Energy Performance and LCA-driven Computational Design Methodology for Integrating Modular Construction in Adaptation of Concrete Residential Towers in Cold Climates

Sheida Shahi[a], Patryk Wozniczka[b], Tristan Truyens[b], Ian Trudeau[b], Carl Haas[a]

[a]Department of Civil and Environmental Engineering, University of Waterloo, Canada
[b]Entuitive Consulting Engineers, Canada
E-mail: sshahi@uwaterloo.ca, patryk.wozniczka@entuitive.com, tristan.truyens@entuitive.com, ian.trudeau@entuitive.com, chaas@uwaterloo.ca

Abstract –

Adaptation of dated residential towers is an urgent issue due to aging housing infrastructure and growing demand for affordable housing. Computational design methodologies have the potential for facilitating optimized design strategies driven by improved energy performance and reduced life-cycle carbon emissions. Modular Construction (MC) can also increase efficiencies in the design and implementation of building adaptation projects and minimize construction waste. The application of MC in the adaptation of existing buildings is gaining interest with improvements to MC technologies and processes, as well as large-scale adoption. There are currently no frameworks for the integration of MC in the adaptation of complex buildings driven by energy performance and Life Cycle Analysis (LCA). To address this gap, a framework is developed for integrating computational design methodologies and design optimization using energy use and LCA for improving overall building adaptation processes. The building adaptation of Ken Soble Tower in Hamilton, Ontario, is used for the functional demonstration. A set of extension modules are considered, and various adaptation scenarios that conform to set design constraints are evaluated for energy use and LCA. The results of this study prove the practicality of using computational design methodologies for the integration of MC in the adaptation of concrete residential towers and can promote the efficiency of improving existing residential infrastructure.

Keywords –

Computational Design; Modular Construction; Life Cycle Analysis; Building Adaptation

1 Introduction

There is a need for the reconsideration of our status-quo linear approach of design and construction with the inevitable end-of-life option of demolition. Adaptation of existing buildings and infrastructure has increased over the past decade as a response to changing environmental conditions, as well as requirements for reducing energy use and production of construction and demolition waste [1]. For a shift to a circular built environment, there is a need to consider building adaptation, including reuse of buildings and materials, with a focus on modularity, disassembly as a means to facilitate continual loops of resources, products and materials in construction [2]. Modular construction facilitates maintenance, repair and reuse during different life cycle stages of a building and minimizes waste generation during construction and deconstruction [3]. Incorporating modular construction strategies in building adaptation projects, specifically modular extensions to existing buildings can improve the condition of an existing building while preparing it for a circular future in which unnecessary demolition is avoided, and the building modules and materials can enter multiple cycles of use.

The success of modular building projects is directly related to appropriate early decision-making due to the planning and coordination focused nature of modular projects. Morphological and modular form generation is improved by environmental performance feedback in an automated design process [4]. Through early design stage optimization, Kiss and Szalay were able to demonstrate environmental savings of 60-80% compared to traditional design methods. Life Cycle Assessment (LCA) is an essential factor in evaluating the potential environmental impact of buildings. Design option optimization often considers a limited number of options [5], highlighting the need to consider generative design options and evaluation methods for correct optimization of multiple factors simultaneously. An early-stage design optimization tool for modular extension to existing buildings needs to consider energy performance, life cycle analysis, as well as the design considerations of modular building extensions. This research presents a framework for integrating performance optimization in Modular Construction (MC) for the application of building adaptation projects. The critical aspect of the proposed model is the integration of computational design strategies for simultaneous analysis of MC metrics, energy analysis and life cycle analysis. The Ken Soble Tower retrofitting project in Hamilton, Canada is used as a functional demonstration of the proposed framework.

2 Background

In a traditional building adaptive reuse feasibility and early design process, many uncertain factors need to be taken into consideration. The client's inputs, including project requirements, budget and timeline, are taken into account as well as an analysis of the existing conditions of the building, including building geometry, overall status and areas for improvement. The client information and analysis are processed by the design team to develop design options, to be analyzed by consultants, including energy consultants, LCA consultants and cost consultants. Feedback from consultants is looped back to the design team, and design options are revised intermittently and shared with the client for feedback. This cycle may repeat many times over many months to arrive at possible suitable, non-optimized design options at best.

Compared to traditionally constructed concrete buildings, prefabricated modular construction can reduce environmental impacts, increase on-site productivity and construction quality [6]. Jallion et al. (2009) demonstrated that prefabrication in controlled factory environments has been shown to reduce construction waste by 52 % [7], and reported by other researchers to range typically between 10-15% [8]. Effective assembly of prefabricated modular units can also improve on-site construction conditions, including reduced construction pollution, noise and occupant disruptions, making it an ideal strategy for dealing with occupied existing buildings and urban areas [9]. MC integrates modular design with prefabrication and Design for Manufacture and Assembly (DfMA) [10]. A great potential in quality and productivity is in prefabrication and modularization of buildings and their components [11]. There are multiple levels of modular construction identifies including 1) Components and sub-assemblies (i.e. millwork, fixtures, etc.), 2) Panelling Systems (i.e. exterior cladding), 3) Volumetric Pre-fabricated assembly (i.e. kitchen and bathroom pods), and 4) Pre-fabricated modular units, incorporating complex systems of assembly used in combination to form an entire building [3], [12]. This research focuses on the application of modular units as a complete prefabricated unit ready for assembly.

The current strategies for the design of prefabricated buildings are similar in many ways to the design system common in traditional construction. The design of prefabricated buildings is a systematic process, including considerations in design, manufacture and assembly. The design process for conventional construction does not consider methods and principles for addressing the manufacturing process involved in prefabricated buildings [6]. The design process and precisely, decisions made in the first 10% of projects determine up to 80% of the building operation costs after construction [13]. As MC relies heavily on design accuracy due to the coordination focused nature of their process, the success of a modular project is directly related to appropriate early design decision-making.

Environmental design optimization is the process of considering and evaluating alternatives in the design phase that impact the overall performance of a design. Energy use and LCA are important factors in evaluating the success of a design strategy and the potential environmental impacts of a building. They can be considered adequately in the early stages of design. Parametric and generative design environments also enable optimization of building geometry, allowing the designers to test design variation with immediate building performance feedback [4]. The consideration of multiple factors including cost, energy and life-cycle performance has become common in the past decade in early-stage design. Granadeiro et al. integrate early design stage automation of building envelope design with energy simulation using grammars [14]. Yu et al. used genetic algorithms and design structure matrix (DSM) to support automated spatial organization in the early stages of design [15].

Modular construction has proven advantages in terms of LCA and LCC compared to traditional construction and can contribute to more energy-efficient buildings through the improved quality of construction [16]. Form generation is improved by environmental performance feedback in an automated design process [4]. Despite this, there are currently no studies highlighting a framework for the integration of early-stage design optimization of energy use, LCA for MC, specifically for large-scale building adaptation projects. Energy use and LCA optimization can be applied using a parametric tool with geometry represented mathematically or as topologies [17] in combination with the application of MC design parameters to design building adaptation scenarios that meet the requirements of modular construction, as well as optimization of environmental metrics.

3 Computational Design Framework

The proposed framework is developed in three stages to integrate a computational design methodology as well as energy and life cycle performance optimizations in MC design processes for building adaptation projects: 1) analysis and parametrization of the existing building, 2) design option generation and simulation and 3) result refinement and optimization. Stage one requires manual work and processing from the user and project designers in processing the existing building and defining parameters. Through a step-by-step analysis of the building, development of design constraints and processing of user inputs, precise design constraints and rules are developed for algorithm input. In the second stage, the developed algorithm generates and analyzes design options for energy use and life cycle performance. Design options that meet the set criteria are displayed in stage three. The framework enables the user to input preferences regarding the generated options, beyond which the algorithm will optimize the options for the defined factors. After optimization, the user can parse through the optimized options and select the most suitable. This framework suggests possibilities for the incorporation of external databases and previously analyzed cases for the development of databases of all feasible solutions leading to a predictive model of performance feeding the results, to be investigated at a later stage of this work. The last two stages of the framework are fully automated and can be processed in real-time (Figure 4).

The developed computational framework is differentiated by geometric simplicity, integration of automated processes and simulation tools and processing of direct manual user input in various stages. Existing computational interfaces, plugins and frameworks are being used in the development of a cohesive tool that integrates existing resources and facilitates integration. The generative design tool is programmed using Grasshopper® visual programming interface and plugins are used within the interface for energy use simulations and optimization. One-Click LCA® is used for preliminary life cycle emission calculations. Future development of the framework will involve the incorporation of external databases and analytical cases, creating a database of feasible solutions over time and developing predictive algorithms (Figure 4).

The Ken Soble Tower in Hamilton, Canada, is selected as a functional demonstration and will be used to demonstrate the functionality of the framework in various stages.

3.1 Stage 1 – Analysis and Parametrization of Existing Building

The first stage in the framework is focused on the analysis of the existing building and parameterization, as well as the development of design constraints. The design constraints are developed by processing the existing building information, defining design parameters and determining user inputs and requirements. Design parameters are defined based on analysis of the existing building, existing site conditions, and planning requirements and restrictions. Design input including adaptation strategies to be considered, such as the extension of the building, recladding of the envelope, re-glazing of the windows and enclosing of existing balconies. In this research, the extension strategy is investigated in the functional demonstration of the Ken Soble Tower.

In the first phase of stage 1, the existing building drawings are analyzed, and the geometry of the existing building, including interior spaces and the building envelope, are modelled. The existing structure is analyzed to determine required design parameters, including structural, environmental and spatial shortcomings of the existing building. The existing building is modelled as zones (Breps) and aggregated into topological complexes. The building geometry is further discretized into panels and elements at the discretion of the project designer.

For efficient MC design, the least number of module variants are required. Development of design constraints early in the process, such as a speculative grid for modular design, will limit the dimensionality of the design problem leading to a heuristic approach and increased accuracy of design options generated. For building an extension, recladding and addition, for example, the following steps are required: 1) building parameters defining modular extension parameters; 2) module parameters including spatial configurations, connection parameters, and growth patterns and restrictions; 3) panel parameters including dimensions of panel divisions, the spatial organization of panels and connection details. To acquire this information, the existing building geometry is analyzed in terms of dimensional and spatial constraints for the extension, and the dimensions of a typical module are determined (**Figure 1**). The typical module dimension and the spatial analysis lead to the determination of rules for "growth." Figure 1 demonstrates the points of "growth", and the direction of permitted extension determined by the designer. At the level of the determined module size, panels are broken down and analyzed in terms of joining conditions that include: 1) attachment of new module to the existing building (*e*), 2) connection of two modules together (*c*) and 3) exterior façade (*f*). Through multiple design exercises, the number of required panel divisions for each panel, panels *a* and *b* are determined for each condition of *e*, *c* and *f*. In the case of the Ken Soble Tower project, the variation of module connections lead to 16 different possible configurations of *e*, *c* and *f* for panel *a,* seven different possible configurations of *e*, *c* and *f* for panel *b* as demonstrated in Table 1. The 23 different panel possibilities result in a total of 22 possible module configurations.

As part of the existing building analysis, the LCA of the existing building is determined considering the existing operational energy use standards. After the modules and panels are determined, use the material take-offs and calculate the life cycle impact, not accounting for energy use for each of the modules separately using One-Click LCA. The combination of these modules will be used in the algorithm to determine the LCA of the combined design options in real-time.

A user input interface using Human UI® for GH® takes into account the preferences of the user regarding various aspects, including budget, number of preferred units, unit size variations, balconies and window placements, etc. An integrated user interface allows for changing initial conditions and input values, selecting modes and paradigms of operation, and integration of user selection and manual search for solutions. User interface – using Human UI® depending on the skill level of a prospective user, one can use Human UI® only or start manipulating the GH® scripts that are part of the framework. The user in our framework is defined as the designer, modeller or client evaluating building adaptation strategies. In our framework, the user can input preferences, review and parse through results and to reconfigure preferences based on project data in real-time. The user inputs and requirements include constraints for the extension, number of additional units required, number of bedrooms per unit and unit square footage as well as environmental goals, including energy efficiency and carbon targets. The building analysis results combined with the input parameters are used to feed the developed algorithm for option generation. The building inputs and analysis, as well as design and user inputs, are combined to create a detailed breakdown of the design constraints (B-3) for the development of the algorithm.

3.2 Stage 2 - Option Generation and Simulation

After defining geometry and selecting strategies, a virtual grid of speculative possibilities is computed. The developed algorithm generates adaptive design options by positioning modules and assigning states based on the information stored in the grid, previously determined in stage 1. The design options are generated using the developed algorithm within GH and Topologic is used to track changes in their topological structure.

Topologic® is a software modelling library enabling hierarchical and topological spatial representations through non-manifold topology [18]. Existing geometry is modelled as Breps (directly modelled or extruded from existing drawings) and then fed as input to the module translating Rhino® 3D Brep object to topologic cells, organizing them and forming topologic complexes. The set of options is generated through a brute force search, being finite and relatively small, allowing for computation and comparison of all the possible options. A topological structure with cells governs the distribution of modules and assignment of states. The generated design options will then be analyzed for energy use and life cycle carbon simultaneously.

The net environmental impacts for each building adaptation design option consider the LCA of the existing building and consideration of the extension of life by 60 years through building adaptation. The LCA of modules and the existing building are calculated in line with EN 15978:2011 standards [19] for LCA Modules A1 to Module D. The energy use of each compiled design option is calculated inside GH® in real-time, using the Honeybee® plugin. Honeybee® supports thermodynamic modelling and creates, runs and visualizes the results of energy models using EnergyPlus® and OpenStudio® simulation engines. The number of extension modules is calculated in Grasshopper® in real-time and calculated using the pre-calculated LCA of each module from stage 1 using the following formula (1):

$$\mathrm{E}_{total} = \mathrm{E}_i[\mathrm{kgCO_2e}] + \textstyle\sum_M \mathrm{n}_M\ \mathrm{E}_M\ [\mathrm{kgCO_2e}]\ + \mathrm{U}_{total}[\mathrm{kWh}](\mathrm{U}_{factor}[\mathrm{CO_2e/kWh}]) \quad (1)$$

Where E_{total} is total carbon emissions including operational energy use, E_i is the carbon emission of the existing building excluding operational energy use, n is the number modules per module type in each design option, M is the type of module used in the design option, E_M is the emission of type M module excluding operational energy use, U_{total} is the total energy use of the building including existing and extension modules, and U_{factor} is the local emission factor.

3.3 Stage 3 – Result Refinement and Optimization

The results of option generation and simulation is visualized using the Human UI® interface in

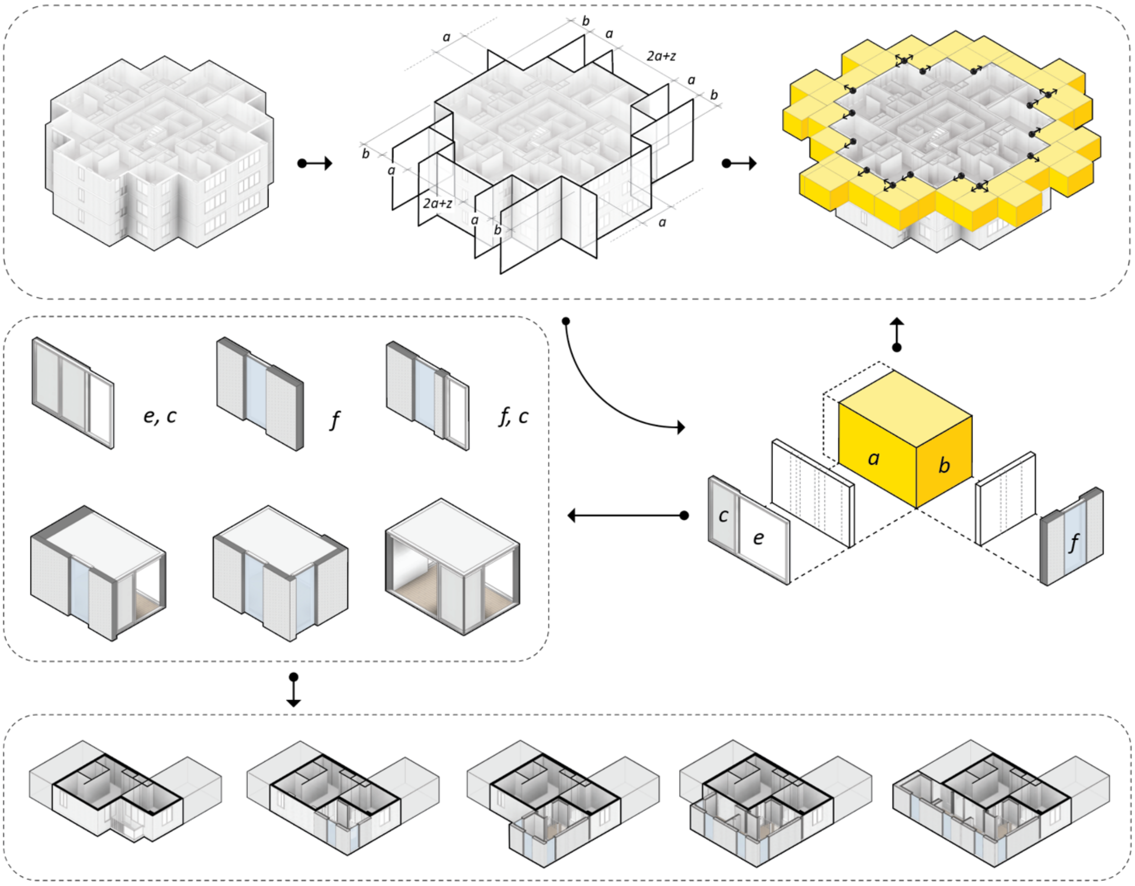

Figure 1. Stage 1 – Parametrization of existing building, determining typical module sizes and panelling configurations, determining possible growth patterns, finalizing module dimensions, and module configurations, determining various module extension options for each existing unit.

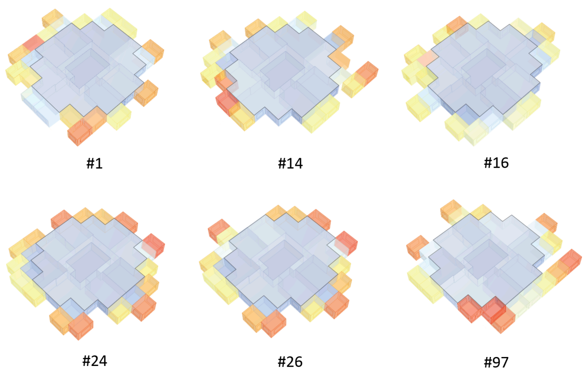

Figure 2. Typical floor plate demonstration of generated design options 1, 14, 16, 97, 24 and 26.

Grasshopper®, through which the user can manually review all the generated and evaluated options and refine the search for the most viable option via sliders limiting the scope of the search. After initial refinement user may choose to run a genetic algorithm and optimize further using the selected option as an initial population. The results can be optimized using multi-objective optimization searching for optimal extensions and materials used, based on performance (R-Value), cost or emissions, and refine the distribution of modules.

Octopus®, a multi-objective evolutionary optimization engine, is used within Grasshopper® for optimization of results in stage 3. It allows the search for many goals at once, producing a range of optimized trade-off solutions between the extremes of each target. Octopus® within Grasshopper® is used to optimize material qualities of modules' envelope exploring trade-offs between energy performance and embodied carbon.

After a predefined amount of iterations of option generations, results are again displayed, and the user can make their final choice and export geometry and data to a predefined format.

From the 100 design option permutations, six designs demonstrate a range of arrangements for a 20-module extension. Figure 2 is a typical floor plate demonstration of the six generated options. Design options 1, 14 and 16 demonstrate similar performance in terms of energy use and LCA. For a 20-module extension, through the generative computational design approach, an 8% saving of heating energy use and 5% of life cycle carbon emissions was achieved. Design 24 and 26 are similar in overall form. Still, the clustering of modules on one side of option 26, and the resulting reduction in the exposed building envelope, results in option 26 outperforming option 24 by 1,895 kWh of heating energy and 10,619 $KgCo_2e$ equivalent of carbon emissions (Figure 3).

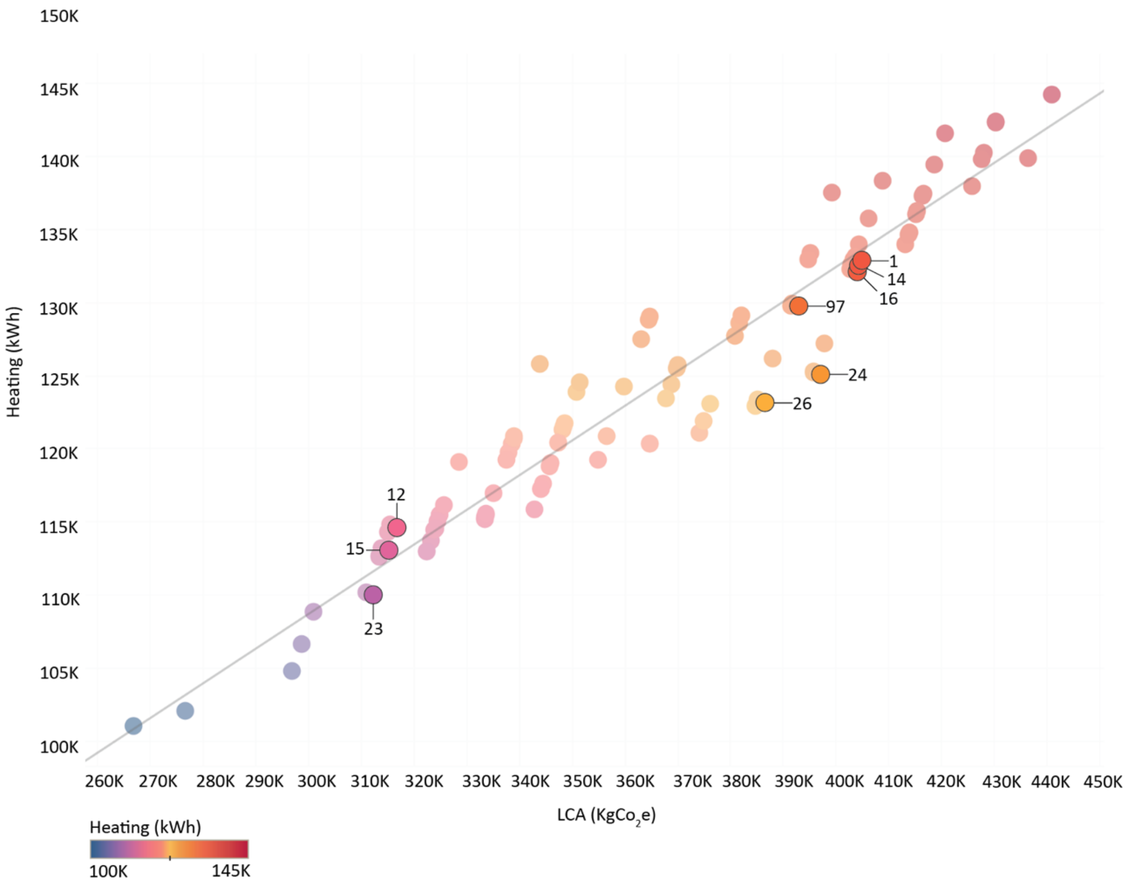

Figure 3. LCA ($KgCo2_e$) and heating energy use (kWh) for 100 design option permutations. Design options are filtered by area of extension – Options 1, 14, 16, 97, 24, 26: 20 module extension (206 m^2) and Options 12, 15, 23: 13 module extension (134 m^2).

4 Conclusion

Adoption of modular construction in building adaptation projects, specifically in extensions to existing buildings, is an essential step in a move to a circular built environment and facilitating the continual use of resources in construction. Parameters and limitations in modular design and the opportunity for design optimization, highlight the importance of incorporating computational design tools in the design of modular buildings. In this paper, a framework is presented for a computational design methodology integrating modular construction in building adaptation projects, while optimizing for energy performance and life cycle impact. The proposed framework is divided into the three stages of analysis and parametrization of the existing building, option generation and simulation and result refinement and optimization. An existing concrete residential building in Hamilton, Canada is used as a functional demonstration of stages one, two and part of stage three of the framework. In stage one, the existing building is analyzed, and a single module size is selected for the extension to the existing building. A grid is developed using rules for module placement, in consideration of the existing building form, interior layouts and required building setbacks. As a result, a growth pattern for the building is determined. The selected module size is broken down into various panelling options that accommodate different module configurations.

An algorithm is developed to generate floor plate module configurations based on the set rules. The energy use and LCA of each design configuration are calculated

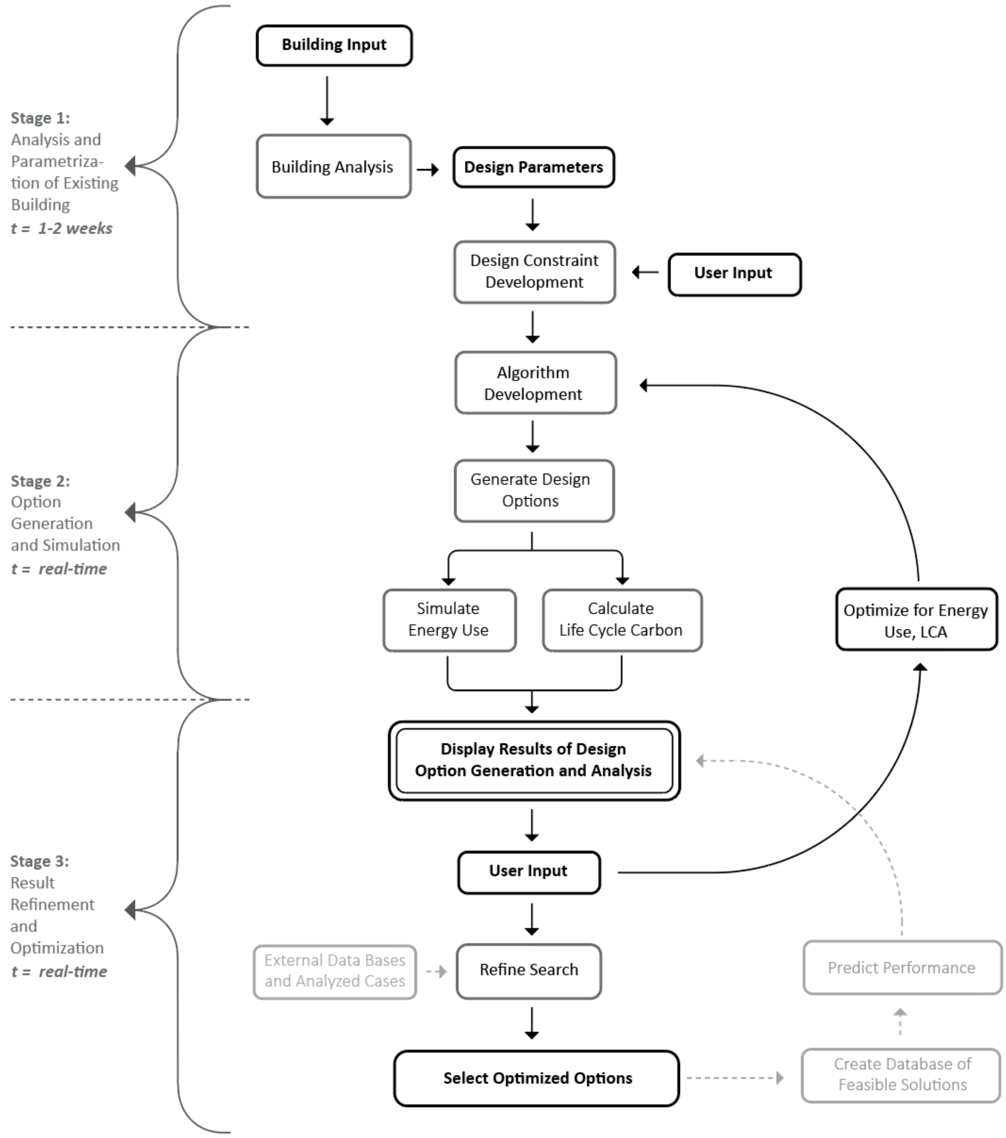

Figure 4. Proposed Computational Design Framework. Framework is separated into the three stages of analysis and parametrization of the existing building, option generation and simulation and result refinement and optimization (the greyed-out portions of the framework are not considered in the functional demonstration and will be pursued in future stages of this work).

simultaneously. A result of 100 permutations ranging from extension of 10 to 20 modules demonstrate the possibility to optimize design option configurations.

The limitations of this research include the exclusion of construction and Life Cycle Cost (LCC) and other environmental factors, such as daylighting, from the optimization model. It is expected that LCC will have a significant impact on design option optimization, and including other environmental factors as part of simulations in stage 2, can increase the quality of generated design options. The design permutations for this research were limited to 100 permutations due to computing limitations. Generating a larger pool of permutations for a single design option will increase the quality and reliability of the design process.

The future of this work will focus on addressing the limitations mentioned and on completing the proposed steps in the framework not investigated in this research. Integration of external databases, linking to other analyzed cases, and the creation of an internal database of feasible solutions will enable the integration of predictive algorithms for enhancing the quality of generated design options.

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