

Article

Development of a Cloud-Based Building Information Modeling Design Configurator to Auto-Link Material Catalogs with Code-Compliant Designs of Residential Buildings

Songyue Wang ^{1,2,*}  and Qian Chen ^{1,*} 

¹ School of Engineering, University of British Columbia Okanagan Campus, 1137 Alumni Ave, Kelowna, BC V1V 1V7, Canada

² Department of Computer Science, The University of Hong Kong, Pokfulam, Hong Kong, China

* Correspondence: sywang@cs.hku.hk (S.W.); qian.chen@ubc.ca (Q.C.)

Abstract: Configurators have recently emerged as essential tools in the construction industry to enable builders to offer a wide range of customizable designs. Due to significant challenges in information integration between construction suppliers and clients, existing configurator systems often lack crucial usability and supply chain information, presenting barriers to wider adoption among residential communities, especially in single-family residence development that requires a high degree of customization. To address this challenge in the design and construction supply chain, this study presents a lightweight cloud-based modular home configuration methodology as a robust unified platform solution to integrate parametric design options with a certified kit-of-parts library to meet local design codes. The configurator prototype developed under this framework seamlessly integrates essential design and supply chain information by leveraging (1) a generative layout design with pre-approved blueprints, (2) a knowledge-based recommender system to link the design process with certified material catalogs, and (3) a user-friendly web interface to present possible designs. The implementation of a single-family housing design adhering to the building codes in the British Columbia Province of Canada illustrates the benefits of the proposed configurator functionalities and efficient supplier data integration. Lightweight and automated, the proposed configurator has substantial potential to be scaled and adopted across different communities.

Keywords: BIM; configurator platform; industrial construction; intelligent designs; information integration



Citation: Wang, S.; Chen, Q. Development of a Cloud-Based Building Information Modeling Design Configurator to Auto-Link Material Catalogs with Code-Compliant Designs of Residential Buildings. *Buildings* **2024**, *14*, 2084. <https://doi.org/10.3390/buildings14072084>

Academic Editor: Heap-Yih Chong

Received: 12 April 2024

Revised: 12 June 2024

Accepted: 15 June 2024

Published: 8 July 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Maintaining a continuous supply of affordable and satisfying residences to shelter residents is one of the priorities for government authorities around the globe [1,2]. Nevertheless, factors such as rising financing rates, an insufficiently skilled labor force, and uncertainties with the supply chain processes in the post-COVID era have posed significant challenges to affordable and rapid housing programs. These obstacles outline the urgency to improve the overall efficiency of housing supply chain processes with fabricable housing designs [3]. In the past decade, researchers and practitioners in the construction domain widely explored and adopted industrialized construction (IC) and digital construction methods, which led to rapid standardization in the design and planning phase, economies of scale in the fabrication phase, and labor reduction for on-site work [4–7]. To facilitate a client-centric planning process and achieve mass customization [8,9], configurators are normally used in IC projects in a way that developers or property owners may specify their preferences, conduct design option simulations, and perform business analysis (e.g., calculating the return on investment of a project supply chain). However, existing IC configurators in the market are mainly focused on commercial development projects and target construction professionals, such as planners, architects, and engineers as software

users [10]. Their system or platform functions lack essential usability and adaptability, posing obstacles to broader acceptance across different residential communities, particularly in single-family residence development where extensive customization, unique supply chain configurations, and specific local building codes are necessary.

Researchers and leading practitioners in construction innovation have made progress in developing cloud-based configurators as adaptable design platforms to manage customer requests, including an intuitive interface to select easily fabricable building modules, referred to as kit-of-parts, used for assembling complete products while fine-tuning building performance metrics. Examples include the cross-phase product configurator for modular buildings using a kit-of-parts developed by Cao et al. [8] and the HiStruct Building Configurator commercialized by HiStruct & FemCAD Solutions [11]. Similar configurator tools find diverse applications across industries, from server computer setup wizards [12] to customizing business jets [13]. For the construction industry, whose supply chain complexities are common [14], the adoption of these configurator solutions can also enhance data flow and collaboration among stakeholders to reduce uncertainties across supply chain processes. For instance, features like bill-of-materials (BOM) export in tools like Testfit [15] inform procurement needs and facilitate financial calculations. However, existing configurators typically target design professionals with specialized knowledge and software, limiting access for community residents to efficiently communicate on single-family projects and understand possible material catalogs. Some modular home fabricators offer web-based configurator-like tools, such as Build Prefab [16], enabling clients to select kit-of-parts combinations from catalogs but restricting customization to a selection of interior items based on a limited amount of pre-drawn plans.

To center customization needs across communities and address technical challenges, this study proposes a light-weight cloud-based configurator platform that highlights three main areas of knowledge contributions: (1) rapid layout customization based on existing generative algorithms and a pre-approved building plan, (2) efficient integration of certified materials catalogs (in the form of BIM object libraries) and auto-matching through a knowledge-based recommender system, and (3) enhanced configurator end-users involvement through an interactive web-based design interface. The proposed configurator realizes the user benefits of mass customization and integrates cross-phase information with generative layout design in the planning stage and a knowledge-based smart recommendation engine for modular components in the procurement stage.

The remaining sections of this paper are organized as follows. Section 2 provides a literature review on existing configurator developments and related technologies for modular construction. Section 3 describes the methodology used to develop the lightweight cloud-based configurator and associated system architecture of the configurator platform. Section 4 presents a proof-of-concept case study of the configurator application in a typical single-story, single-family modular housing project. Section 5 elaborates on the evaluation of the effectiveness and areas of improvement for the proposed configurator, followed by the conclusions and future research directions in Section 6.

2. Literature Review

2.1. Configurators for Manufacturing and Industrialized Construction

Configurator tools, systems, and platforms have roots in CAD (Computer-Aided Design) for manufacturing product designs (e.g., vehicles and furniture) and evolve into Building Information Modeling (BIM)-based applications when being adapted to the construction industry to incorporate parametric modeling and rule-based building design [17]. Early configurators focused on simple product configurations, but advancements in computing power and optimization algorithms have enabled more complex configurators capable of handling intricate design rules and constraints for mass customization of products. A configurator is usually developed to provide an interface for customers or professionals who are attending to customer requests to select easy-to-fabricate modules, known as kit-of-parts, to assemble the complete product and tune the performance

metrics [8]. Cao et al. [8] proposed a cross-phase configurator that spans across planning, design, and product selection phases so that the manufacturability of a kit-of-parts used in a specific product could be evaluated in the design phase to reduce the lead time and rework. Such a framework demonstrates the configurator's ability to facilitate multi-party collaboration and information exchange through a parametric model and its associated parameters, extending beyond its well-known role in enabling customization. Despite the prevalence of various configurator methodologies used to serve design and architectural practitioners in commercial developments, the potential of configurators for a full model of detached residential housing development has been inadequately studied. The technology and knowledge prerequisites for commercial configurators in the market restrict direct access by clients during the project design phase. Some modular home fabricators provide configurator-like web wizards for clients to select a combination of kit-of-parts from their product catalog [16]. Such a system can be connected to downstream activities, such as automated inventory checking or the generation of quotation information. Despite this, clients are only able to configure products based on one of the pre-drawn plans instead of customizing a layout that suits their land parcels and living needs.

With the rapid advancement of Artificial Intelligence (AI), alongside the development of configurator algorithms, various literature has explored the use of generative algorithms for design automation [18,19], given a plot of apartment boundaries and user preference. Huang and Zheng [20] developed a novel method to conduct floor plan analysis and generation with a Generative Adversarial Neural Network (GAN). Patterns are recognized by turning floor plan images into blocks of colors, each representing a functional area with Pix2PixHD, a high-resolution image-to-image translation tool [21]. In the generation phase, the user is allowed to indicate locations for doors and windows. Also based on Pix2PixHD, Chaillou [22] prototyped ArchiGAN, a three-model generation stack, including footprint massing, program (functional area) repartitioning, and furniture layout. ArchiGAN has proven its benefits over the manual partitioning of room areas, especially for large-scale residential complexes or single homes with irregular enclosure shapes. Although ArchiGAN implements a user-friendly web-based interface to take inputs, the usability of the generated results is a concern. Its pipeline outputs are in raster image formats only, which cannot be further processed by architects and designers, for example, to add building envelopes or check for compliance [22,23].

To address the need to produce 3D rule-based and meaningful parametric models instead of raster images, BIM objects have been seen as a potential way to establish a digital hub that integrates all rule-based design information regarding the customizable properties and geometries of the building to coordinate among different stakeholders and across the entire building lifecycle. The Construction Management Association of America [24] highlighted that the successful adoption of BIM could improve communication and collaboration among project participants, as well as enhance compliance with specifications and standards from the perspective of mass customization. Such features made parameters-rich BIM ideal to be included in configurators as objects for selection [19,25]. Similarly, Zhang et al. (2018) [4] proved that BIM can be utilized by home buyers to communicate their preferences to interior designers unambiguously in the pre-design stage with their implementation of a BIM recommender system. Yet, the possibility of connecting to online BIM repositories to acquire a real-time mass data feed of certified materials for accurate processing (e.g., recommendation) has not been observed in the technological design of existing BIM-based configurator prototypes. Therefore, some native features in BIM repositories that streamline the design and procurement process, including automated quotation requests, have been inadequately utilized.

2.2. Configuration of Buildings to Meet Regulations and Supply Chain Capacity

By leveraging configurators, stakeholders in the construction industry can efficiently navigate through the complex landscape of building regulations (e.g., pre-approved building plans) while optimizing building configurations to align with the availability of ma-

materials and components from the supply chain. For example, as described by the U.S. Department of Housing and Urban Development's Office of Policy Development and Research (USHUD) [26], pre-approved plans are published by city councils or qualified architecture companies, which have already been reviewed by authorities for life, safety, and structural compliance. With only minor variations in the interiors, housing projects developed with those pre-approved architectural designs could entitle significant cost and time savings throughout the permitting process. Currently, more than 20 municipalities in the US and Canada have rolled out pre-approved blueprint programs. Despite this, most of the initiatives are only applicable to accessory dwelling units (ADUs) instead of entire single-family homes [27]. In areas with pre-approval schemes for complete residential units, the adoption of an existing drawing is a non-trivial task. Developers are normally required to visit the municipality office in person to examine and purchase drawings with a high level of detail before any interior configuration can be carried out [28].

There are ongoing administrative efforts regarding the mass adoption of pre-approved building plans at the national level. Recommendations have been made to Canadian housing authorities to implement a unified catalog for pre-approved and federal building code-compliant home designs [29] to streamline the acquisition of vetted blueprints for home developers. This administrative push toward standardization and efficiency has gained traction globally, with countries like Canada exploring strategies to facilitate the acquisition of vetted blueprints for residential buildings with digital repositories [30,31].

Moreover, there is compelling evidence to suggest that standardized building plans can lead to cost savings for developers and homeowners alike. A study by the National Institute of Standards and Technology [32] found that adopting standardized designs and components in construction projects can result in savings of up to 30% in construction costs. These savings can be attributed to various factors, including a reduced design time, streamlined procurement processes, and economies of scale in material purchasing. Furthermore, standardized building plans can have significant implications for sustainability and environmental conservation. By promoting the use of energy-efficient designs and materials, policymakers can contribute to the reduction in carbon emissions and the preservation of natural resources. A report by the World Green Building Council [33] highlights the potential of standardized building codes to drive innovation in sustainable construction practices, leading to greener and more resilient communities. In light of these benefits, the call for a unified catalog of pre-approved and federal building code-compliant home designs in Canada is not only timely but also essential for the continued growth and development of the residential construction industry. It is imperative to develop a novel computer-aided residence design framework in complement with such proposed digital repositories of blueprints to fully utilize their strength in reducing the time and resources spent on the design and approval process for homeowners.

In the meantime, researchers have used recommender systems to provide users with highly tailored and code-compliant content, aligning user requirements with building standards. Recommender systems operating in various algorithms have proven their commercial value in promoting sales and customer experience in different industries [34,35]. Extensive existing research work is focused on collaborative filtering [36], a recommender technique widely used in e-commerce. However, collaborative filtering is based on connecting the user's past activities (e.g., purchase, rate, or share of an object) with others' actions (community behaviors). Such dependency on enormous historical data made this approach unrealistic in construction kit-of-parts procurement settings. Another type of recommender system, a knowledge-based recommender, could resolve the issue of source data availability, as matching criteria are explicitly designed with information about user profiles, product attributes, and domain knowledge (e.g., compatibility constraints) [37]. Focused on the recommendation of BIM objects for interior finishing, Zhang et al. [4] applied a recommender by leveraging both knowledge-based recommendations and image similarity matching with a convolutional neural network, achieving elimination of products with incompatible attributes and prioritized results to match the user's preference. However, little research

work has investigated the integration of such a recommender in the housing supply chain, integrating upstream kit-of-parts compatibility checking and downstream quotation and procurement process, due to the complexities in building designs and difficulties in supply chain data acquisition.

2.3. Knowledge Gap

The current body of knowledge around housing and building product configurator development showcases the extensive potential of a configurator in customizing the dimensional or other performance properties of buildings. Some of them allow the clients and users to configure the building in a walk-through model directly in a web browser to even place an inquiry or quotation request. However, the intelligence of a configurator is not fully realized due to technical challenges in data integration, building regulations, and the involvement of non-expert household users. By streamlining the planning and approval process, reducing costs, and promoting sustainability, policymakers can create an environment conducive to innovation and growth in the construction sector. The implementation of a unified catalog of pre-approved and building code-compliant home designs in a configurator system has the potential to revolutionize the way residential buildings are designed, constructed, and inhabited, ultimately benefiting developers, homeowners, and society as a whole. Without such know-how, there exists a research gap in the scalable use of pre-approved blueprints, fabrication-aware and procurement-aware selection of certified materials, and homeowner's involvement in the decision-making process. This study proposes a configurator methodology that implements a state-of-the-art generative design tool and knowledge-based recommender system in a single platform with a web user interface. This work may serve as a first illustration of how to break supply chain silos in the construction industry by configuring code-compliant and buildable housing designs.

3. Methodology

This study proposes a novel configurator framework as the methodological contribution to the existing configurator platform designs, which integrates generative layout design and a recommender system for BIM catalogs. Aiming at conveying such a residential housing design approach with software vendors and housing developers, we considered reproducibility and adaptability throughout the framework and prototype development processes. The development of the proposed configurator is divided into 4 phases: ideation, seeding, realization, and evaluation. Figure 1 illustrates the detailed research steps.

In the ideation phase, we identified challenges in the implementation of IC configurators by reviewing the literature on BIM-based configurators, layout-generation algorithms, and kit-of-parts recommender systems. Additionally, the entire prototype was devised to fulfill the following non-functional requirements: (1) interoperability—possibility to exchange data with other software and systems, e.g., Autodesk Revit; (2) lightweight—can be operated without special hardware or installation of software locally; (3) malleability—able to accommodate add-on modules, e.g., life cycle analysis [38]; and (4) usability—presents self-explanatory interfaces for non-professional users.

The seeding process refers to populating databases with initial data before any business logic is implemented in codes. As up-to-date and code-compliant parameter sets for pre-approved plans and kit-of-parts lay the foundation for both the layout-generation and procurement-recommendation processes, we took it as a separate step prior to prototype realization. To achieve real-time integration of product catalog from upstream fabricators, we obtained a platform-wide API key to BIMStore [39], a BIM repository containing kit-of-parts available in multiple markets. Parameter sets of kit-of-parts in each category were retrieved from BIMStore with API calls and loaded into MongoDB with an automated script. The local copy of the parameter sets was synced with BIMStore periodically to track newly listed or removed items. Considering the complexity of parameters for any single BIM object, collection partitioning was used when seeding the database [40]. The parameter sets were stored in 3 MongoDB collections: Products, ProductParamSets, and Manufacturers.

The Products collection is seeded with a fixed schema containing pre-defined metadata fields about the product only. Product-specific or category-specific contents made up of variable fields (e.g., finish type and fire ratings) are stored in the Data field of documents in the ProductParamSets collection instead. It is possible for a single product to be linked with multiple documents in ProductParamSets, each representing a variant. Unstructured files, such as Revit models and product certification documents, are not included in the seeding phase. Instead, a URL or platform UUID is used to point the parameter set to file resources. Figure 2 shows the data attributes in the BIM object dataset to be collected and seeded with an Entity-Relationship (ER) Diagram excerpt.

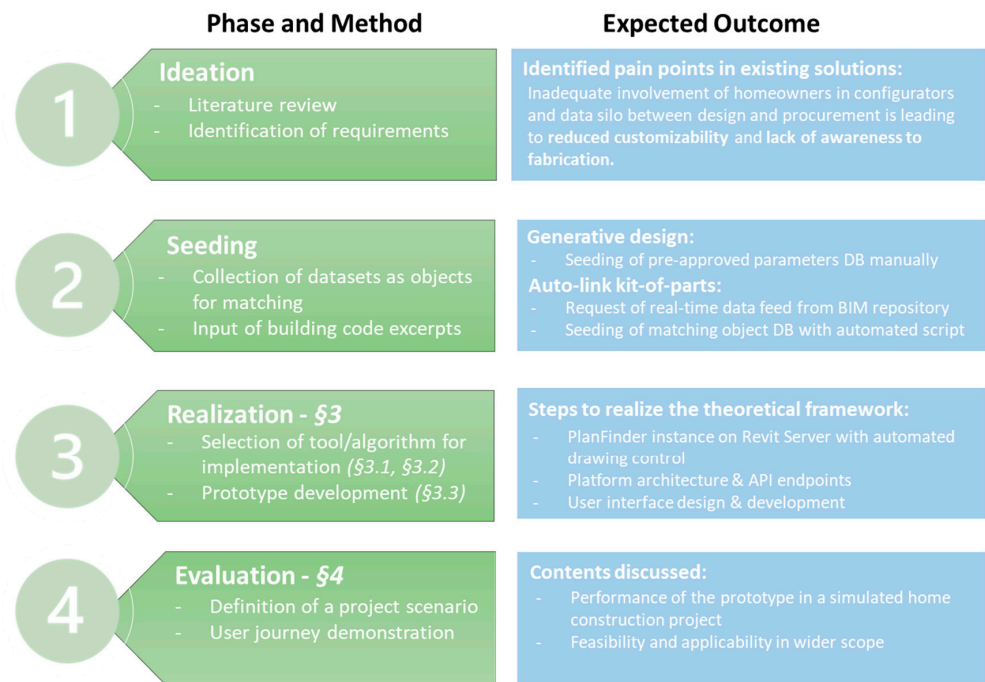
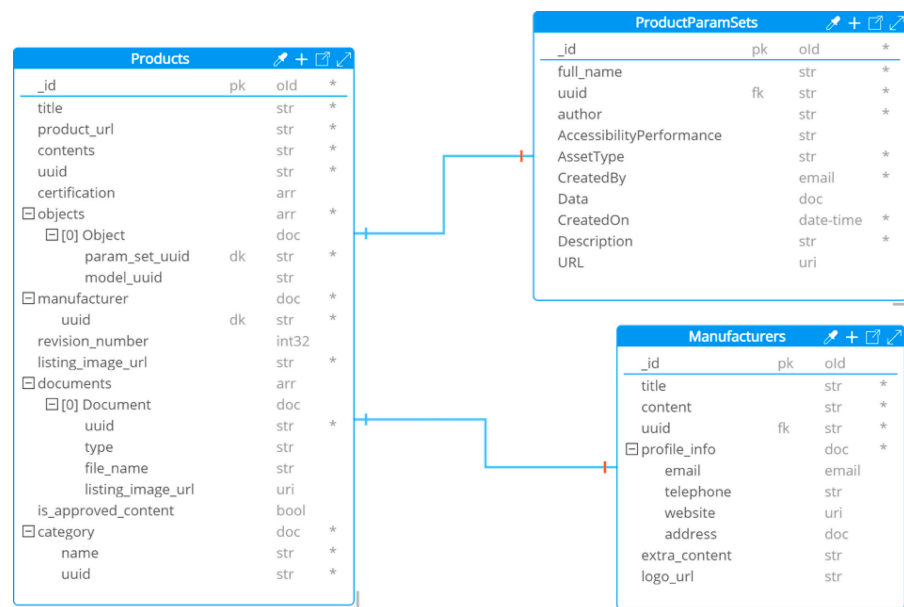


Figure 1. Research steps used to formulate the proposed configurator framework.



*Required fields. An object will be discarded if any required field cannot be fetched.

Figure 2. Collection and seeding of certified kit-of-parts parameter sets.

In addition to the referential plan and product objects, selected excerpts from building codes were also set up in the seeding phase, either in the form of JSON file (to be interpreted by the rule-based matching engine) or database query strings. Figure 3 shows the collection, redaction, and seeding of building code-based product selection rules. In the manual process of converting certain building codes or design guidelines into machine-readable and machine-executable formats, we considered such rules in 2 types: static rules and context-dependent rules. For static filtering rules that are universally applicable and only focus on the object (e.g., accessible design standards), they were processed into pre-stored MongoDB query strings. On the other hand, some provincial building codes were redacted as rule-engine definitions, as project context also needs to be considered (e.g., project location and size of a window well). Actual context parameters will be automatically parsed into the placeholder variables by the rule engine in runtime for kit-of-parts selection.

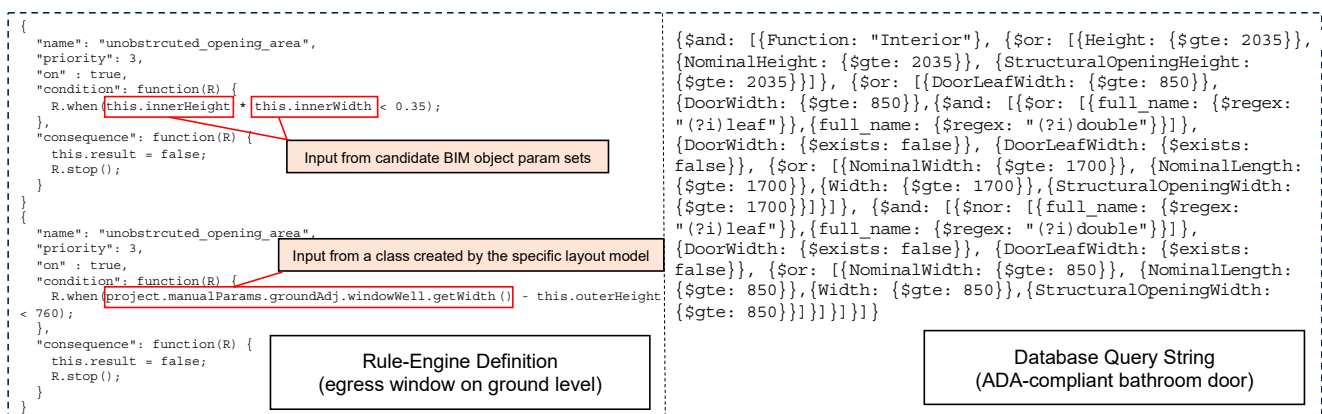


Figure 3. Collection, redaction, and seeding of building code-based product selection rules.

For the generative layout designs, the proposed framework utilized an open generative design tool, PlanFinder [41], which employs diffusion algorithms to produce 3–8 candidate layouts based on user-defined functional components, available land area, and desired exterior openings. These layouts are provided to the user in PDF, Autodesk Revit, and IFC formats, facilitating subsequent steps such as architect revision and compliance review. Then, the framework integrates the recommender system with the generative layout designs to address the lack of transparency in the construction materials market by employing hybrid mechanisms: knowledge-based filtering and text mining and semantic analysis. The knowledge-based filtering, implemented with a rule engine, screens out unsuitable BIM objects based on predefined rules, such as compliance with local building codes. Meanwhile, text mining analyzes descriptive wording input by the user to compute similarity scores for each object, prioritizing those that align closely with the user's preferences. The SBERT-transformer large language model [42] is selected for Natural Language Processing (NLP) to facilitate corpus-matching. This prototype aims to address research gaps while meeting non-functional requirements such as interoperability, lightweight operation, malleability, and usability. The detailed technical steps of realizing the proposed configurator framework are elaborated upon in Sections 3.1–3.3.

3.1. Generative Layout Design

Layout planning is usually an empirical step performed by interior designers and approved by the client. To reduce the time taken in preliminary drawing and maintain the degree of customization, the design configuration phase of our platform relies on a generative design tool, PlanFinder [41], which is based on diffusion algorithms. PlanFinder is capable of producing 3–8 candidate layouts, given the required functional components, shape and size of the plot that is available for construction, and desired exterior opening (external door or window) locations. In addition, this intelligent design tool allows

user-centric constraints to be defined during project generation, for example, a minimal dimension for each of the functional areas. The dimensional constraints, including locations of the openings, are retrieved from a database containing parameter sets of various pre-approved drawings. The specification for functional components is input by the user in an interactive interface. The generated plans are returned to the user in PDF, Autodesk Revit, and IFC formats. Subsequent steps, including architect's revision, compliance review, and extraction of material schedules, can be completed seamlessly. The preferred layout selected may serve as the prospective design directly or as a reference for interior designers to draft a more tailored one efficiently. Once a version of the layout is finalized, it will be forwarded to an architect to conduct building envelope fine-tuning and compliance checking. Figure 4 summarizes the steps used to generate BIM-based code-compliant floor layout designs to be pre-approved by local municipalities.

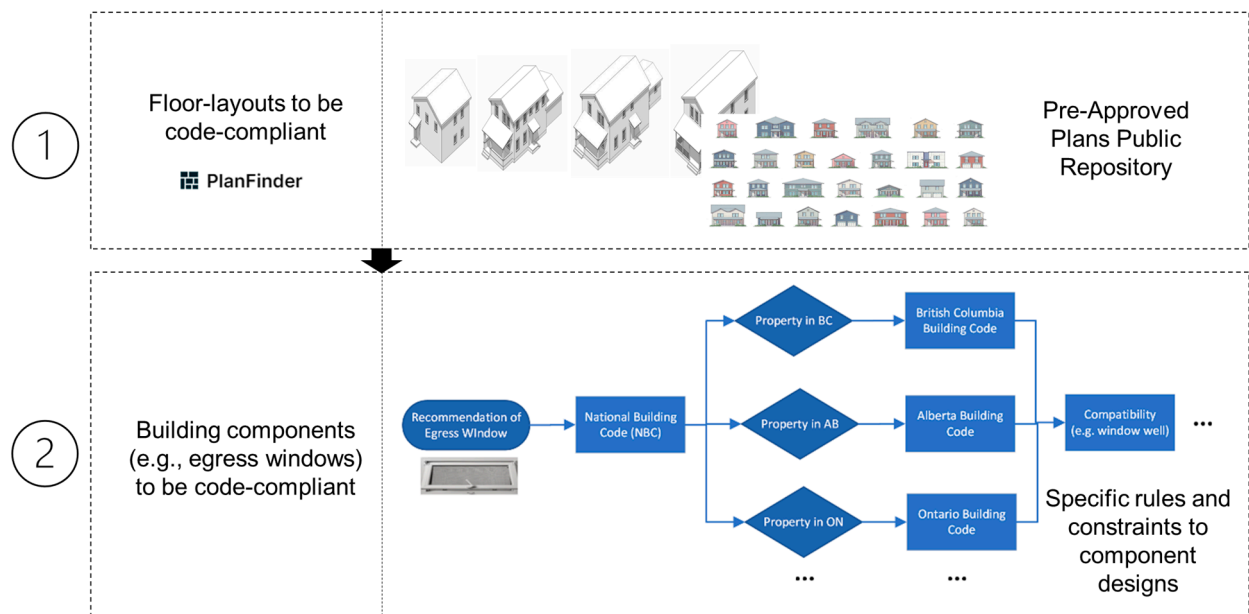


Figure 4. Steps to generate BIM-based code-compliant floor layout designs to be pre-approved by local municipalities.

3.2. Recommender System

The construction materials and kit-of-parts market is often characterized by a notable lack of transparency and the absence of a centralized repository for available information. Significant efforts are needed from the client to research the available product and their manufacturers to make informed decisions. To develop a recommender system that assists clients' decision-making processes in construction procurement settings, we prototyped a recommender that operates on hybrid mechanisms: (1) knowledge-based filtering and (2) text mining and semantic analysis. Building Information Modeling (BIM) repositories were used as the primary source of input data as they offer parameter sets of a product in machine-readable and interoperable formats (e.g., XML or JSON).

Initially, we connected all resources from the seeding stage, including databases for kit-of-parts parameters and pre-defined filtering rules, to the recommender pipeline in the backend server [36]. The knowledge-based filtering runs on top of node-rules 9.1.1, a forward-chaining rule engine library for Node.js environment. It is composed of various decision nodes to screen out BIM objects that are certainly not suitable for a particular project—for example, incompatible kit-of-parts or non-compliant modules with local building codes. Compared to hardcoded matching logic with conditional statement or regular expression solely, implementation of a rule engine enables optimization of rule evaluation

(scalability) and external rule management (adaptability), as the condition of filtering can be adjusted by non-developers without republishing a new version of the code.

Following the completion of constraint-based filtering, the second recommendation methodology, text mining, does not enforce any strict constraints, and it focuses on satisfying the user's preferences rather than building codes or compatibility logic. It takes descriptive wordings typed or checkboxes selected by the user as input. By going through the product summary and documentation (promotional brochure, technical specifications, and installation guides) on the BIM repository, a similarity score for the corpus is computed for each object. The similarity score ranges from 0 to 1, with a relatively higher one indicating the object is closer to the client's expectations and will be given higher priority to appear in the client's kit-of-parts selection screen. Due to the feature of full-text linkage, the SBERT-transformer large language model [42] is selected as the Natural Language Processing (NLP) algorithm for corpus-matching. Figure 5 summarizes the steps used to generate a list of recommendations for kit-of-parts and associated specifications.

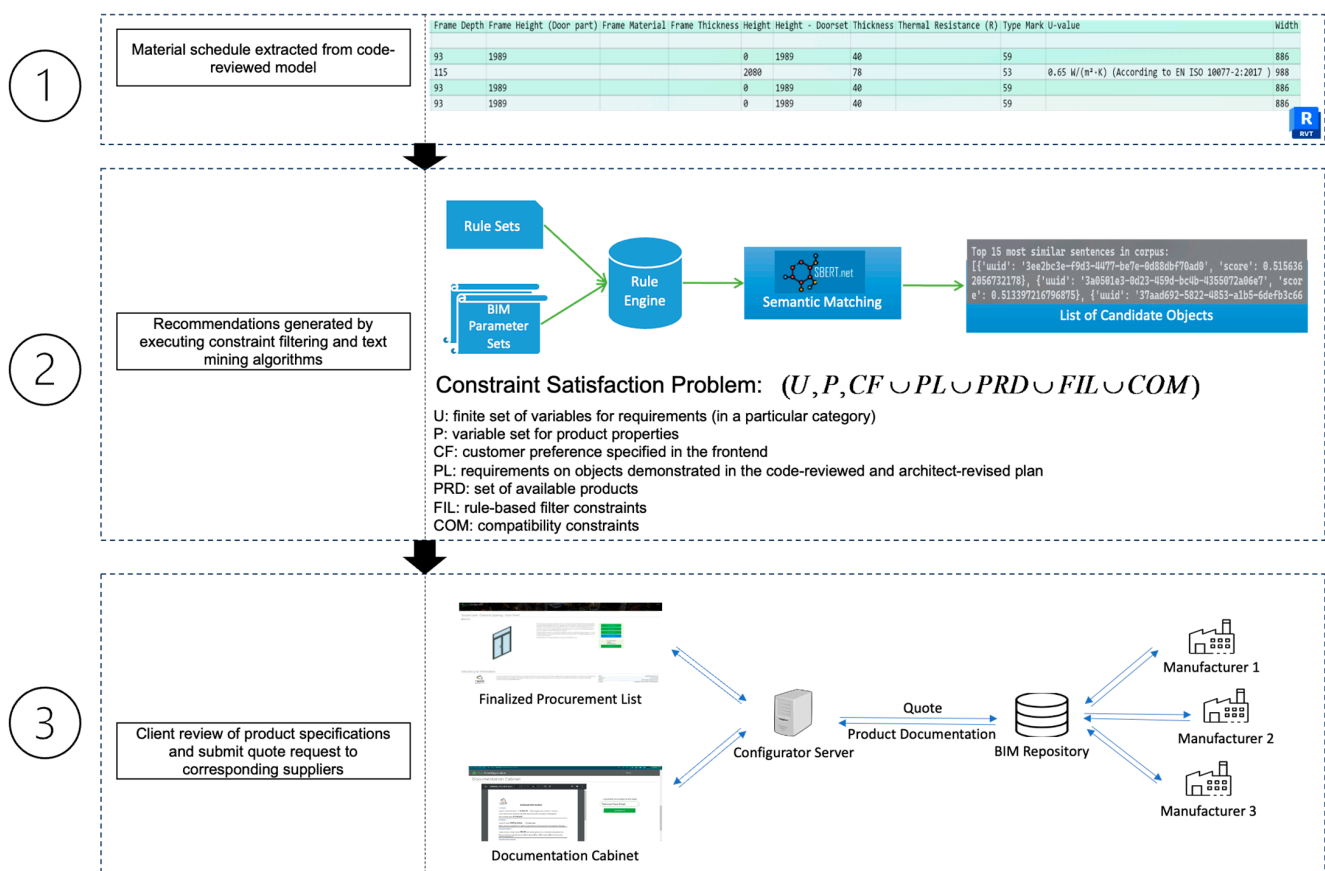
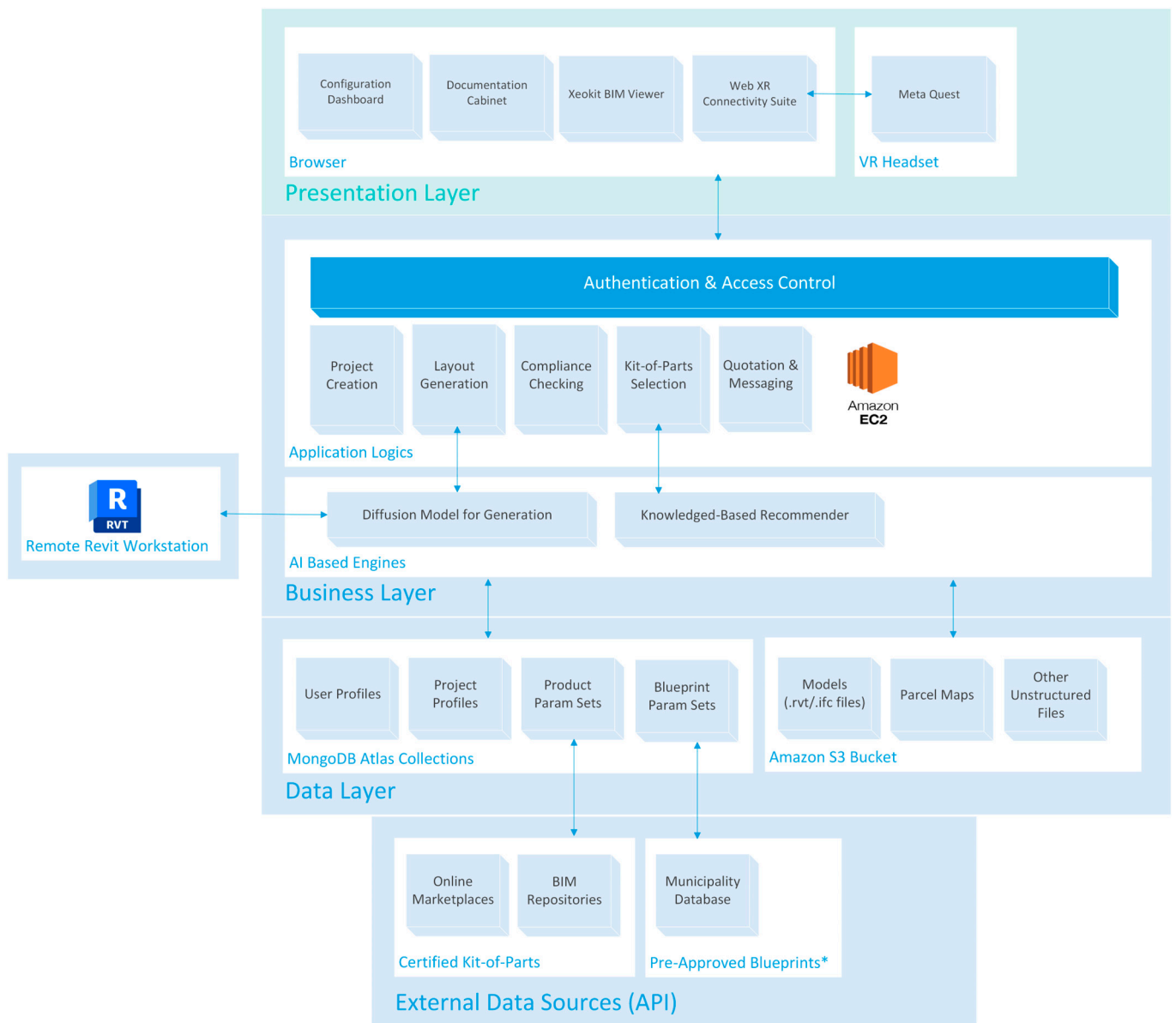


Figure 5. Steps to generate a list of recommendations for kit-of-parts and associated specifications.

3.3. Configurator System Architecture

Like other web-based productivity tools in the manufacturing industry, the system implementation follows a three-tier architecture (Figure 6), namely, a combination of the presentation layer, business (application) layer, and data layer [43]. To satisfy the interoperability, usability, and scalability requirements, it is necessary to determine appropriate technical specifications and execution environment assumptions for each layer. The user is expected to use a WebKit-based browser, IE 11+, or Firefox, with MacOS or Windows 7+ as the operating system. The business layer is deployed on an AWS EC2 server (T3 instances) with 32GB RAM and 8 virtual CPUs. MongoDB Atlas, a fully managed storage service based on MongoDB, was selected as the data layer solution, coupled with various external data sources.



*Deliverable feature but not implemented in the current prototype

Figure 6. The system architecture of the configurator prototype.

3.3.1. Presentation Layer

The presentation layer is required to possess a component-based architecture to realize the pluggability requirement, as proposed in system requirements. Therefore, React.js was selected as the web framework. One of the key strengths of React.js lies in its virtual DOM (Document Object Model) implementation. By maintaining a lightweight in-memory representation of the actual DOM, React.js can efficiently track changes and update only the necessary components, resulting in faster rendering times and improved performance. Moreover, React.js promotes a declarative programming paradigm, where developers describe how the UI should look based on the application's state rather than imperatively manipulating the DOM directly. This approach leads to more predictable and maintainable code, as well as facilitating easier debugging and testing. By dividing complex user interfaces into modules with their own states, the codebase is made more reusable and easier to maintain. This allows programmers to implement new user-viewable features and update existing ones without affecting other components.

3.3.2. Business Layer

The business layer components, including all HTTP request handlers, recommender system, and connectivity modules to the design generator, are hosted on an AWS EC2 cloud server. The request handlers are implemented with Express.js on Node.js 16 runtime to achieve service modularization. Part of the recommender system and its utilities are coded in Python 3 due to the variety of NLP libraries prevailing in its ecosystem. By tapping into this ecosystem, the configurator can harness advanced NLP techniques to interpret user inputs, extract meaningful information from material catalogs, and generate personalized recommendations. This approach enhances the user experience, streamlines decision-making processes, and ultimately contributes to the configurator's effectiveness in facilitating the design and procurement of residential buildings.

3.3.3. Data Layer

The data layer is of the utmost importance in our architecture. Due to the storage space and query processing time considerations, a document (JSON)-based No-SQL database management system, MongoDB, was used. Unstructured data, such as product documentation of finalized kit-of-parts, parcel maps, and municipality regulations in PDF or spreadsheet formats, were stored in an object-based storage service (Amazon S3 Bucket). Third-party data sources (e.g., BIM object repositories, geolocation service, and fabricator quotation portals) were integrated into the data layer through external API calls.

The Representational State Transfer (REST) system design style was implemented throughout the configurator's architecture. Each data object (user, project, kit-of-parts, model, and unstructured document) in the platform is indexed by a universal unique identifier (UUID), and all transfer of data is facilitated via HTTP methods. Besides scalability benefits, organizational users (e.g., community housing providers) may leverage API endpoints of the configurator server to build extended and customized programmatic functionalities, incorporating automated design and procurement of housing into their own business procedures. For example, community housing providers may implement automated reporting to enhance accountability and compliance with internal policies [44].

4. Proof-of-Concept Prototyping for a Single-Family Housing Project in BC, Canada

4.1. Project Description and Assumptions

As a client-facing productivity tool, the completion of a configuration and procurement cycle is essential to validate whether the user's journey is properly designed and whether backend logics are effectively implemented. In the proof of concept, a single-family, single-story residence construction project in South Vancouver was selected as the illustrative example. The project was initiated by a private developer (property owner). The residence should be comprehensively designed and procured for each module to fulfill its intended functionalities. This means that for a bathroom unit, elements such as the layout, interior textures, and fixed kit-of-parts must be included. The only components that may be omitted are those pertaining to mechanical, electrical, and plumbing (MEP) systems. The simulation was based on a less stringent but realistic assumption on the regulation of the usage of a pre-approved plan—that is, adjustments in the interior layout are allowed if no exterior structure or opening location is affected [45].

4.2. Demonstration of the Usability of the Configurator Platform

4.2.1. Project Setup

The homeowner begins to interact with the configurator platform by inputting basic information about the planned construction, including the site of the project, the expected number of occupants, and a plot of buildable ground area. An example of a project setup interface and automatic generation of plans (floor layout) is shown in Figure 7. In this stage, automated project location validation will be performed by the Geographic Information System (GIS) deployed on the configurator backend. Such validation depends on pre-defined rules to determine whether the adoption of pre-approved plans is feasible and notify

the backend architect of any location-specific compliance considerations (e.g., applicable municipality zoning by-laws) for reference in the model-tuning stage. Subsequently, the user will be prompted to indicate their preference for functional areas (e.g., bedrooms, guest WC, and walk-in closet), which will be fed to the generative design tool.

The screenshot displays the 'Plan Configurator' web interface. On the left, a sidebar contains project details for '14032 30a New Home', including Project ID, Primary Contact Email, Project Alias, Construction Type, Project Location, No. of Occupants, and Estimated Value of V. The main area is divided into three sections: 'Project setup information' (top), 'Automatic generation of plans based on functional preferences' (middle), and 'Functional Preference' (bottom). The 'Automatic generation of plans' section features a 'Plan Generator' with a yellow floor plan on a map and input fields for 'Buildable Plot Length' (16.40) and 'Buildable Plot Width' (6.30). The 'Functional Preference' section includes radio buttons for 'Number of Bedrooms' (2 selected), 'Number of Bathrooms' (1 selected), and checkboxes for 'Storage', 'Guest WC', 'Closed Kitchen', 'Walk-In Closet', and 'Meter Box Room' (all selected).

Figure 7. Configurator project setup interface and automatic generation of plans (floor layout).

4.2.2. Layout Configuration

Once the plan generation server has responded with candidate layouts, the configurator backend will transmit the model to the client in both IFC and Autodesk Revit formats. The user will be directed to a panel view for preliminary decision making. An example of a layout selection interface and 3D model preview is shown in Figure 8. To mitigate the need for non-professional end users to install BIM or CAD software, xeokit-bim-viewer 2.4.9, a JavaScript-based lightweight 3D model viewer is embedded in the frontend code [46] so that a preview of the layout, texture, and kit-of-parts can be rendered within the browser. Eventually, the client may select one preferred layout to be brought to the tuning and compliance review stage. In this process, architects intervene in the high-level-of-detail Revit model in the backend to fit the layout in a code-compliant building envelope.

Conventionally, once the initial ideation for layout design is completed, it is the architect's main responsibility to formulate a complete set of drawings for compliance. They are required to consider the following: (1) safety and structural integrity, (2) energy efficiency, (3) environmental concerns and accessibility, and (4) zoning regulations [47]. Since most of the required attributes for the building envelope (e.g., insulation, structural durability, and ventilation) are implemented in pre-approved blueprints, the role of an architect in the

compliance drawing process is transitioned to confirming zoning requirements, fitting the parametric model into a pre-approved envelope, and adopting permitted options to reduce construction costs or increase value—for example, simplifying or removing porch columns and brackets from the blueprint-based design, as discussed by the building authority of the City of South Bend [45].

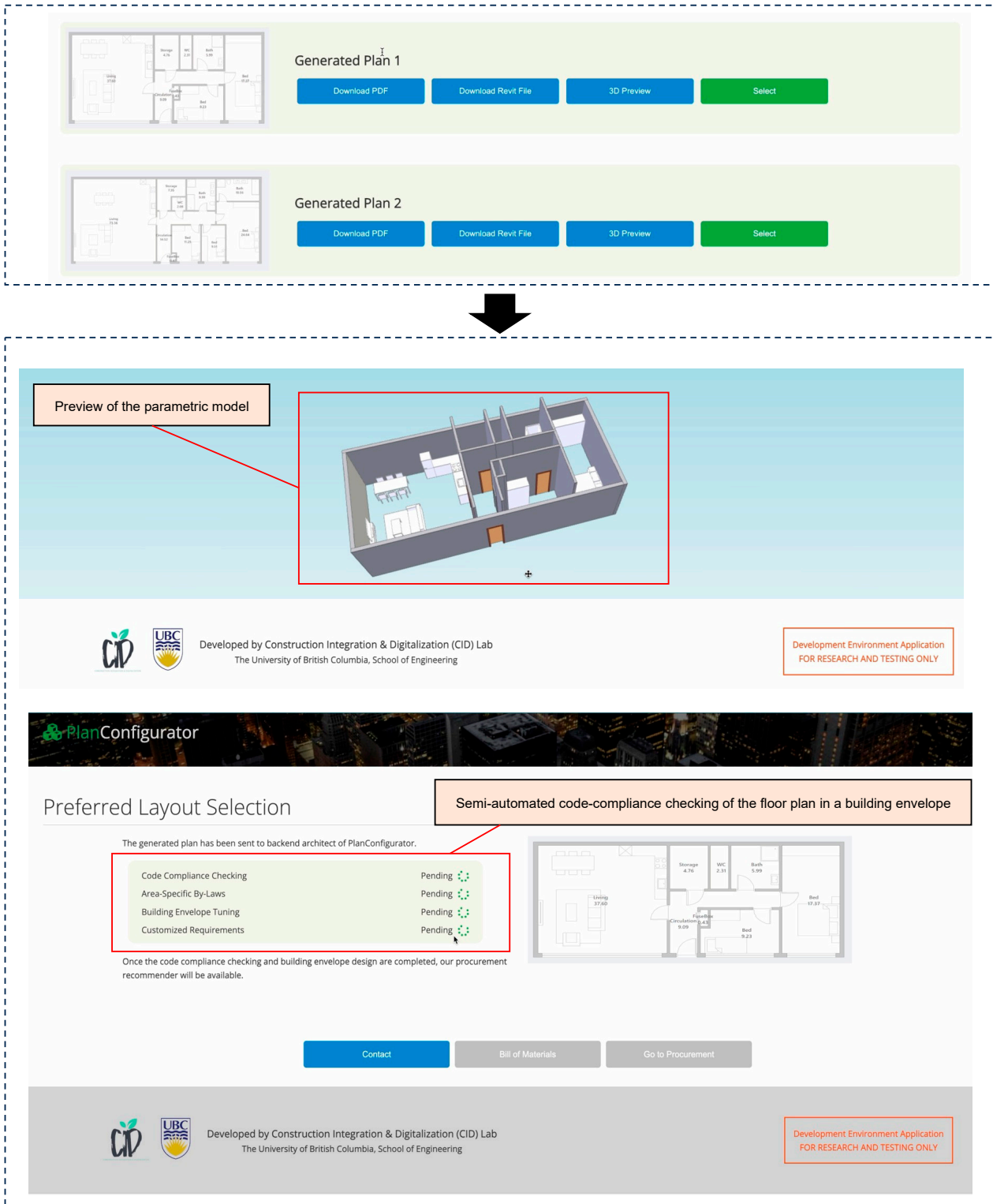


Figure 8. Layout selection interface and 3D model preview.

4.2.3. Product Configuration and Procurement Screening

After receiving the tuned model and materials schedule, the user's journey comes to product configuration. The knowledge-based recommender will be triggered for an optimized kit-of-parts procurement solution. The product selection wizard showcases to the user the most appropriate kit-of-parts, and all key information for procurement decisions (e.g., BIM files, product summary, manufacturer's profile, and relevant certification) is integrated into the same interface. An example of a recommended material catalog and documentation cabinet is shown in Figure 9. Leveraging the messaging and quotation capability of BIMStore, the user may issue quotation requests to a group of vendors. A list of product descriptions and specifications will be associated with the user's account if a selection is finalized. Related personnel may refer to the product brochures, installation guides, technical data sheets, and environmental product declarations (EPD) disclosed by the manufacturer and vendor. Such a document cabinet feature enables the user to easily manage key information of their procurement in the full lifecycle of the construction, from on-site assembly to post-completion maintenance. A step-by-step overview of the user's interaction with the configurator and associated information flows is shown in Figure 10.

The screenshot displays the PlanConfigurator interface. At the top, a banner shows a recommended material catalog for a 'Double Leaf - Outward Opening - Over Panel' door system. Below this, the 'Documentation Cabinet' section is visible, containing technical data and specifications for the selected object. The technical information includes U values (1.4 W/m²K), G values (0.47 g value), acoustic values (38 dB), and weather performance details. A sidebar on the right indicates that 7 documents are available for this object, with a dropdown menu showing 'Technical Data Sheet' and a 'Download All' button.

Figure 9. Recommended material catalog and documentation cabinet.

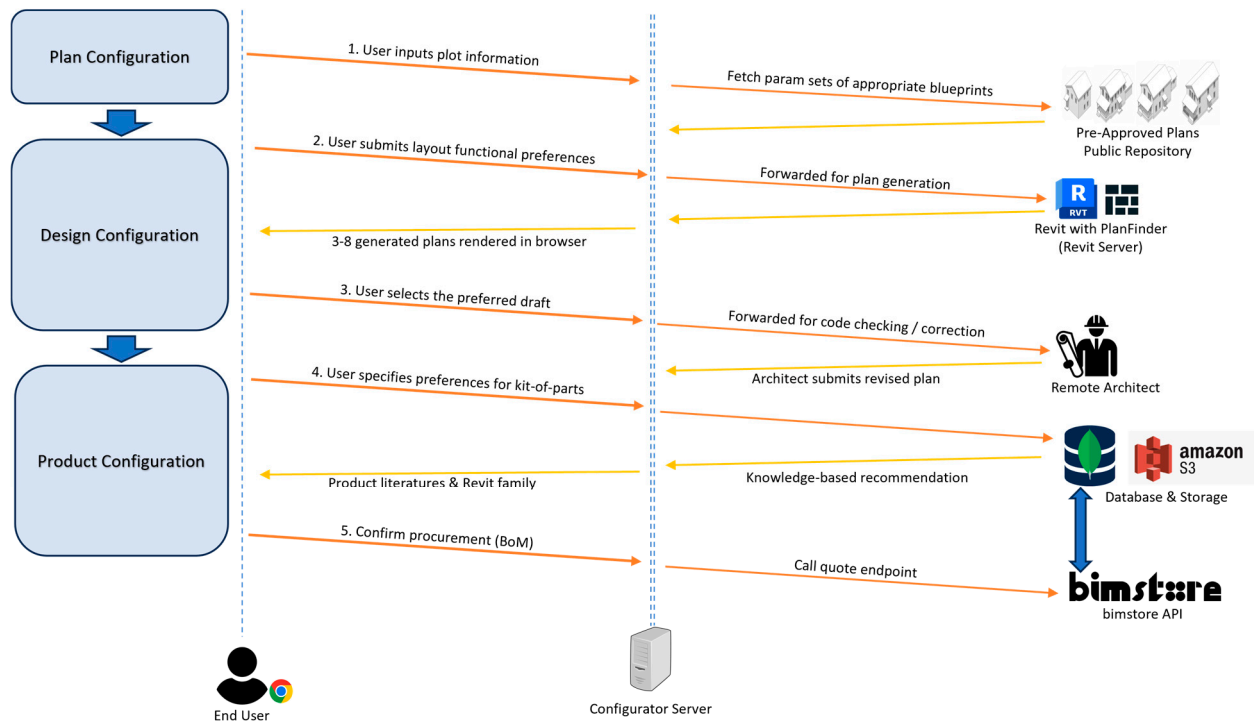


Figure 10. Step-by-step overview of the user's interaction with the configurator and associated information flows (i.e., user's journey with the proposed configurator).

5. Discussion

5.1. Expedited Pre-Construction Phase Due to Code-Compliant Designs and Certified Materials

With an increased degree of automation, the proof of concept demonstrates a significant cut in the planning time spent on interior layout design and kit-of-parts selection, two overwhelming phases where property owners inevitably participate. Though a detailed time study or cost study was not implemented alongside the prototyping test due to limited research resources, several government partners quoted during the CMHC project webinar that the potential reduction in working hours of professional designers could be achieved to meet mass customization needs in BC, and property owners can potentially benefit from supply chain-related labor cost savings because of the certified material catalog. In addition to the shortened drawing process, the AI-powered plan generator also exhibits the potential to expedite compliance checking and final issuance of a building permit in cases where pre-approved blueprints are applicable in the location of the project. It is feasible to run generative algorithms on a range of pre-approved blueprint models instead of boundary parameter sets, provided the presence of a unified blueprint catalog and partnerships with municipalities through the implementation of API connections.

Despite the observed benefits of a shortened pre-construction phase and reduced working hours, interior layout generation based on a pre-approved plan may raise concerns about design accuracy and the degree of customization. By examining the generated parametric models visually and analyzing the runtime log in the backend, we discovered that such layout generation outputs are capable of accurately reflecting the user's indicated preferences, and the extracted material schedule can be properly parsed and processed by the recommender system. As diffusion-based generative algorithms are non-deterministic [48], the outputs can vary, even if two configuration instances have identical ground boundaries and user-centric inputs. Yet, PlanFinder's output is not flawless in terms of circulation design. For example, conflicting door swings may block circulation, resulting in a need for manual correction by the architect in some cases.

Meanwhile, the scope and standard operating procedure (SOP) for pre-approval schemes varies among different municipalities. The part that directly affects the diversity of

buildings and customization potentials is the definition of “permitted variations” [26] and the corresponding processes in which the changes are proposed, reviewed, and approved. In addition, the current practice of listing blueprints usually involves a competitive process (e.g., design competition) held on a routine basis, which may lead to homogeneity of the building facade and administrative overhead [49]. Fortunately, the issue of inconsistency in the permitted customization level and limited building envelope options can be addressed by adopting a discretionary approach to archive standardized design or centralizing the supervision of pre-approval schemes at the provincial/state level [49,50].

5.2. Streamlined Communication with Suppliers and Product Fabricators

Conventionally, property owners and the general contractor acting on their behalf are required to reach out to various manufacturers to request product specifications, submit quote requests, and place orders. Such a manual process through telephone, email, and personal visits is time-consuming [51,52]. The lack of a standardized approach to managing communications and returned information may lead to human errors and delays, hence affecting optimal decision making for procurement. The proposed cloud configurator integrates all information flow between the project team and suppliers of kit-of-parts in a single dashboard, addressing inefficiency in data exchange. As communications with manufacturers are channeled by the BIM repository’s messaging API endpoints, they can receive and respond to client requests with the BIM repository they are currently registered with, following their existing workflow. By expanding API access to more BIM repositories, users can reach manufacturers in various geographical locations to further broaden available options for the client, reduce lead time, and optimize logistics costs.

5.3. Simplified Implementation of Inclusive Designs through Intelligent Recommendations

Inclusive housing design refers to creating living spaces that are accessible and accommodatable to individuals of all ages, abilities, and backgrounds [53]. It is an extension of accessible design, which considers the safety and living experience of all members in a household, including tots, children, working-age residents, and seniors [54]. Currently, there is an inadequate systematic methodology for clients or contracted designers to efficiently select kit-of-parts to achieve inclusive design. The suitability of kit-of-parts needs to be reviewed on a one-by-one basis in the procurement process. The smart recommender system embedded in the configurator empowers efficient screening of objects to meet the special needs of one or more targeted groups. For example, a collection of rule-based constraints adapted from the Americans with Disabilities Act Accessible Design Guidelines [55] are incorporated in the rule engine. Users may filter various compliance interior components, such as bathroom units, hallways, and doors, with a single click. Since inclusive design constraints are defined in JSON format, designers are also allowed to redact their own sets of product selection criteria. Further improvements to the platform include providing them with an interactive interface that translates requirements parameters to machine-readable formats and saves them as rule nodes so that they can reuse their work to implement inclusive design in other projects in the future.

5.4. Increased Client Involvement Due to Its Potential to Integrate Immersive Environments

Client involvement in the planning and design phase of a residential housing project is essential to ensure that customized components are delivered as expected and the costs associated with those are well understood. Conventionally, the client needs to maintain close contact with their designer to convey their customization specifications and provide feedback to the designer’s preliminary work. Drawings need to be transmitted between the client, designers, and contractors back and forth, which lasts for the entire planning stage until the initiation of permit acquisition. Such a practice may frequently lead to misunderstanding of the client’s needs, surprises, and rework. In a survey [56] conducted on 1000 Americans who were exposed to residence development as property owners, 59% of respondents claimed they felt stressed, anxious, or frustrated during the construction

process. Moreover, 88% of owners believed they should have made different decisions during the planning phase. The configurator prototype enables owners to work with designers in a parallel manner, instead of the traditional waterfall approach, on both design and product configuration.

Differently from various existing commercial configurator solutions targeted at professionals, the property owner manipulates the model and bill of materials directly, guided by the recommender system. Pre-construction drawings are updated in an agile way. Interactive decision analysis enables succinct validation of design with a focus on prospective living experiences [57]. The built-in browser-based BIM 3D viewer provides clients and designers with real-time visualization of configuration outcomes. Users with active software subscriptions can download models with a higher level of detail for examination in BIM or CAD tools, such as Autodesk Revit or Rhino 3D. The proposed configurator platform, leveraging a microservices-based system architecture, exhibits a high degree of extensibility as a web-based application. The proof of concept has affirmed the feasibility of incorporating Virtual Reality (VR) technologies with the Oculus Quest 2 headset. Such implementation could significantly enhance the immersive design preview experience.

6. Conclusions and Future Work

The concept of a configurator has received significant attention in recent years alongside the development of industrialized construction, which typically utilizes a combination of algorithms to provide users with a seamless and interactive customization experience. The current literature about configurator development showcases the challenges in supply chain information integration and system scalability, hindering broader acceptance across diverse communities due to challenges in accommodating extensive customization, unique supply chains, and local building codes. By leveraging generative designs, recommendation systems, and Building Information Modeling (BIM) repositories, this study proposes a comprehensive methodological framework for cloud-based lightweight configurator development. Through a proof-of-concept demonstration of configuring single-family housing in British Columbia, Canada, the proposed configurator prototype efficiently achieved code-compliant designs and intelligent material catalog matching (i.e., recommendation). This research lays the groundwork for more streamlined residential project supply chain processes. Additional testing and refinement of the configurator prototype in geographically different real-world scenarios will be crucial to validate its effectiveness and ensure its practical utility in diverse construction contexts.

Aiming for a larger scope in the future, this study will be extended to include functions of the industrialization of a holistic construction supply chain to meet mass customization needs. Previous studies have advocated for design in manufacturing and assembly by integrating manufacturing expertise during the design phase. Designers often lack the requisite production knowledge and product availability information to initiate and deepen design models, leading to delays and potential design rework issues only discovered late in the production cycle. Rectifying such issues demands additional efforts in configurator development and validation across different project stages.

By understanding the impact of supply chain coordination complexity on the adoption of the configurator, it is possible to define benchmarks or performance indicators to validate the usefulness of the configurator platform. Methods to conduct the validations may include surveys or user acceptance test (UAT) benchmarking, involving homeowners, architects, kit-of-parts suppliers, and building authority personnel. For instance, visualizing the flow of procured kit-of-parts or incorporating a supplier management system that tracks outstanding contracts and orders can be substantially helpful in monitoring supply chain performance. Considering that the design and supply information are stored consistently in a cloud-based platform across different project stages, stakeholders can retrieve the information at the end-of-life stage of the building project to plan for “reconfiguration” and disassembly-oriented design strategies. Therefore, future research will also focus on building configurator designs for reconfiguration to improve construction resource efficiencies.

Author Contributions: Conceptualization, Q.C. and S.W.; methodology, Q.C. and S.W.; software, S.W.; validation, Q.C. and S.W.; formal analysis, S.W.; investigation, S.W.; resources, Q.C.; data curation, S.W.; writing—original draft preparation, Q.C. and S.W.; writing—review and editing, Q.C. and S.W.; visualization, S.W.; supervision, Q.C.; project administration, Q.C.; funding acquisition, Q.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Canada Mortgage and Housing Corporation funded project “Kit-of-Parts Platform System (KOPPS) to Provide Affordable, Sustainable and Resilient Housing in Canada” (Fund No: PO006788-1), and The APC was funded by the University of British Columbia Aspire Fund (Fund No: AWD-022769 UBCOVR 2022).

Data Availability Statement: Some or all data, models, or simulation codes that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: Special thanks are also given to BIMStore, which provided an open API for the authors to develop the integrated BIM object database for the configurator platform.

Conflicts of Interest: The authors whose names are listed for this paper declare no competing and/or conflicting interests.

References

1. Read, D.C.; Sedgwick, D.; Hughen, W.K. Ten pieces of advice US municipal planners should follow when evaluating prospective affordable housing partners. *Plan. Pract. Res.* **2024**, *39*, 558–563. [CrossRef]
2. Canada Mortgage and Housing Corporation. Insights into Housing Supply in Canada’s Largest Cities. 19 April 2023. Available online: <https://www.cmhc-schl.gc.ca/blog/2023/insights-housing-supply-canadas-largest-cities> (accessed on 20 March 2024).
3. Ng, M.S.; Chen, Q.; Hall, D.M.; Hackl, J.; Adey, B.T. Designing for digital fabrication: An empirical study of industry needs, perceived benefits, and strategies for adoption. *J. Manag. Eng.* **2022**, *38*, 04022052. [CrossRef]
4. Zhang, Y.; Liu, H.; Al-Hussein, M. Recommender system for improving BIM efficiency: An interior finishing case study. In Proceedings of the Construction Research Congress, New Orleans, LA, USA, 2–4 April 2018. [CrossRef]
5. Chen, Q.; Adey, B.T.; Haas, C.; Hall, D.M. Using look-ahead plans to improve material flow processes on construction projects when using BIM and RFID technologies. *Constr. Innov.* **2020**, *20*, 471–508. [CrossRef]
6. Esfahani, M.E.; Rausch, C.; Sharif, M.M.; Chen, Q.; Haas, C.; Adey, B.T. Quantitative investigation on the accuracy and precision of Scan-to-BIM under different modelling scenarios. *Autom. Constr.* **2021**, *126*, 103686. [CrossRef]
7. Kedir, F.; Chen, Q.; Hall, D.M.; Adey, B.T.; Boyd, R. Formative scenario analysis of the factors influencing the adoption of industrialised construction in countries with high housing demand—the cases of Ethiopia, Kenya, and South Africa. *Constr. Manag. Econ.* **2022**, *40*, 690–710. [CrossRef]
8. Cao, J.; Bucher, D.F.; Hall, D.M.; Lessing, J. Cross-phase product configurator for modular buildings using kit-of-parts. *Autom. Constr.* **2021**, *137*, 103437. [CrossRef]
9. Jensen, K.N.; Nielsen, K.; Brunoe, T.D. Application of mass customization in the construction industry. In *Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth*; Springer: Cham, Switzerland, 2015; pp. 161–168. [CrossRef]
10. Cao, J.; Hall, D. An overview of configurators for industrialized construction: Typologies, customer requirements, and technical approaches. In Proceedings of the 2019 European Conference on Computing in Construction, Chania, Greece, 10–12 July 2019; pp. 295–303. [CrossRef]
11. HiStruct & FemCAD Solutions. Building Configurator. 2023. Available online: <https://www.histruct.com/> (accessed on 20 March 2024).
12. Renewtech ApS. DELL EMC Server Configurator. Renewtech. Available online: <https://www.renewtech.com/server-configurator/dell.html> (accessed on 20 March 2024).
13. Bombardier. (n.d.) Build Your Own Plane. Available online: <https://businessaircraft.bombardier.com/en/configurator#!/aircraft> (accessed on 20 March 2024).
14. Chen, Q.; García de Soto, B.; Adey, B.T. Supplier-contractor coordination approach to managing demand fluctuations of ready-mix concrete. *Autom. Constr.* **2021**, *121*, 103423. [CrossRef]
15. TestFit. TestFit Overview: Real Estate Feasibility Platform. 2023. Available online: <https://www.testfit.io/overview> (accessed on 7 November 2023).
16. Built Prefab. Build and Price Tool. 2023. Available online: <https://builtprefab.com/product/build-and-price-your-home#floorplan> (accessed on 7 November 2023).
17. Piroozfar, P.; Farr ER, P.; Hvam, L.; Robinson, D.; Shafiee, S. Configuration platform for customisation of design, manufacturing, and assembly processes of building façade systems: A building information modelling perspective. *Autom. Constr.* **2019**, *106*, 102914. [CrossRef]

18. Bhilare, S.; Khatri, D.; Rangnekar, S.; Chen, Q. Using BIM to Facilitate Generative Target Value Design for Energy Efficient Buildings. In Proceedings of the International Symposium on Automation and Robotics in Construction, Chennai, India, 5–6 July 2023; IAARC Publications. 2023; Volume 40, pp. 667–674. [CrossRef]
19. Jeong, W.; Kong, B.; Adhikari, M.D.; Yum, S.G. The Development of a Framework for the Automated Translation of Sketch-Based Data into BIM Models. *Buildings* **2024**, *14*, 916. [CrossRef]
20. Huang, W.; Zheng, H. Architectural Drawings Recognition and Generation through Machine Learning. In Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Mexico City, Mexico, 18–20 October 2018. [CrossRef]
21. Wang, T.-C.; Liu, M.-Y.; Zhu, J.-Y.; Tao, A.; Kautz, J.; Catanzaro, B. High-Resolution Image Synthesis and Semantic Manipulation with Conditional GANs. 2017. Available online: <https://arxiv.org/pdf/1711.11585.pdf> (accessed on 24 March 2024).
22. Chaillou, S. Archigan: Artificial intelligence X architecture. In *Architectural Intelligence*; Springer: Singapore, 2020; pp. 117–127. [CrossRef]
23. Yong, L.; Chibiao, H. A generative design method of building layout generated by path. *Appl. Math. Nonlinear Sci.* **2022**, *7*, 825–848. [CrossRef]
24. Construction Management Association of America. FMI/CMAA Eighth Annual Survey of Owners 2007. McLean, VA. 2007. Available online: <http://www.cmaafoundation.org/files/surveys/2007-survey.pdf> (accessed on 20 March 2024).
25. Farr ER, P.; Piroozfar PA, E.; Robinson, D. BIM as a generic configurator for facilitation of customisation in the AEC Industry. *Autom. Constr.* **2014**, *45*, 119–125. [CrossRef]
26. United States Department of Housing and Urban Development’s Office of Policy Development and Research (USHUD). Portland, Oregon: Living Smart Program. 2024. Available online: https://www.huduser.gov/portal/casestudies/study_101711_1.html (accessed on 24 March 2024).
27. Patras, E.S. Need to Boost Housing Production? Consider Pre-approved Building Plans. Greater Ohio Policy Center. 3 October 2023. Available online: <https://www.greaterohio.org/blog/2023/9/27/need-to-boost-housing-production-consider-pre-approved-building-plans> (accessed on 20 March 2024).
28. Regional District of North Okanagan. Pre-Approved Building Plans for Sale. 2023. Available online: <https://www.rdno.ca/purchaseplans> (accessed on 24 March 2024).
29. Richter, T.; Moffatt, M.P.; Brooks, M. The National Housing Accord: A Multi-Sector Approach to Ending Canada’s Rental Housing Crisis. Canadian Alliance to End Homelessness. 2023. Available online: https://assets.nationbuilder.com/caeh/pages/453/attachments/original/1692060486/2023_National_Housing_Accord.pdf?1692060486 (accessed on 24 March 2024).
30. District of Columbia Department of Buildings. Pre-Approved Plans FAQs. 2023. Available online: <https://dob.dc.gov/node/1618206> (accessed on 20 March 2024).
31. City of Tucson. City of Tucson Casita Model Plan Library. 2023. Available online: <https://casitas-in-tucson-cotgis.hub.arcgis.com/pages/casita-model-plan-library> (accessed on 26 March 2024).
32. National Institute of Standards and Technology (NIST). Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry. 2004. Available online: <https://nvlpubs.nist.gov/nistpubs/gcr/2004/nist.gcr.04-867.pdf> (accessed on 8 April 2024).
33. World Green Building Council (WGBC). The Circular Built Environment Playbook. 2023. Available online: https://worldgbc.org/wp-content/uploads/2023/05/Circular-Built-Environment-Playbook-Report_Final.pdf (accessed on 24 March 2024).
34. Widayanti, R.; Chakim MH, R.; Lukita, C.; Rahardja, U.; Lutfiani, N. Improving Recommender Systems using Hybrid Techniques of Collaborative Filtering and Content-Based Filtering. *J. Appl. Data Sci.* **2023**, *4*, 289–302. [CrossRef]
35. Chiu, M.C.; Huang, J.H.; Gupta, S.; Akman, G. Developing a personalized recommendation system in a smart product service system based on unsupervised learning model. *Comput. Ind.* **2021**, *128*, 103421. [CrossRef]
36. Koren, Y.; Bell, R. Advances in Collaborative Filtering. In *Recommender Systems Handbook*; Springer: New York, NY, USA, 2011; pp. 145–186. [CrossRef]
37. Aggarwal, C.C. Knowledge-based recommender systems. In *Recommender Systems*; Springer: Cham, Switzerland, 2016; pp. 167–197. [CrossRef]
38. Namaki, P.; Vegesna, B.S.; Bigdellou, S.; Chen, R.; Chen, Q. An Integrated Building Information Modeling and Life-Cycle Assessment Approach to Facilitate Design Decisions on Sustainable Building Projects in Canada. *Sustainability* **2024**, *16*, 4718. [CrossRef]
39. BIMStore. Download BIM objects for Revit—Free BIM Library. 2023. Available online: <https://www.bimstore.co/> (accessed on 30 November 2023).
40. Copeland, R. *MongoDB Applied Design Patterns: Practical Use Cases with the Leading NoSQL Database*; O’Reilly Media: Sebastopol, CA, USA, 2013; pp. 75–83.
41. PlanFinder. About PlanFinder. 2023. Available online: <https://www.planfinder.xyz/about> (accessed on 7 November 2023).
42. Reimers, N.; Gurevych, I. Sentence-BERT: Sentence Embeddings Using Siamese BERT-Networks. *arXiv* **2019**, arXiv:1908.10084. Available online: <https://arxiv.org/abs/1908.10084> (accessed on 24 March 2024).
43. IBM. What Is Three-Tier Architecture? 2020. Available online: <https://www.ibm.com/topics/three-tier-architecture> (accessed on 21 March 2024).
44. BC Housing. Financial Management Guide: Housing Provider Kit. BC Housing. 2015. Available online: <https://www.bchousing.org/publications/Housing-Provider-Kit-Financial-Management-Guide.pdf> (accessed on 30 November 2023).

45. City of South Bend. South Bend Pre-Approved Buildings: Process. 2022. Available online: https://southbendin.gov/wp-content/uploads/2022/08/SBBT_Process_22-0812.pdf (accessed on 20 March 2024).
46. Xeolabs. Xeokit SDK: Web Programming Toolkit for AEC Graphics. 2023. Available online: <https://xeokit.io/> (accessed on 24 March 2024).
47. British Columbia Office of Housing and Construction Standards. Changes for Local Governments Under Section 5 of the Building Act—Appendix to Section B1 of the Building Act Guide. 2020. Available online: https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/construction-industry/building-codes-and-standards/guides/section_b_appendix_dec_2020_update.pdf (accessed on 20 March 2024).
48. Ho, J.; Jain, A.; Abbeel, P. Denoising diffusion probabilistic models. *Adv. Neural Inf. Process. Syst.* **2020**, *33*, 6840–6851.
49. Enger, S. What’s Not to Like?—Pre-Approved Plans Offer Faster Permitting, Cheaper Housing, Quality Design. MRSC Insight Blog. 3 July 2014. Available online: <https://mrsc.org/stay-informed/mrsc-insight/july-2014/what%E2%80%99s-not-to-like-%E2%80%93-pre-approved-plans-offer-fast> (accessed on 30 April 2024).
50. BC Gov News. New Standardized Designs Will Help Build More Homes Quicker [Press Release]. 19 September 2023. Available online: <https://news.gov.bc.ca/releases/2023HOUS0158-001798> (accessed on 30 April 2024).
51. Chen, Q.; Adey, B.T.; Haas, C.T.; Hall, D.M. Exploiting digitalization for the coordination of required changes to improve engineer-to-order materials flow management. *Constr. Innov.* **2022**, *22*, 76–100. [CrossRef]
52. Olanrewaju, A.; Tan, S.Y.; Kwan, L.F. Roles of communication on performance of the construction sector. *Procedia Eng.* **2017**, *196*, 763–770. [CrossRef]
53. Gamble, P. Building in Inclusive Design: A Modern Housing Perspective (Viewpoint 71). Housing Learning & Improvement Network. 2015. Available online: https://www.housinglin.org.uk/_assets/Resources/Housing/Support_materials/Viewpoints/HLIN_Viewpoint71_Inclusive-Design.pdf (accessed on 20 March 2024).
54. Inclusion BC. Inclusion BC Housing Fact Sheets. 2023. Available online: <https://inclusion-bc.org/wp-content/uploads/2023/09/Inclusion-BC-Housing-Fact-Sheets.pdf> (accessed on 26 April 2024).
55. United States Department of Justice Civil Right Division. Guidance on the 2010 ADA Standards for Accessible Design. 2010. Available online: <https://www.ada.gov/assets/pdfs/guidance-2010-standards.pdf> (accessed on 24 March 2024).
56. Duffy, P.S. Most Americans Have Regrets about Buying a New Construction Home (2022 Data). 2022. Available online: <https://www.realestatewitch.com/buying-new-construction-home-2022-data/> (accessed on 30 November 2023).
57. Yogeewaran, K.; Chen, Q.; García de Soto, B. Utilizing augmented reality for the assembly and disassembly of panelized construction. *J. Inf. Technol. Constr.* **2023**, *28*, 571–584. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.