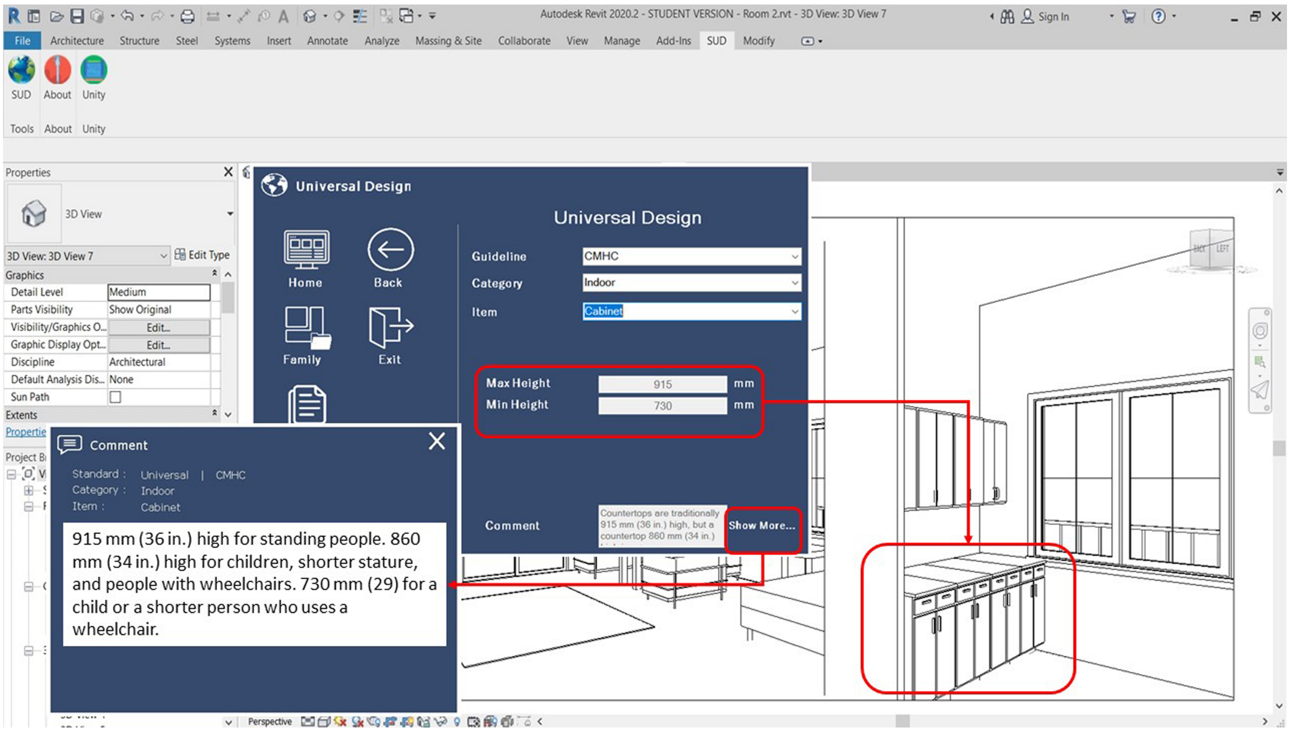

Figure 5. Selecting appropriate guideline and item and receiving related data.

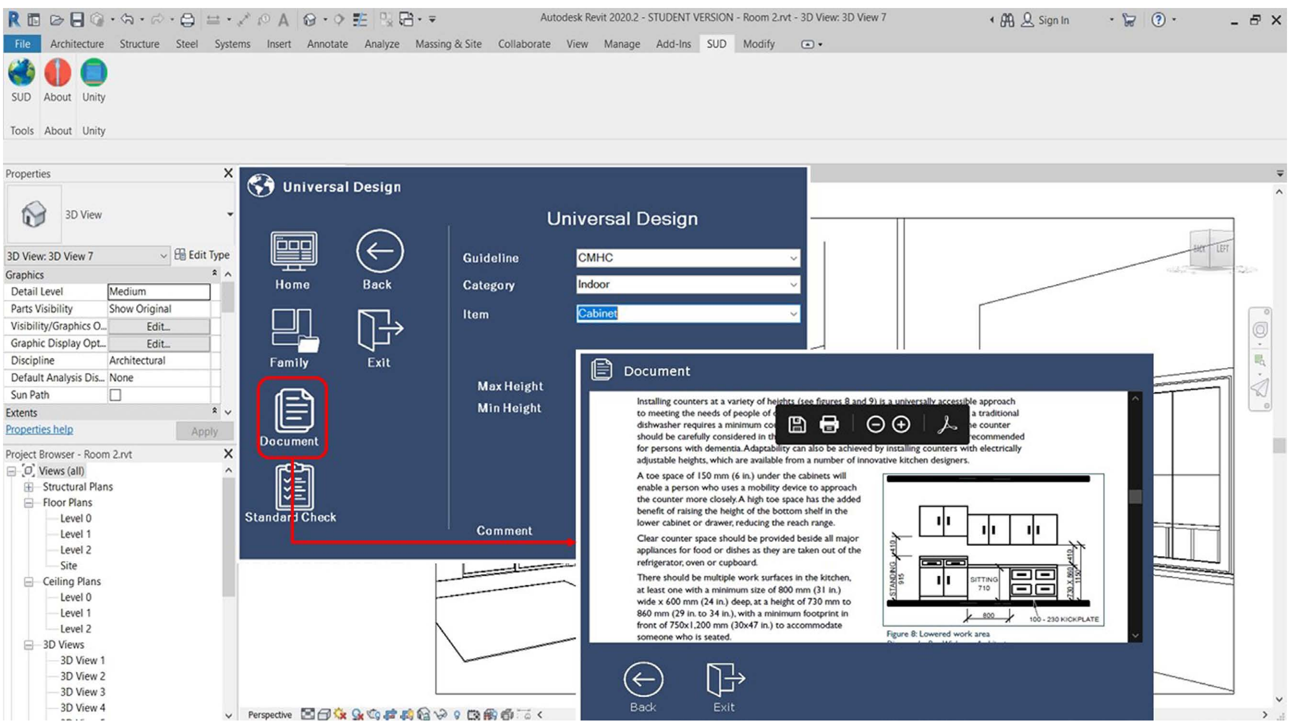

Figure 6. Viewing original documents.

The last button on the form is the "Standard Check" button. By clicking that button, the designer can check if the components used in the 3D design model comply with the selected guideline and to make sure the standard's requirements

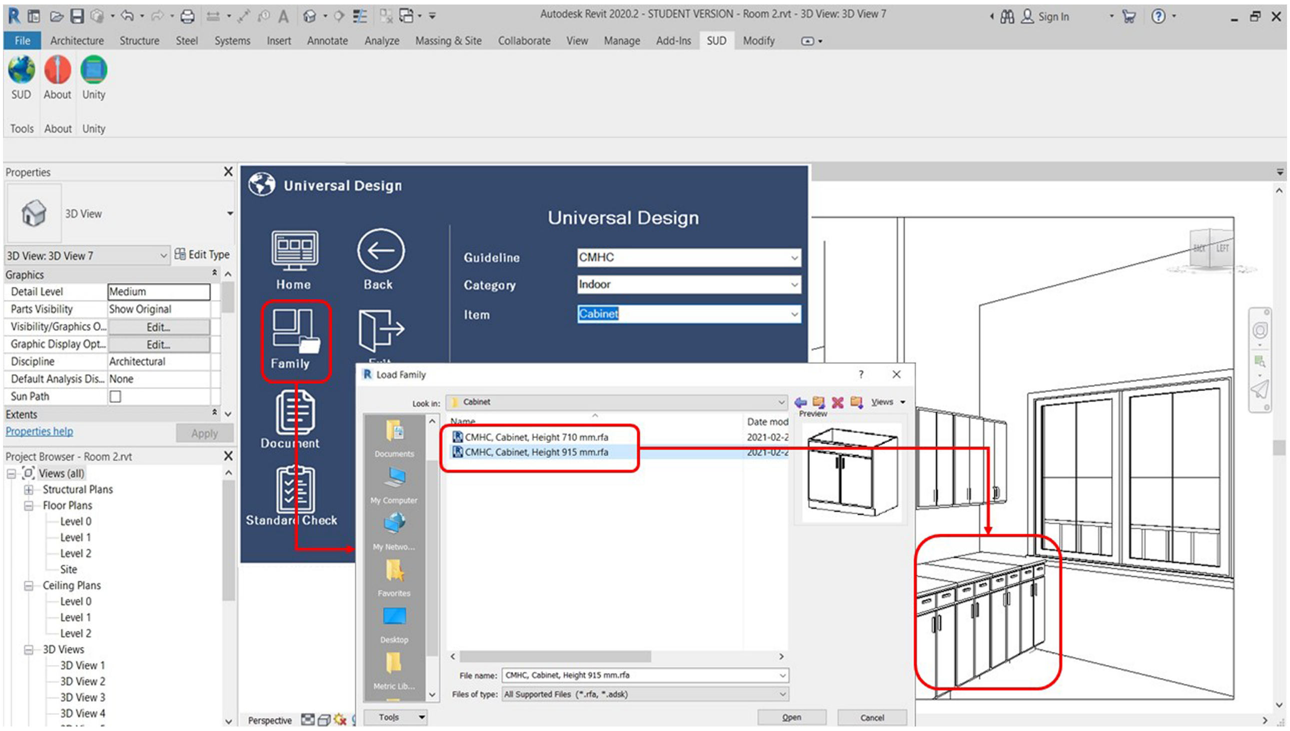

Figure 7. Automatically placed families in the appropriate location and ready to use in the design.

are met. If errors are found, they will be highlighted in red. For example, if the designer selected the Universal Design guideline from the city of Calgary, the Indoor category, and Door as an item, as shown in Figure 7, a new screen opens upon hitting the "Standard Check" button, where all the standard selections, guidelines and the specific item are listed. The item(s) that does/do not meet the requirements of the selected guideline are highlighted in red, as shown in Figure 8, where doors number 2 and 3 have their width less than the minimum width of 920 mm as stated in the selected guideline. To fulfill the model's transparency requirement, adequate notes were added for each section to help designers better understand the functions of the selected section and its use, as shown in Figure 9.

The developed model is bilingual; therefore, designers can select their language of preference before using the model and its associated components, As shown in Figure 10.

5. Discussion

The automated model described in this study helps designers to have full access to the various standards and guidelines related to universal and accessible designs along with the National Building Code of Canada (NBCC), as well as to access multiple guidelines and standards from other countries in an attempt to increase the efficiency and variety of the data needed to design universal buildings. Comparing the presented model with the ones listed in the literature, which integrate BIM with UD and incorporate Universal Design standards used

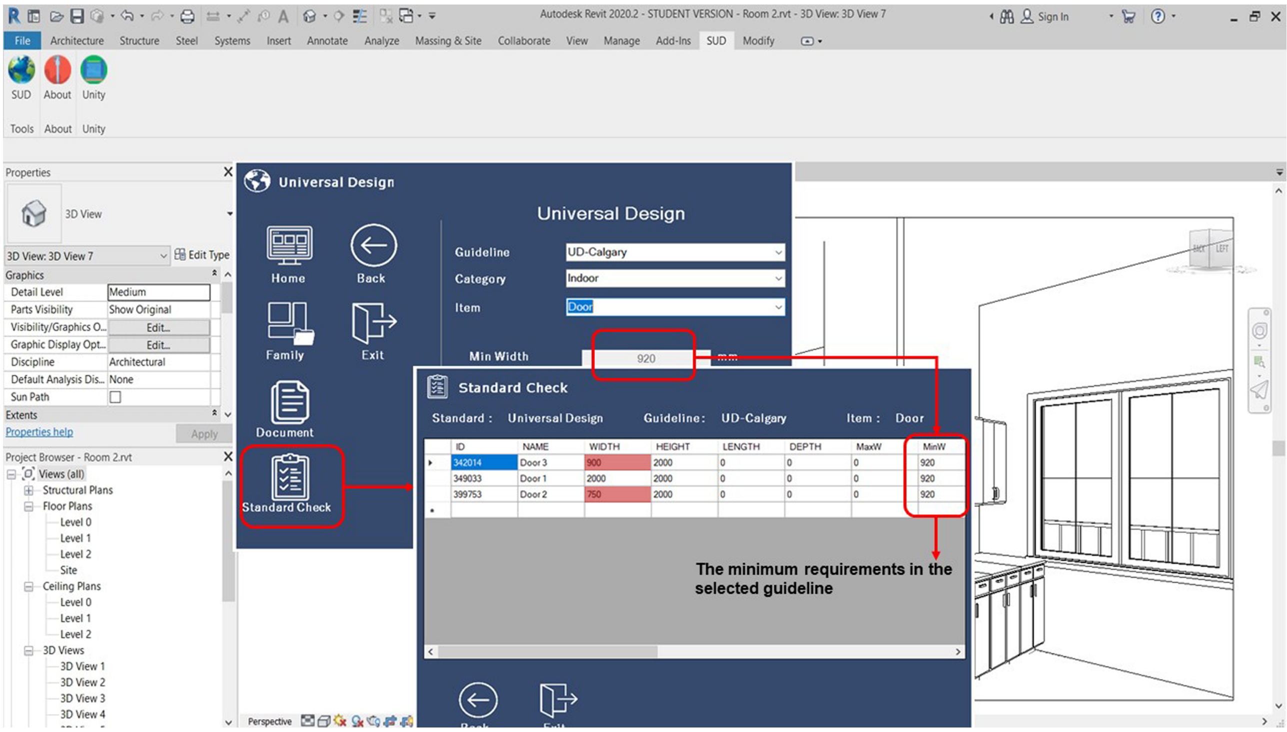

Figure 8. Comparing items dimensions in the 3D model with the selected guideline.

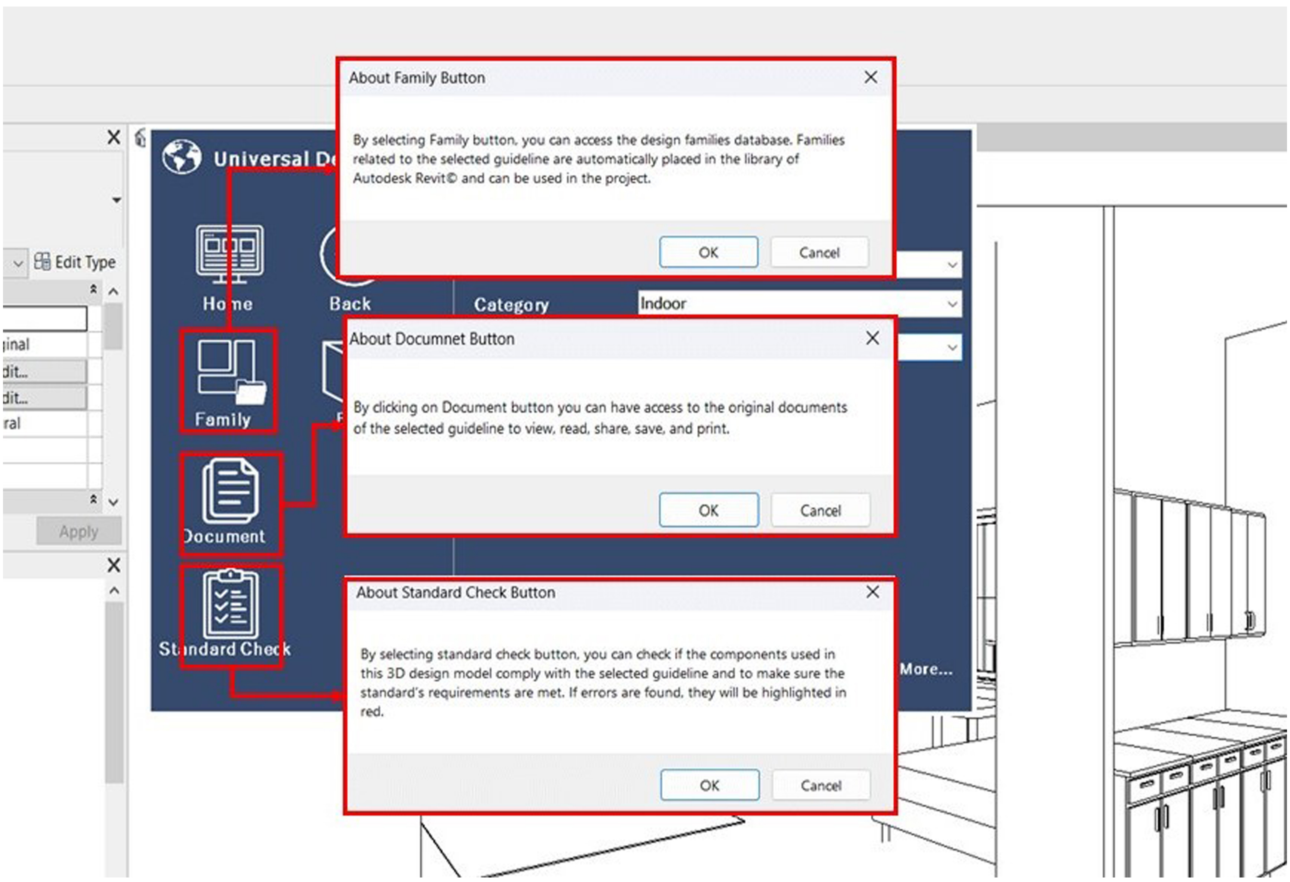

Figure 9. Function and use of each section.

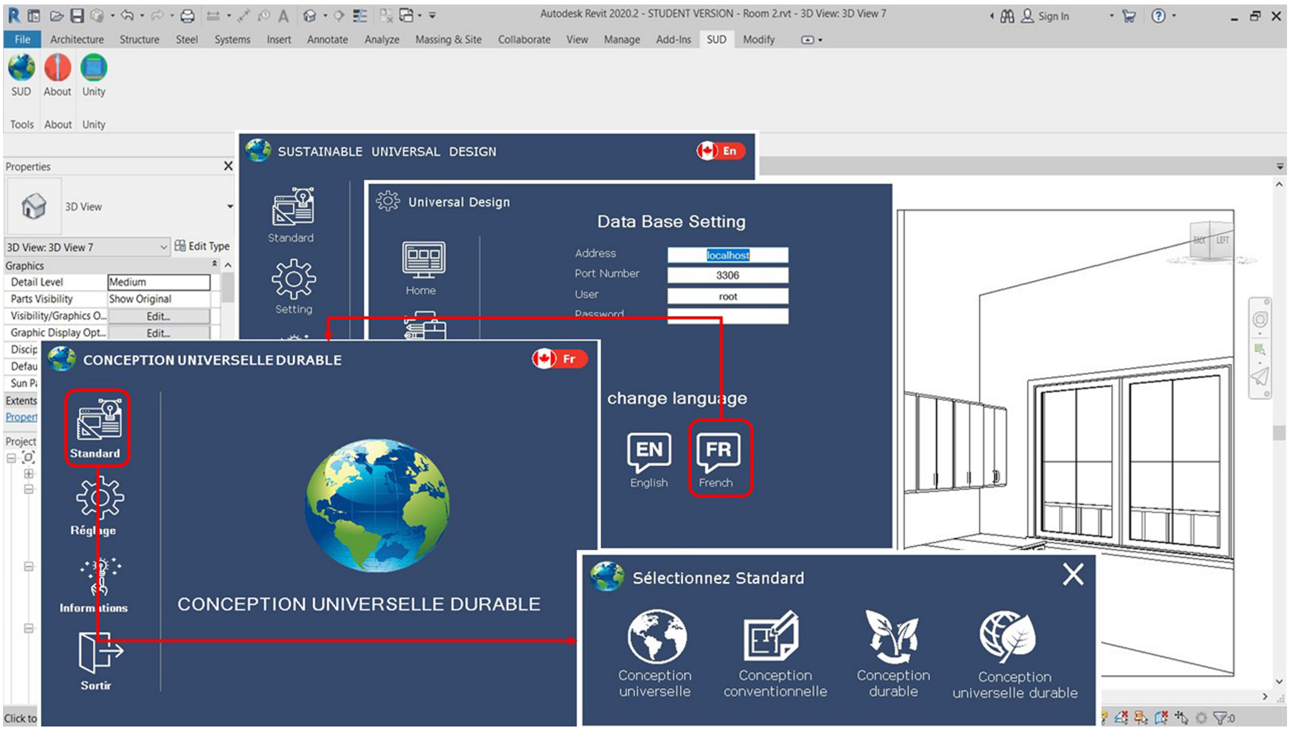

Figure 10. Bilingual capability of the created model.

at the conceptual design stage, reveals that the current model is comprehensive, merges different standards and guidelines, supplies designers with build-in copies of those standards and has a one step further by being able to check the design if it meets the selected standard and guideline. While the ones listed in the literature are limited to one single standard, which is the NBCC.

They have reduced the number of predefined design families for components most commonly used in designing buildings. For instance, Jrade and Valdez [18] proposed a model to include a database management system that stores architectural components and elements that are universally designed based on the National Building Codes of Canada, while Jrade and Jalaei [17] continued the work of Jrade and Valdez [18] and presented a model that links BIM with energy analysis and LCA tools to execute sustainable universal design at the conceptual stage for designing Canadian houses. One of the advantages of the current model is its competency to provide designers with a variety of information about all the design elements in the form of dimensions, colour, texture, and other descriptive information, in addition to providing instant access to the original documented standards in an automatic way. Despite that some of the existing studies are related to the integration of universal design standards and Building Information Modeling at the conceptual design stage, but those are focused on creating design families based only on the National Building Codes of Canada and integrating them into BIM tools, whereas this study incorporates various universal design and accessible design standards and guidelines including the NBCC to help designers have instant access to various type of data as well as newly created design families that are compatible with those standards and guidelines including multiple guidelines and standards collected from other countries via an automated model in an attempt to increase the efficiency and variety of the information needed for the design of universal buildings regardless of their locations. Another innovation of the developed model is its ability to automatically check the design elements and compare them with the selected standard or guideline to verify that the design elements meet the selected standard and guidelines' requirements. Regardless of the many advantages of the described model (*i.e.*, reducing future modification and alteration, minimizing the associated costs of designing homes based on inhabitants' needs), it has several limitations and constraints. One of its major limitations is that not all the building components were converted as Autodesk Revit© families to meet the UD standards. Therefore, designers must read the guidelines and apply their requirements while designing and using those components. Designers can access those guidelines from within the described model via a plug-in that was developed and inherited into BIM tool. Once a specific item is selected, the designer has instant access to the guideline and the descriptive data related to that item. Another limitation of the model is that most of the guidelines cover policies related to accessibility in buildings only, while universally designed buildings need additional information beyond the ones of accessibility, which means it does not cover all the areas that are necessary to achieve a complete universally designed building. Thus, for future work, it is recommended to enhance the model's efficiency by storing additional data and suggestions concerning universal design to accommodate more people to the greatest extent possible. The authors are working on adding aging-in-place policies to the model to extend and enhance its database to help designers consider seniors' needs when designing age-in homes. Moreover, the databases are cloud-based; while there are several advantages of cloud storage services over physical/local storage methods, such as easily sharing files and collaborating with others, but they still have some limitations as well (*i.e.*, designers must have continuous access to the internet when using the model to benefit from all the data and newly created design families stored in the external database).

6. Conclusion

This paper described the development of an integrated model that couples BIM and universal design standards and accessibility guidelines to be considered by designers when modeling the design of building projects for Canadians to age in them. The philosophy of universal design, UD, persuades the development of design guidelines used during the design process. UD makes facilities usable over the entire lifespan of inhabitants. The increased use of BIM by the AEC industry due to its integration capabilities with external applications provides an opportunity to incorporate universal design and accessible design standards into the BIM environment at the early stage of designing building projects. One of the novelties highlighted in the developed model residents is the development of an automated method that employs a newly created plug-in to assist designers in instantly accessing UD standards and incorporating them while designing proposed buildings at the conceptual stage. The model's development was implemented through three phases; phase 1 focused on collecting, categorizing and storing data from various universal design and accessible design guidelines, then databases were created to store these data as well as the newly created/modified design components; phase 2, consisted of developing new plug-ins in BIM tool (Autodesk Revit) to link the developed databases with Revit by using its API and C# in order to automate the process of retrieving necessary information and components from the database; phase 3, comprised the creation of a 3D BIM model by using the data from the databases of phase 1 and the plug-ins of phase 2. This study focuses on the conceptual design stage of facilities, where designers need to have access to vital information when selecting and applying the UD standards to proposed projects that should meet owners' goals. Reducing future modification and alteration and minimizing associated costs are parts of the utmost advantages of the developed model. Adopting UD principles early during the design stage contributes to creating and constructing buildings that comply with elderlies' requirements who want to age in their homes rather than going to long-term care facilities where there is a high risk for them to be affected by unpredictable situations such as Covid-19 pandemic. Future work can explore integrating plan review systems and building code checker software into the model to enhance the capability of the model's code compliance checking. Furthermore, adding aging-in-place policies to the model enhances the efficiency of the database and helps designers consider seniors' needs when designing age-in homes.

Acknowledgements

The authors acknowledge the fund provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) to support the current research.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Statistics Canada (2015) Canada's s Population Estimates: Age and Sex, July 1, 2015. *The Daily*, September 29, 1-5. http://www.statcan.gc.ca/daily-quotidien/150929/dq150929b-eng.htm

[2] Globe Newswire (2020) Aging in Place Report Reveals 86% of Urban Canadian Baby Boomers/Older Adult Homeowners Want to Live in Their Homes for as Long as Possible. Globe Newswire, March 4, 2020. https://www.globenewswire.com/news-release/2020/03/04/1994809/0/en/Aging-in-

Place-Report-Reveals-86-of-Urban-Canadian-Baby-Boomers-Older-Adult-Homeowners-Want-to-Live-in-their-Homes-for-as-Long-as-Possible.html

[3] Government of Ontario (2021) Long-Term Care Homes|COVID-19 (Coronavirus) in Ontario. https://covid-19.ontario.ca/data/long-term-care-homes

[4] Alsayyar, B. and Jrade, A. (2015) Integrating Building Information Modeling (BIM) with Sustainable Universal Design Strategies to Evaluate the Costs and Benefits of Building Projects. Proceeding Conference, International Construction Specialty Conference of the Canadian Society for Civil Engineering (ICSC) (5th: 2015).

[5] Bianco, L. (2020) Universal Design: From Design Philosophy to Applied Science. *Journal of Accessibility and Design for All*, **10**, 70-97.

[6] Nygaard, K.M. (2018) What Is Universal Design—Theories, Terms and Trends. *IFLA WLIC* 2018, Kuala Lumpur, 26 August 2018, 1-6. https://library.ifla.org/id/eprint/2250

[7] Andersson, J. (2011) Architecture for the Silver Generation: Exploring the Meaning of Appropriate Space for Ageing in a Swedish Municipality. *Health & Place*, **17**, 572-587. https://doi.org/10.1016/j.healthplace.2010.12.015

[8] Wu, W. and Handziuk, E. (2013) Use of Building Information Modeling in Aging-in-Place Projects: A Proof of Concept. *Proceedings of the* 2013 *ASCE International Workshop on Computing in Civil Engineering*, Los Angeles, 23-25 June 2013, 443-450. https://doi.org/10.1061/9780784413029.056

[9] McCunn, L.J. and Gifford, R. (2014) Accessibility and Aging in Place in Subsidized Housing. *Seniors Housing & Care Journal*, **22**, 18-29.

[10] Ahrentzen, S. and Tural, E. (2015) The Role of Building Design and Interiors in Ageing Actively at Home. *Building Research and Information*, **43**, 582-601. https://doi.org/10.1080/09613218.2015.1056336

[11] Government of Canada (2015) Thinking about Your Future? Plan Now to Age in Place. https://www.canada.ca/en/employment-social-development/corporate/seniors/forum/aging-checklist.html

[12] Petersson, I., Lilja, M., Hammel, J. and Kottorp, A. (2008) Impact of Home Modification Services on Ability in Everyday Life for People Ageing with Disabilities. *Journal of Rehabilitation Medicine*, **40**, 253-260. https://doi.org/10.2340/16501977-0160

[13] Iecovich, E. (2014) Aging in Place: From Theory to Practice. *Anthropological Notebooks*, **20**, 21-32.

[14] Liu, S.Y. and Lapane, K.L. (2009) Residential Modifications and Decline in Physical Function among Community-Dwelling Older Adults. *Gerontologist*, **49**, 344-354. https://doi.org/10.1093/geront/gnp033

[15] Jalaei, F., Jrade, A. and Nassiri, M. (2015) Integrating Decision Support System (DSS) and Building Information Modeling (BIM) to Optimize the Selection of Sustainable Building Components. *Journal of Information Technology in Construction*, 20, 399-420.

[16] Wu, W. and Kaushik, I. (2015) A BIM-Based Educational Gaming Prototype for Undergraduate Research and Education in Design for Sustainable Aging. 2015 *Winter Simulation Conference* (*WSC*), Huntington Beach, 6-9 December 2015, 1091-1102. https://doi.org/10.1109/WSC.2015.7408236

[17] Jrade, A. and Jalaei, F. (2014) Using Building Information Modeling to Evaluate the Costs and Benefits of Adopting Sustainable Universal Houses in Canada. *Interna-*

tional Journal of 3D Information Modeling, **3**, 56-76.
https://doi.org/10.4018/ij3dim.2014100104

[18] Jrade, A. and Valdez, P.Z. (2012) Integrating Building Information Modeling with Universal Design Requirements for High Accessible Homes. *Construction Challenges in a Flat World*, *Proceedings of the* 2012 *Construction Research Congress*, West Lafayette, 21-23 May 2012, 1291-1300.
https://doi.org/10.1061/9780784412329.130

[19] Mustaquim, M.M. (2015) A Study of Universal Design in Everyday Life of Elderly Adults. *Procedia Computer Science*, **67**, 57-66.
https://doi.org/10.1016/j.procs.2015.09.249

[20] Kadir, S.A. and Jamaludin, M. (2013) Universal Design as a Significant Component for Sustainable Life and Social Development. *Procedia—Social and Behavioral Sciences*, **85**, 179-190. https://doi.org/10.1016/j.sbspro.2013.08.349

[21] Iwarsson, S. and Ståhl, A. (2003) Accessibility, Usability and Universal Design—Positioning and Definition of Concepts Describing Person-Environment Relationships. *Disability and Rehabilitation*, **25**, 57-66.
https://doi.org/10.1080/dre.25.2.57.66

[22] Watchorn, V., Hitch, D., Grant, C., Tucker, R., Aedy, K., Ang, S. and Frawley, P. (2021) An Integrated Literature Review of the Current Discourse around Universal Design in the Built Environment—Is Occupation the Missing Link? *Disability and Rehabilitation*, **43**, 1-12. https://doi.org/10.1080/09638288.2019.1612471

[23] Persson, H., Åhman, H., Yngling, A.A. and Gulliksen, J. (2015) Universal Design, Inclusive Design, Accessible Design, Design for All: Different Concepts—One Goal? On the Concept of Accessibility—Historical, Methodological and Philosophical Aspects. *Universal Access in the Information Society*, **14**, 505-526.
https://doi.org/10.1007/s10209-014-0358-z

[24] Carr, K., Weir, P.L., Azar, D. and Azar, N.R. (2013) Universal Design: A Step toward Successful Aging. *Journal of Aging Research*, **2013**, Article ID: 324624.
https://doi.org/10.1155/2013/324624

[25] Canadian Human Rights Commission (2006) International Best Practices in Universal Design: A Global Review.
https://www.chrc-ccdp.gc.ca/en/resources/publications/international-best-practices-universal-design-a-global-review

[26] CSA (2020) A Canadian Roadmap for Accessibility Standards. Canadian Standards Association, Toronto.
https://www.csagroup.org/article/research/a-canadian-roadmap-for-accessibility-standards

[27] CNRC (2015) National Building Code of Canada 2015. Volume 1, Issued by the Canadian Commission on Building and Fire Codes, National Research Council of Canada, Ottawa.
https://nrc-publications.canada.ca/eng/view/object/?id=c8876272-9028-4358-9b42-6974ba258d99

[28] Nwadike and Wilkinson, S. (2020) Challenges Facing Building Code Compliance in New Zealand. *International Journal of Construction Management*, **22**, 2493-2503.

[29] Soliman-Junior, J., Tzortzopoulos, P. and Kagioglou, M. (2022) Designers' Perspective on the Use of Automation to Support Regulatory Compliance in Healthcare Building Projects. *Construction Management and Economics*, **40**, 123-141.
https://doi.org/10.1080/01446193.2021.2022176

[30] Sampaio, A.Z. (2017) 4D/BIM Model Linked to VR Technology. *Proceedings of the*

Virtual Reality International Conference, Laval, 22-24 March 2017, 1-4. https://doi.org/10.1145/3110292.3110298

[31] Ding, L., Zhou, Y. and Akinci, B. (2014) Building Information Modeling (BIM) Application Framework: The Process of Expanding from 3D to Computable nD. *Automation in Construction*, **46**, 82-93. https://doi.org/10.1016/j.autcon.2014.04.009

[32] Wu, T.H., Wu, F., Liang, C.J., Li, Y.F., Tseng, C.M. and Kang, S.C. (2019) A Virtual Reality Tool for Training in Global Engineering Collaboration. *Universal Access in the Information Society*, **18**, 243-255. https://doi.org/10.1007/s10209-017-0594-0

[33] Antwi-Afari, M.F., Li, H., Pärn, E.A. and Edwards, D.J. (2018) Critical Success Factors for Implementing Building Information Modelling (BIM): A Longitudinal Review. *Automation in Construction*, **91**, 100-110. https://doi.org/10.1016/j.autcon.2018.03.010

[34] Kamel, E. and Memari, A.M. (2018) Review of BIM's Application in Energy Simulation: Tools, Issues, and Solutions. *Automation in Construction*, **9**, 164-180. https://doi.org/10.1016/j.autcon.2018.11.008

[35] Abanda, F.H., Vidalakis, C., Oti, A.H. and Tah, J.H.M. (2015) A Critical Analysis of Building Information Modelling Systems Used in Construction Projects. *Advances in Engineering Software*, **90**, 183-201. https://doi.org/10.1016/j.advengsoft.2015.08.009

[36] Zhang, F., Chan, A.P.C., Darko, A. and Li, D. (2021) BIM-Enabled Multi-Level Assessment of Age-Friendliness of Urban Housing Based on Multiscale Spatial Framework: Enlightenments of Housing Support for "Aging-in-Place." *Sustainable Cities and Society*, **72**, Article ID: 103039. https://doi.org/10.1016/j.scs.2021.103039

[37] Jalaei, F., Jalaei, F. and Mohammadi, S. (2020) An Integrated BIM-LEED Application to Automate Sustainable Design Assessment Framework at the Conceptual Stage of Building Projects. *Sustainable Cities and Society*, **53**, Article ID: 101979. https://doi.org/10.1016/j.scs.2019.101979

[38] Cheng, J.C.P. and Das, M. (2014) A BIM-Based Web Service Framework for Green Building Energy Simulation and Code Checking. *Journal of Information Technology in Construction*, **19**, 150-168. https://www.itcon.org/2014/8

[39] Choi, J. and Kim, I. (2017) A Methodology of Building Code Checking System for Building Permission Based on openBIM. 2017 *Proceedings of the* 34*rd ISARC*, Taipei, 28 June-1 July 2017, 945-950. https://doi.org/10.22260/ISARC2017/0131

[40] Kincelova, K., Boton, C., Blanchet, P. and Dagenais, C. (2020) Fire Safety in Tall Timber Building: A BIM-Based Automated Code-Checking Approach. *Buildings* (*Basel*), **10**, Article No. 121. https://doi.org/10.3390/buildings10070121

[41] Patlakas, P., Livingstone, A., Hairstans, R. and Neighbour, G. (2018) Automatic Code Compliance with Multi-Dimensional Data Fitting in a BIM Context. *Advanced Engineering Informatics*, **38**, 216-231. https://doi.org/10.1016/j.aei.2018.07.002

[42] Narayanswamy, Liu, H. and Al-Hussein, M. (2019) BIM-Based Automated Design Checking for Building Permit in the Light-Frame Building Industry. *Proceedings of the International Symposium on Automation and Robotics in Construction*, Banff, 21-24 May 2019, 1042-1049. https://doi.org/10.22260/ISARC2019/0139

[43] Häußler, M., Esser, S. and Borrmann, A. (2021) Code Compliance Checking of Railway Designs by Integrating BIM, BPMN and DMN. *Automation in Construction*, **121**, Article ID: 103427. https://doi.org/10.1016/j.autcon.2020.103427

[44] Khattra, S.K., Rai, H.S. and Singh, J. (2022) Towards Automated Structural Stability

Design of Buildings—A BIM-Based Solution. *Buildings* (*Basel*), **12**, Article No. 451. https://doi.org/10.3390/buildings12040451

[45] Türkyılmaz, E. (2016) A Method to Analyze the Living Spaces of Wheelchair Users Using IFC. *Procedia—Social and Behavioral Sciences*, **222**, 458-464. https://doi.org/10.1016/j.sbspro.2016.05.136