A SYSTEM ARCHITECTURE FOR THE INTEGRATION OF SMOKE PROPAGATION SIMULATION, EVACUATION SIMULATION, AND BUILDING INFORMATION MODELING

A Dissertation

by

CHENGDE WU

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Mark J. Clayton
Co-Chair of Committee,	Wei Yan
Committee Members,	Jeff S. Haberl
	Julian H. Kang
Head of Department,	Robert Warden

December 2017

Major Subject: Architecture

ABSTRACT

A new software system architecture was designed to integrate smoke propagation simulation, evacuation simulation, and Building Information Modeling (BIM). The integrated software prototype automates the majority of the simulation workloads, enabling seamless data flow from BIM to smoke propagation simulation and evacuation simulation, and thus providing architects rapid feedback in design decision process.

As the key to integrating smoke propagation with BIM, the research produced two spatial transformation algorithms and a room selection algorithm to resolve the incompatibility caused by the need to simplify the BIM representations for use in CFAST. With these algorithms, smoke propagation simulation of real-world buildings can be easily performed on a BIM model. To demonstrate the integration of smoke propagation simulation and BIM, a software prototype was developed with Revit Architecture and CFAST. In addition, a visualization module was developed to present simulation results, which are usually in thousands of lines of numbers, in a visually understandable format.

A simple BIM-based multi-agent evacuation simulation model was developed to provide architects with more informative design feedback. At each simulation step, each agent collects the data of the surrounding environment, such as CO concentration at their head level and room temperature. The results of the simulation can be visualized as graphs and animations which help architects to visually identify bottlenecks and examine the clarity of circulation design.

The validity of the algorithms was tested by FDS simulations and CFAST simulations. The analyses of the FDS validation tests showed that the transformation algorithms introduced 5-10% error for the majority of the test cases. A few extreme cases showed more than 10% error. The analysis tests showed that the room selection algorithm

introduced 2-7% error.

Intensive use of the software can provide insights to a designer that may result in new solutions to increase fire safety. A series of FDS simulations as experiments scrutinized how ceiling design and door design affect building fire safety. The results of the experiments showed that opening 16-25% of the ceiling can deter smoke propagation up to 60% by holding smoke inside plenum area.

ACKNOWLEDGMENTS

I would like to thank Dr. Clayton and Dr. Yan for guiding me through the research, enlightening me in many aspects of my career, and helping me with my personal life during my Ph.D. program. Thanks also to Dr. Haberl and Dr. Kang for providing valuable advice and feedback to help me improve my research. I would also like to thank Dr. Miranda for sharing his insights on life with me, Dr. He for supporting my career in many ways and helping me with my personal life, and Dr. Rogers for guiding me in teaching design studio. Many thanks to the professors whose courses I took at the department of architecture and the department of computer science, especially Dr. Akleman, for nurturing me with knowledge and made me humble enough to realize that what I know is not even comparable to a drop of water in the ocean.

My sincere gratitude to Dr. Sanghyun Lee, my MS program advisor, who enlightened me in my early academic career and guided me to the PhD program at Texas A&M. Many thanks to my friends in or once in College Station with me. The memories I have with all of you are invaluable, the happy hours we spent together was the energy tank to my life, and the inspiration from you is indispensable to my Ph.D. program. I would also like to thank my students in Architecture and Visualization department at Texas A&M, and the students at Kaywon University of Art and Design in Korea. You made me realize what to fulfill in my teaching career. Lastly, special thanks to my parents and brother for their unconditional support.

All the honor to God.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a dissertation committee consisting of Dr. Mark Clayton (chair), Dr. Wei Yan (co-chair), and Dr. Jeff Haberl at the department of Architecture, and Dr. Julian Kang at the department of Construction Science.

All work for the dissertation was completed independently by the student.

Funding Sources

The department of architecture provided teaching assistantship for six semesters.

CRS center at the college of architecture provided three years of scholarship during 2014-2017; the state of Texas provided education grant during 2014-2015; and the International Student Services at Texas A&M University provided scholarship during 2015-2016.

The final year of the graduate study was supported by a dissertation fellowship from the Office of Graduate and Professional Studies at Texas A&M University. I would like to express my sincere gratitude for the support.

NOMENCLATURE

AABB	Axis Aligned Bounding Box
AEC	Architecture, Engineering, and Construction
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
BIM	Building Information Modeling
CAAD	Computer Aided Architectural Design
CFAST	Consolidated Fire And Smoke Transport
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO2	Carbon Dioxide
COHb	Carboxyhemoglobin
CSV	Comma Separated Values
FDS	Fire Dynamic Simulator
FSEG	Fire Safety Engineering Group
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HRR	Heat Release Rate
IBC	International Building Code
IFC	Industry Foundation Classes
NBIMS	National Building Information Model Standard

NIST	National Institute of Standards and Technology
NURBS	Non-Uniform Rational Basis Spline
USFA	United States Fire Association
WFSC	World Fire Statistics Centre
WPF	Windows Presentation Foundation

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Building fires cause many fatalities each year. From 2007 to 2009 there were more than 10,000 building fire deaths each year in 27 industrialized countries, an average of 8.3 deaths per million population (figure 1.1) [1]. In addition, expanding populations are increasingly moving to cities and living in high-density development areas where fire risks are greater.

Country	Adjusted estimates (fire deaths) 2007	2008	2009
Australia	115	120	175
Austria	30	55	40
Barbados	5	5	
Canada	230	295	240
Czech Republic	135	150	120
Denmark	70	90	70
Finland	95	110	110
France	605	595	595
Germany	**435**	**500**	540
Greece	240	130	110
Hungary	175	**180**	150
Ireland	55	45	55
Italy	250	285	285
Japan	2050	2000	1900
Netherlands	70	100	60
New Zealand	35	35	35
Norway	70	70	55
Poland	600	585	565
Portugal	75	65	55
Romania	440	410	355
Singapore	5	1	1
Slovenia	15	10	10
Spain	255	270	205
Sweden	110	130	140
Switzerland	15	30	25
United Kingdom	465	475	460
United States	3750	3650	3300

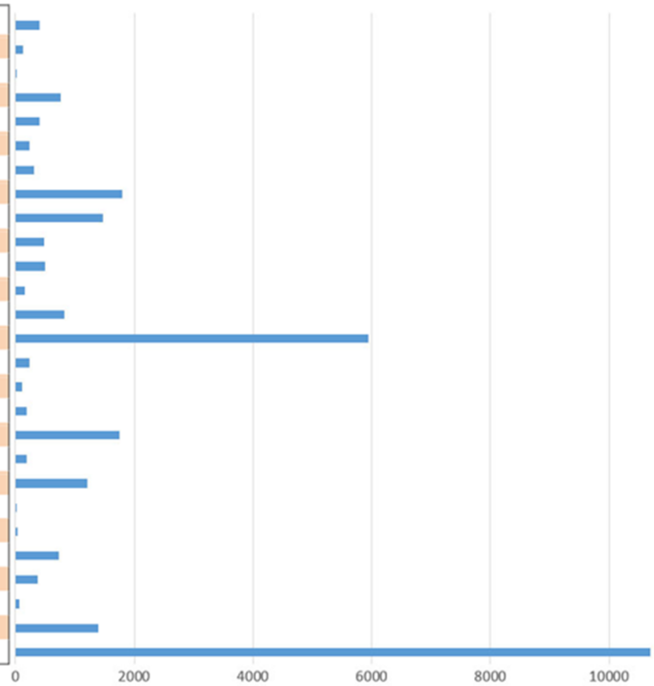


Figure 1.1: The number of fire deaths in 27 industrialized countries from 2007 to 2009 [1].

Protecting occupants from building fires is one of the major tasks of architects in building design. There are two major methods that architects can employ to achieve building fire safety: building code compliance and building fire simulation. In the typical architectural design process, building fire safety relies solely on the compliance of the building codes. As building codes address more fire safety issues day by day, code-compliant building designs can achieve a high level of fire safety. In addition, building code checking can be automated which greatly reduces the time and errors of manual code checking [2][3].

Despite the ubiquitous adoption of the building code compliance in practice, simulation-based design has its distinct advantages over conventional code-based design. One of the advantages is that simulation-based design may provide architects with more freedom in design and more space for innovation. Simulation-based design focuses on the performance of buildings while code-based design focuses on provision of conventional features specified through a regulatory process. Prescriptive building codes mandate designers to follow predefined solutions to solve a problem, while performance based codes only define desired outcome of the design, and the solution to solve a problem is up to designers. This grants designers more freedom to design, more space for innovation, and more responsibility at the same time [4]. For example, International Building Code (IBC) 1016 limits the maximum travel distance to the nearest stair in order to assure occupants' safe evacuation. In figure 1.2, although design scheme A complies with the provision mentioned above, occupants in the right wing (gray area) need to escape through the fire source which can render them unconscious in the split of a second, a very common factor causing deaths in building fires [5]. In design scheme B, on the other hand, occupants always have a choice to run away from the fire source. People can stay in 0.3% of carbon monoxide (usually very dense smoke) for 15 minutes without risking their lives [6]. Thus people are more likely to escape safely in design scheme B than in design scheme A, despite the fact that the egress distance in design B exceeds the maximum distance required by the building codes. Overall, simulation-based design can be a complementary solution for code-based design.

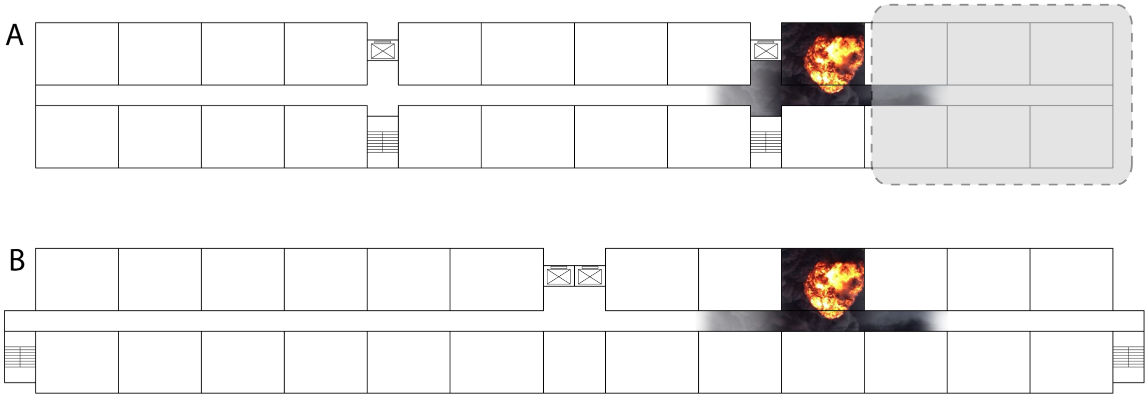


Figure 1.2: Fire safety comparison between plan A and plan B.

Another advantage of simulation-based design is that it has the potential to discover new knowledge that is not incorporated into building codes. The nature of building codes is to prevent similar disasters from happening again based on the lessons learned in the previous incidents. On the other hand, the nature of simulation is to predict consequences beforehand based on the laws of physics or the laws of nature. Because of this fundamental difference, simulation-based design process can discover new knowledge that building codes have not yet captured. Section 6 provides examples of how simulation-based design can discover new knowledge that is not yet captured by building codes, supported by detailed simulation data. If smoke propagation simulation becomes a normal routine in practice, it is expected that more and more new knowledge will be discovered.

Building fire safety can be assessed by the speed of smoke propagation and the speed of occupant evacuation. In a building fire, occupants are safe only if they can evacuate without their lives being threatened by toxic smoke. In this sense, simulating occupant evacuation can help architects to understand the fire safety of their design more comprehensively.

1.1 Problem Statement

Despite its advantages mentioned above, smoke propagation simulation and evacuation simulation are not incorporated in typical architectural design process [7]. Informal observations suggest that the primary reason is the difficulty and slowness resulting from the incompatibility between the different building models used in design and simulation. Currently, to simulate occupant evacuation or smoke propagation of a building, the building drawings must be re-modeled in simulation applications according to idiosyncratic special purpose description conventions. This re-modeling process is time-consuming, error-prone, and the simulation results of the same building can vary significantly from one user to the next due to alternative methods for modeling or errors that are difficult to identify. In addition, manual data entry must be repeated every time when the design of the building changes, which worsens the problem considering that a building design usually changes many times before it is ready for construction. This workload is one of the main obstructions to incorporating smoke propagation simulation and evacuation simulation into design process. If this problem were eliminated through automation of the data exchange between design program and simulation program, smoke propagation simulation and evacuation simulation could become a common part of design process.

In addition to the input process, simulation running time also deters the use of smoke propagation simulation in building design. Some smoke propagation simulation models utilize Computational Fluid Dynamics (CFD) which is computationally expensive by nature. Simulating a building in a CFD-based smoke propagation simulation application can easily take several days or even several weeks. Considering the numbers of iterations needed in order to improve the design, it is not viable to integrate CFD-based smoke propagation simulation model into design process given the limited timeframe of typical design projects.

An alternative to solve the simulation running time problem that CFD-based models have is to use zone models which simplifies building geometry and simulation process. With zone models, the simulation running time can be reduced to a few minutes instead of days to weeks. However, the simplification of the building geometry triggers different problems. A zone model, such as CFAST (Consolidated Fire And Smoke Transport), simplifies a room to a cuboid shape. Rooms in the real world take a variety of shapes besides cuboid. Because there is no standardized shape conversion method, converting a non-cuboid shape to a cuboid shape is likely to vary from user to user, which causes inconsistency in simulation results even within the same building design. In addition, the shape conversion process needs to be done manually which adds additional workload and increases probability of error.

Cumbersome input process, long simulation running time, and the lack of a standardized model simplification method hinder the adaptation of smoke propagation simulation and evacuation simulation during building design process. Designers can better understand the consequences of their design decisions on fire safety issues if smoke propagation simulation and evacuation simulation are incorporated in architectural design process.

1.2 Research Questions

This research is initiated to investigate the following primary research questions:

- Can smoke propagation simulation and evacuation simulation be integrated into design process such that the integrated system is useful to typical designers?
- Does the integrated system have any side benefits besides its practical use?

The primary questions can be answered through the following secondary questions:

- Can smoke propagation simulation and evacuation simulation be integrated into popular design support software, such as a BIM authoring tool?
- Does the integrated system produce sufficiently accurate results?
- Does the integrated system provide a simulation procedure that is easy to use?
- Does the integrated system provide informative simulation results?
- Can the integrated system help designers to discover new knowledge?

The hypothesis of this research is formulated as the following:

Smoke propagation simulation and evacuation simulation can be incorporated into architectural design process and become useful to typical designers by giving rapid feedback. In addition, the integrated process has other benefits besides its practical use, such as discovering new knowledge.

1.3 Research Goals and Objectives

The goals of this research are:

- To design a new software system architecture that integrates smoke propagation simulation and evacuation simulation into architectural design process;
- To present an argument that the integrated system is useful to typical designers;
- To investigate other benefits of the integrated system.

The integrated system should automate significant aspects of smoke propagation simulation and evacuation simulation process, simplify and accelerate the process, provide designers with rapid feedback, and thus help designers make data-driven design decisions regarding building fire safety. It should also be tightly connected to a design tool, such as a BIM authoring software system.

The goals of this research can be achieved by completing the following quantifiable concrete objectives:

- Identifying the primary factors that hinder the integration of a smoke propagation simulation tool and an architectural design tool, i.e. the reasons that cause the incompatibility;
- Devising algorithms to overcome the incompatibility between the models used in smoke propagation simulation and BIM;
- Developing a software prototype to demonstrate the integration of smoke propagation simulation, evacuation simulation and BIM;
- Validating the accuracy of the algorithms that are used in the integrated system;
- Discovering whether the integrated system is easy-to-use and produces informative results;
- Investigating whether the integrated system can discover new knowledge that is not yet captured by building codes.

1.4 Research Workflow

The workflow of this research is shown in figure 1.3. The first step is to devise algorithms to convert real rooms drawn in BIM to smoke propagation simulation models. The next step is to develop a software prototype, using Revit as the BIM tool and CFAST as the smoke propagation simulation tool, to implement the model conversion algorithms. The subsequent steps are to run validation tests to demonstrate the accuracy of the algorithms, compare user experience to see how easy to use the integrated system is, develop a BIM-based evacuation simulation model, and develop a visualization module to provide informative feedback. The last step of this research is to discover new knowledge

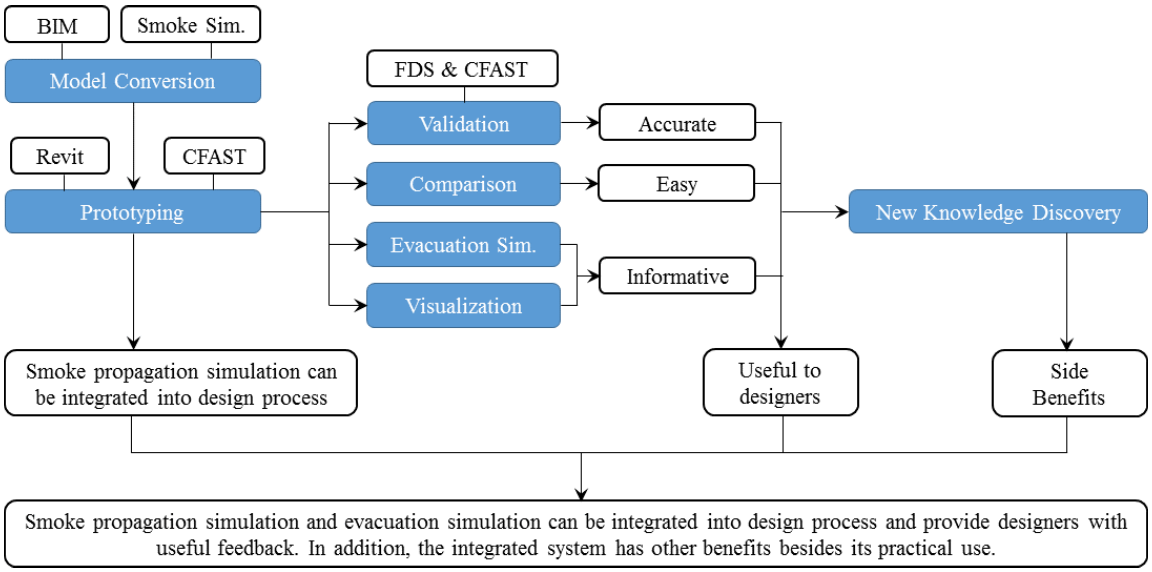


Figure 1.3: Research workflow diagram.

through simulations. After these steps, the research questions will be answered and the research hypothesis can be either proved or rejected.

1.5 Significance of the Research

In practical aspect, integrating smoke propagation simulation into architectural design process can help designers to perform smoke propagation simulation easily, and better evaluate the safety of building designs with respect to fires, without acquiring detailed specialist expertise in how to perform smoke propagation simulation. Ultimately, the integrated system provides architects with a new tool that helps them make data-driven design decisions, and thus improve the fire safety of their design.

The integrated system provides a platform for designers and researchers to discover new knowledge through smoke propagation simulation. Because the tool accelerates the process of fire safety related simulations, researchers can perform more analyses in the same amount of time, potentially exploring more hypotheses in greater depth to generate new knowledge. Section 6 demonstrates how the integrated system can contribute to expanding the boundary of our knowledge base.

With respect to education, the integrated system can help architecture students to better understand building fire safety without the demand of extensive knowledge in engineering and math. By incorporating simulation tools into design tools, it provides students with a more visual and straightforward way of learning building fire safety in addition to the conventional way of reading and interpreting building code books.

1.6 Research Scope

Toxic smoke and extreme temperature of the fire are the two primary factors that cause fatalities in building fires. A study [8] shows that 80% of the fatalities in building fires are caused by toxic smoke and 11% are caused by actual fire. Hence, this research focused on the simulation of smoke propagation. The simulation of actual fire was excluded from this study.

The main goal of this research was to investigate the integration of smoke propagation simulation, evacuation simulation, and architectural design. The simulation results can provide designers with rapid feedback on how their building design performs in terms of fire safety. In the prototype software system, the subsequent optimization of the design based on the simulation results has been left to the designers, i.e. design optimization is excluded from the scope of this research.

A simple evacuation simulation model is developed in this research to help designers qualitatively and quantitatively evaluate the fire safety of their design. However, the evacuation simulation software is only to demonstrate that evacuation simulation can be integrated with BIM and smoke propagation simulation. Validating the model that is used in the evacuation simulation is excluded from the research.

The integration of the existing smoke propagation simulation models and BIM is focused on spatial configuration. The integrated system can simulate with or without mechanical ventilation, fire alarms, and fire suppression systems. However, it only simulates to the extent that the existing simulation model supports. Extending the functionalities of the smoke propagation simulation model is not included in the research.

1.7 Organization of the Dissertation

Section 2 reviews previous studies on the relevant topics, including smoke propagation simulation models, existing simulation software, validation of the smoke propagation simulation models, and the use of BIM in practice. This research builds upon the existing models and the findings of the previous studies.

Section 3 presents the algorithms that are used to overcome the incompatibility between BIM and smoke propagation simulation models. A prototype software was developed with Revit API to demonstrate the integrated system of BIM and smoke propagation simulation. Pilot tests were also conducted to assess the integrated system and its effectiveness in incorporating smoke simulation into the design process.

Section 4 presents two different ways of providing feedback to the designers: by visualizing smoke propagation; and by performing evacuation simulation based on the smoke propagation simulation results. The evacuation simulation provides both qualitative and quantitative feedback.

Section 5 presents the validation of the algorithms used to integrate smoke propagation simulation and BIM. A variety of building models with different sizes are simulated with FDS and CFAST to test the validity of the algorithms.

Section 6 presents the new knowledge that were found as the side benefits of integrating smoke propagation simulation into design process. The findings are confirmed through a series of FDS simulation tests.

Section 7 concludes with the findings, limitations, and suggestions for future work.

Validation tests in section 5 resulted in hundreds of graphs. To make the main text concise, only two of the graphs are included in section 5 as examples, and the rest of the graphs are presented in Appendix A and B.

2. LITERATURE REVIEW

Although extensive research has been conducted on smoke propagation simulation, the methods require specialized expertise not commonly held by designers and consequently have not been integrated into common practice. In the 1970s and 1980s, researchers conducted combustion experiments extensively to understand the physical characteristics of fire and the chemical properties of commonly used building materials when on fire. The data collected from the experiments were used to develop smoke propagation simulation models and software that are used to predict the behavior of building fires. This section reviews the previous studies on fire experiments, smoke propagation simulation models, the existing smoke propagation simulation software, and the validity of the models and software. This section also briefly reviews the previous studies on BIM adoption in practice to investigate the value of incorporating smoke propagation simulation into a BIM-enabled design process.

2.1 Fire Experiments

Understanding the physical characteristics of fire and smoke is an essential key to modeling fire and smoke. Since the 1970s, researchers have extensively experimented with fire to unveil various characteristics of fire and smoke. Many researchers have tested the ignition behavior of various flammable materials such as cardboard, newspaper, canvas, cotton cloth, rubber strip, polyurethane foam [9], polystyrene, epoxy [10], different types of polymeric materials [11], different types of wood [12], etc. While conducting these experiments, many parameters were monitored, including ignition temperature, time to ignite, Heat Release Rate (HRR), yields of combustion, toxicity of each type of gas, oxygen depletion, and so on. Among the parameters, HRR is considered to be the most important factor in a building fire. HRR is the energy released per unit of time, which is the major factor determining how fast fire spreads. Not surprisingly, extensive experiments have been conducted to determine the HRR of a variety of building materials and furniture, including chairs, sofas, closets [13], other upholstered furniture [14], silicones (foams, elastomers, and resins) [15], different species of wood [16][17], dry partition walls [18], PolystyreneClay Nano-composites [19], fiber reinforced polymer (FRP) composites [20], and many others. The data collected from the experiments has been the foundation for modeling building fires.

In addition to obtaining data from experiments, some researchers approached the question in a different way, formulating equations to calculate HRR. Based on Thornton's [21] finding that HRR and oxygen level is related, Huggett [22] calculated the HRR of a combination of materials by measuring oxygen consumption, which was proved to be quite accurate in his experiment. Janssens [23] also provided a set of equations to determine the HRR by oxygen consumption.

Researchers also have conducted extensive research on how building fire and smoke spread horizontally and vertically, from one object to another through radiation, convection, and conduction. In some of the earlier work, Larson [24] conducted comprehensive research on flame radiation, wall heat conduction, and laminar convection. Quintiere [25] also reviewed full-scale and down-scaled model experiments to study fire growth and spread in building compartments. To better understand the effect of radiation in fire spread, Quintiere [26] later tested ignition temperature, thermal inertia, and flame spread speed of 36 building materials caused by radiation. About the same time, Hasemi [27] conducted experiments on the flame spread of vertical walls with the combustible surface. Cheney et al. [28] developed fire spread/time curve to show the fire growth and acceleration. The results from these experiments have laid the foundation for the simulation models developed in the later days.

Pyrolysis is the thermo-chemical decomposition of any organic material without the existence of oxygen at a high temperature. Pyrolysis often occurs when there is a shortage of oxygen during combustion. Along with the pyrolysis process, smoke is released with heat. Smoke contributes to death in two ways: first by incapacitating victims and causing death directly by toxic gases, and/or secondly by indirectly inhibiting people from escaping because of reduced visibility. Smoke can contain more than a dozen types of gases, but CO (carbon monoxide) is the only toxicant that has been proved to directly cause deaths in a building fire [6][8]. Currently, there is not enough evidence that any other toxic gases such as HCN (hydrogen cyanide) or HCl (hydrogen chloride) directly cause deaths, although they might contribute to early incapacitation. In the experiments on mice, toxic gases other than CO shortened time to deaths [29]. Researchers also studied how long a human can survive in various concentration of CO. Bernard [30] listed the distance people can travel in different concentrations of CO. Terrill et al. [6] found that people can remain in 0.3% of CO for 15 minutes without risking their lives. However, people become incapacitated at a COHb (Carboxyhemoglobin) level of 30%, and a level of 50-60% COHb is lethal [31]. The scarcity of oxygen is another threat. When oxygen drops under 7% people can become incapacitated or even die. However, low oxygen levels only occur when the air (smoke) is very hot, approximately 600^oF [31], which means that people are threatened by extreme heat before the low oxygen level occurs. This is consistent with the findings of Terrill et al. [6] that the threat from CO is greater than heat, which is greater than oxygen deficiency.

2.2 Smoke Propagation Models

As physical characteristics of fire have been revealed with countless experiments, researchers strived to model building fire using mathematical equations and computer simulation. Smoke propagation models can be classified as zone models or field models, also known as CFD (Computer Fluid Dynamic) models (figure 2.1). The two types of models are inherently different. Zone models are simpler and the simulation running time is very short, usually under a few minutes. On the other hand, CFD models are more complex and the simulation running time is much longer, usually days to weeks.

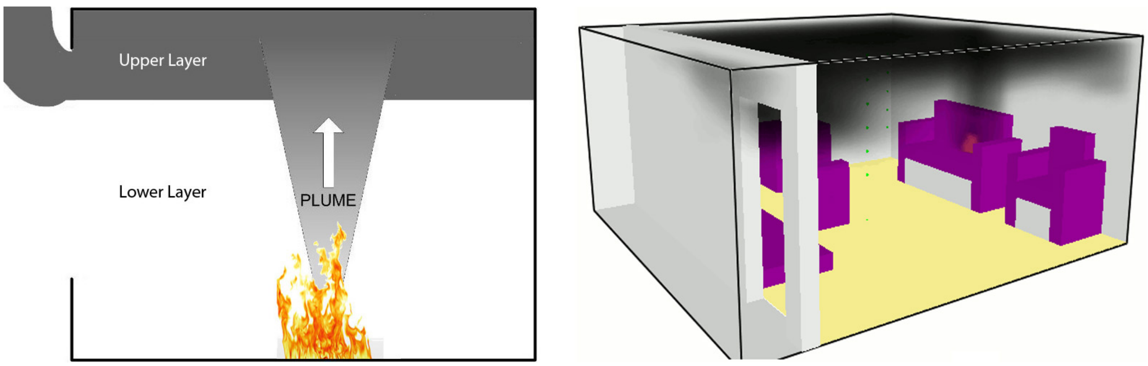


Figure 2.1: Two-zone model (left) and CFD model (right).

There are three types of zone models: one-zone model, two-zone model, and multi-zone model. One-zone models assume that each room is one homogeneous space with the same air composition and temperature. In two-zone models, a room is stratified into an upper zone which is filled with hot and toxic smoke, and a lower zone which is filled with fresh air. Multi-zone models divide a room into many (e.g., thousands of) zones to simulate the microenvironment of each zone. Two-zone models are the most commonly used considering fast simulation speed and acceptable accuracy [32]. Hokugo [33] conducted fire experiments on a 10-story building, and the results showed that a two-zone model is suitable for the spaces on the same floor, but does not apply well to vertical spaces such as stair cases. The temperature of the smoke drops quickly while it rises in vertical shafts, which is called the chimney effect in smoke propagation simulation, and the air becomes murky instead of forming two distinctive layers. Based on their experiment of burning a multi-story building, He et al. confirmed the existence of chimney effect in vertical shafts and the clear separation between the upper and lower zones in more typical rooms [34]. They also found that stratification is not dominant in rooms that are remote from the origin of the fire. They suggested that for these rooms a one zone model would be adequate.

A CFD model discretizes a continuous space into a myriad of small cuboids, and the concentration of the gases and the temperature of each cuboid are simulated by solving the Navier-Stokes equation. Compared to zone models, CFD models generate more accurate results, but the down side is that CFD models require much longer simulation run time.

2.3 Smoke Propagation Simulation Software

Numerous smoke propagation simulation prototypes have been developed based on the models suggested, including open source software and proprietary software. Among the smoke propagation simulation applications, CFAST and FDS, both developed by the National Institute of Standards and Technology (NIST), are the two most commonly used applications. CFAST and FDS are open-source and the user's manuals and developer's manuals are well documented in publicly available form. Commercial simulation applications such as Kobra-3D [35] and SMARTFIRE [36] are also currently available. Kobra-3D and SMARTFIRE are CFD-based models which simulate heat transfer and smoke propagation. Major parameters simulated in Kobra-3D and SMARTFIRE include temperature, optical smoke density, and the concentration of the gas species. However, the costly license fees discourage designers from using Kobra-3D or SMARTFIRE.

CFAST is a two zone model that solves a system of differential equations, including the conservation of mass, the conservation of energy (equivalently the first law of thermodynamics), and the ideal gas law [37]. CFAST predicts the pressure, gas species concentration, layer height, and temperature given the accumulation of mass and enthalpy in the two layers at each discrete time step. The system of equations also calculate the mass and enthalpy flow between the zones due to the physical phenomena of plumes, natural and forced ventilation, convective and radiative heat transfer, and so on. However, no pyrolysis (i.e., thermochemical decomposition of organic material in a fire) model is included in CFAST to predict the fire growth. Pyrolysis rates of common building materials and furniture are provided by previously published fire experiments. To use CFAST users have to specify each fire source and fuels with pyrolysis rate.

FDS is a CFD-based model that contains a pyrolysis model, a combustion model, a hydrodynamic model, and a radiation transport model. The pyrolysis model in FDS simulates the decomposition of solid fuels such as building materials and furniture. The FDS combustion model simulates the chemical reaction of decomposed fuel and the oxygen in the air. The FDS hydrodynamic model simulates low-speed, thermally-driven air flow emphasizing the smoke and heat transport from a fire. The term low-speed is used to exclude situations similar to explosions. The FDS radiation transport model simulates the heat transfer by radiation through the gas-soot mixture using approximately 100 discrete angles. The result of combining these models is that FDS can simulate the fine distribution of gas concentration and the temperatures in a space. In addition, FDS also calculates soot density and visibility [38].

FDS uses a rectilinear mesh structure to define geometries such as walls and furniture. Unfortunately creating meshes for an FDS input file requires the use of a text-based interface which involves a great amount of work. By the demand of facilitating the input process, many third-party applications have been developed. Currently available third-party applications are PyroSim, ASPIRE Smoke Detection Simulation, Project Scorch, BlenderFDS, and CYPE-Building Services [39]. The first four applications take mesh files as input, and CYPE takes IFC files as input to generate FDS input files. There are also third-party applications that convert a mesh or a solid to a partial FDS file. The rest of the information that is necessary to run FDS simulation must be added by editing the FDS input file. These applications greatly shorten the time for preparing the input files for FDS simulation.

2.4 Validation of the Models Used in CFAST and FDS

Considering the consequences of building fires, the validation of CFAST and FDS is essential. To confirm the accuracy of CFAST and FDS, numerous validation studies have been performed by comparing the results of real fire experiments with the results of simulations. Key validation research of the models used in CFAST and FDS was funded by US Nuclear Regulatory Commission Office of Research for the fire safety of nuclear power plants where building fire can cause catastrophe [40].

Many researchers have also validated the CFAST model besides NIST. For example, the Naval Research Lab conducted experiments of a real fire in vessel compartments induced by the enormous heat of launching rockets on the deck [41]. The data was collected and compared to CFAST simulation results. They found that although there are some mismatches, overall CFAST simulation predictions compared reasonably well with experimental results. Another research team compared results of experimental data with CFAST simulated data using five test cases [42]. The comparison also showed that CFAST simulation results are reasonably close to the actual experiment data. Salley et al. [40] conducted validation tests on eight out of 15 fire phenomena for nuclear power plants. They concluded that the simulation results of the temperature and height of hot gas layer, oxygen and carbon dioxide (CO2) concentration were consistent with experiments, but smoke concentration tended to be over-predicted. The travel delay of the smoke in corridors [43] and chimney effect in vertical shafts [44] were also validated with experimental data.

The models used in FDS also have been through numerous validation tests. In these tests, researchers conducted real scale fire experiments for different settings, such as in a tunnel, a single small room, a single large room, a set of multiple rooms, etc. [45]. Through these validation tests, researchers confirmed the physical phenomena (radiation, plume, etc.) that are modeled in FDS.

2.5 BIM Adoption in Practice

National Building Information Model Standard (NBIMS) Project Committee defines Building Information Modeling as:

A digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition [46].

BIM uses building components such as walls, windows, doors, roofs, etc. to represent a building. These building components contain geometric information and non- geometric information such as materials and the properties of the materials. In addition, BIM also stores the relational information between multiple components. For example, window 2 is hosted by wall 6, room A and room C are connected through door 3, and so on. The structure that BIM stores data enables a Building Information Model to supply necessary information throughout the lifecycle of a building: design, operation, construction, and demolition. The data stored in a Building Information Model can also be extracted for the use of fire simulation [47], energy simulation [48], acoustic simulation [49], material takeoff [50] and many other fields.

In contrast, conventional Computer Aided Architectural Design systems (shortened as CAAD) use primitive 2D and 3D geometries, such as line, arc, box, cylinder, surface, etc. to represent a building. Although efforts have been made to link a greater variety of non-geometric information, CAAD is essentially a drafting system in digital media and does not have the capability to distinguish building components, e.g. a wall from a slab, since they are all just represented as lines, rectangles or other primitive geometries. As the result, CAAD models usually do not have rich enough semantics to supply the necessary information for simulations without human interpretation of the drawings.

Because of its advantages, BIM has emerged as the replacement for CAAD and the use of BIM in the AEC industry has been surging. Becerik-Gerber conducted a survey to find the BIM adoption rate in the US [51]. Among the 424 people who responded to the survey, two-thirds of them use BIM for 60-100% of their projects. Another report [52] showed that BIM adoption in North America has grown from 28% in 2007 to 71% in 2012. They also reported that about 90% of large and medium-to-large organizations are engaged with BIM which is notably higher than small ones (49%). Becerik-Gerber's study showed that the major BIM solutions used in the US include Revit (41.6%), Navisworks (12.4%), Archicad (10.7%), Bentley (8.0%), and others.

Smoke propagation simulation largely is performed separately from design process or is even completely absent. Given that BIM is becoming the standard in architecture industry, designers could easily perform smoke propagation simulation during design process if smoke propagation simulation is incorporated into BIM and provides informative feedback in acceptable simulation time.

3. INTEGRATION OF BIM AND SMOKE PROPAGATION SIMULATION *

As discussed in the previous section, zone models are simpler and the simulation running time is very short, usually under a few minutes, while CFD models are more complex and the simulation running time is much longer, usually days to weeks. These differences between the two types of smoke propagation models places different challenges upon integration of simulation and BIM. For an integrated software system to be useful to architects in design process, the integrated system must be accurate, easy to use, and fast. Without any of these three criteria, the integrated system loses its practicality.

3.1 Selection of the Simulation Model and the BIM Tool

Although CFD models provide better accuracy compared to zone models, the simulation running time of CFD models is usually very long. If computing power grows 50% per year as it did until the 1990s, the simulation running time using CFD models would be reduced to an acceptable range in the near future. However, computer hardware engineers have encountered barriers to sustaining the rapid improvement since 2005 with relation to CPU clock, memory access speed, and CPU power consumption [53]. As the result, the computing power of modern PC did not improve substantially in the past 10+ years which indicates that the half century of rapidly increasing computing speed has come to a halt. The speed gap between CFD models and zone models on a desktop computer is unlikely to be reduced noticeably in the foreseeable future.

Cloud computing technology can be a potential solution to reduce the simulation running time of CFD models. Many computation-intensive applications, such as rendering

*Part of this section is reprinted with permission from "Facilitating Fire and Smoke Simulation Using Building Information Modeling" by Wu et al., 2015. Communications in Computer and Information Science, 527, pp. 366-382, Copyright [2015] by Springer. [47]

and simulation, have moved the platform from desktop to cloud. When a client computer sends computing workload to cloud through the Internet, the workload is divided and assigned to thousands or more computers for parallel computing. As the result, the computing time can be reduced dramatically. Examples include AutoDesk Cloud Rendering, Green Building Studio, and many more. However, to run CFD using cloud computing, the CFD application must be hosted by a cloud server. Currently, no cloud server hosts CFD-based smoke propagation simulation applications, nor is installing the executable file of the application on a general purpose cloud server permitted due to security reasons.

When the simulation running time of CFD models and zone models shows insignificant difference, the integration of BIM and CFD models can be reconsidered. At this moment, due to the unacceptably long simulation running time on desktop computers and the unavailability of using cloud computing, CFD models are not good candidates to be integrated into design process.

Zone models, on the other hand, are fast but its oversimplified simulation model places a different challenge to the integration with BIM. CFAST, as an example, describes the shape of a room with only three parameters, width, depth, and height. With these three parameters, the only shape of rooms can be simulated in CFAST is cuboid, despite the variety of shapes of rooms in real-world buildings. This oversimplification causes incompatibility between real-world buildings, their representation in BIM, and the zone models. In this research, a set of algorithms were devised to solve the incompatibility between BIM and the oversimplified zone models.

Overall, a zone model is a more viable solution for the integration of BIM and smoke propagation simulation. To demonstrate the integration between BIM and smoke propagation simulation, within many existing BIM applications and zone models, Revit Architecture was selected as the BIM authoring software because of its highest adoption rate in practice, and CFAST was selected as the smoke propagation simulation model because it is free, well-documented, and the accuracy has been validated. Since the major difficulty to integrate CFAST into Revit is ensued from the limitations of CFAST, identifying the limitations of CFAST and devising algorithms to overcome the limitations are essential to the integration of CFAST and Revit.

3.2 Identifying the Limitations of CFAST

BIM authoring tools utilize advanced geometry engines that are capable of generating very complex geometries. On the other hand, CFAST uses simplified geometries to define building shapes. CFAST was developed as stand-alone software in FORTRAN language when version 1.0 was first released in 1990. FAST, the predecessor of CFAST, dates even earlier than CFAST v1.0. To run simulations in CFAST, the definition of buildings had to be simplified to accommodate the hardware technology of the time. This simplified definition of a building used in CFAST is one of the major difficulties that impedes the integration of BIM and CFAST.

There are two major limitations in CFAST which cause the incompatibility. The first limitation is that the shape of the rooms in CFAST model must be cuboid. CFAST defines the geometry of a room with six parameters: width, depth, height, and its base point coordinates X, Y, Z. On the other hand, the geometric definition of a room in BIM is much more complex and can accommodate virtually any shape that exists in the real-world. Therefore, a building model in BIM cannot be simulated using CFAST without mapping from the complex shapes in the BIM to the cuboid shapes allowed in CFAST.

The second limitation is that the maximum number of rooms allowed to be simulated in CFAST is restricted to 30. A building with more than 30 rooms triggers a fatal error which blocks CFAST from starting the simulation. If we arbitrarily select 30 rooms from the whole building to perform simulation, the results are likely to be inaccurate. As an extreme example, selecting a subset of 30 totally disconnected rooms from a group of interconnected of rooms will produce meaningless simulation results. This limitation requires software users to interpret and transform a real-world building design such that it conforms to the simplified definitions of the CFAST model.

3.3 Algorithms to Overcome the Limitations of CFAST

Conventionally, users must manually transform the rooms of various shapes to cuboids in order to perform smoke propagation simulation in CFAST. This transformation process is time-consuming and likely to generate different results depending on the methods each individual uses to transform the shapes. Furthermore, there is no explicit protocol for how to simulate buildings that have more than 30 rooms. In this dissertation, I present transformation algorithms to automatically transform non-cuboid rooms to be compatible for CFAST simulation. I also present a room selection algorithm to select 30 rooms from any building that has more than 30 rooms. This allows users to simulate up to 30 of the most critical rooms in a building. The validation of the transformation algorithms and the room selection algorithm is documented in section 5.

3.3.1 Transformation Algorithms

To reconcile the different geometry representations between BIM and CFAST, I present a transformation algorithm for general rooms and a transformation algorithm for corridors. Different algorithms are used for general rooms and corridors because smoke behaves differently in the two types of rooms and they are classified differently in CFAST. In general rooms the upper layer, which consists of hot smoke, is separated almost instantaneously from the lower layer which consists of fresh air. In corridors, however, the propagation of smoke is delayed horizontally from one end to another [43].

For non-cuboid shaped general rooms, a cuboid with the same floor area and the same proportion of the Axis Aligned Bounding Box (AABB) of the room is used for simulation

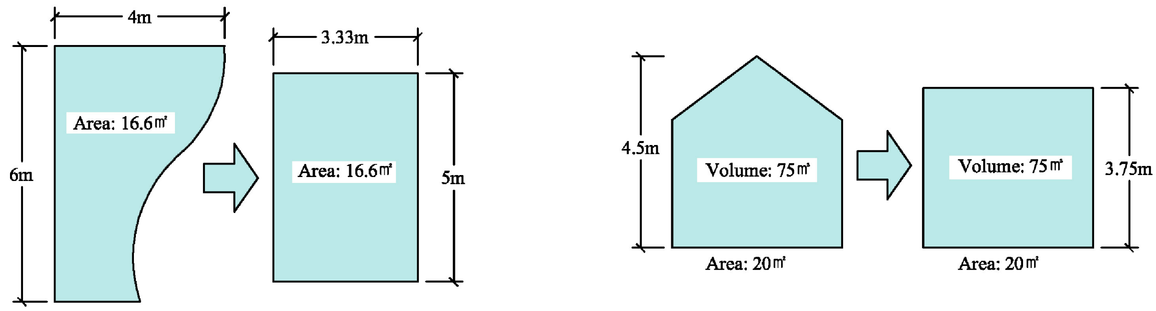


Figure 3.1: Transformation of a non-cuboid room. In the plan view (left), the two floor plans have the same floor area and proportion (2:3). In the section (right), the shapes have the same volume and floor area.

(figure 3.1, left). The height of the room is calculated by dividing the volume by the floor area of the room (figure 3.1, right). The area and the volume of the rooms are readily retrievable from the BIM, and the AABB of the rooms can be easily calculated based on the geometries of the rooms, which also can be retrieved from the BIM. This algorithm is based on the assumption that volume and proportion are the primary factors that affect smoke simulation in general rooms.

The method used for transforming general rooms is inappropriate for transforming corridors because of the delayed horizontal smoke propagation in the corridors. As shown in figure 3.2, if a T-shaped corridor (in plan view) is transformed using the same method as in the general rooms, the simulation results will not accurately represent the reality. This is because smoke takes much longer to propagate from one end to another in the original T-shaped corridor compared to the transformed rectangular space. Therefore another method should be used for corridors.

In figure 3.3 (left), when room A catches fire, point p1 is where smoke first enters the T-shaped corridor. Point p2, the furthest point from p1, is the last point that smoke reaches. The distance between p1 and p2 (d1 + d2) is used as the length of the transformed corridor;

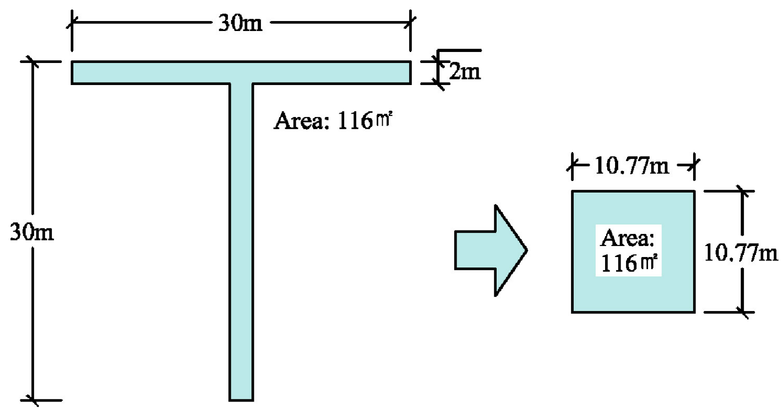


Figure 3.2: Transformation of corridors using the same method as used in general rooms. Smoke in the two spaces will behave in totally different ways.

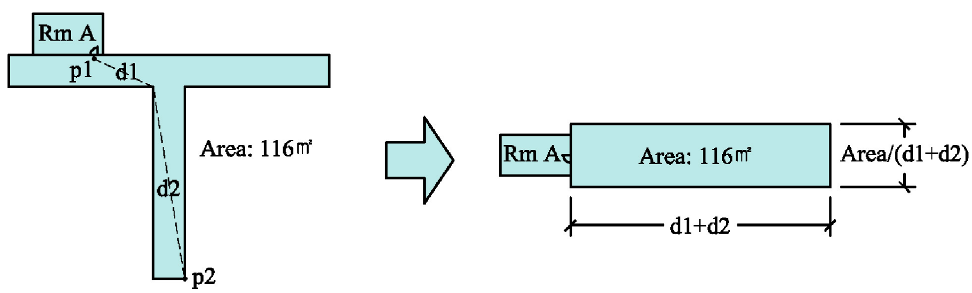


Figure 3.3: Transforming a corridor by smoke travel distance.

floor area divided by the length is used as the width (figure 3.3 right), and volume divided by floor area is used as the height of the transformed corridor. This way, the longest time that smoke travels in the original T-shaped corridor and in the transformed CFAST corridor is expected to be similar.

3.3.2 Room Selection Algorithm

CFAST can only simulate buildings with maximum of 30 rooms. To simulate smoke propagation for buildings with 30+ rooms using CFAST, a room selection algorithm can be used to choose the 30 rooms that have the shortest smoke travel distance from the fire origin. The validity of this algorithm is tested in section 5. If the algorithm is valid, we can simulate at least 30 of the most critical rooms of the building. The underlying assumption is that the occupants that are closer to the fire origin (by smoke travel distance) are more vulnerable because they have less time to safely evacuate.

The smoke travel distance of each room from the fire origin can be calculated with network graph algorithms. This process can be easily automated due to the object-oriented structure of BIM. BIM stores the properties of each building component as well as the relationship between the components. For example, an interior door knows which two rooms it connects. If a door connects a room and the exterior, the door is classified as an exterior door. By extracting the connectivity information of all the doors iteratively we can easily generate the topological room-door connection graph of the building as shown in figure 3.4.

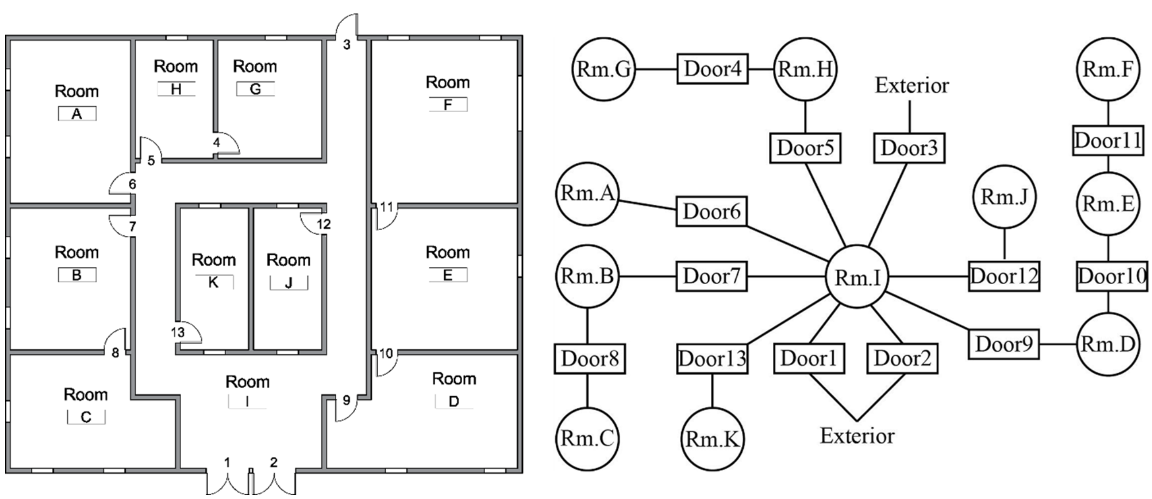


Figure 3.4: A sample building in BIM (left) and its topological graph (right).

The topological graph does not contain distance information of each connection. For example, although we know that door 5 and door 2 are connected through room I, we don't know the shortest travel distance between the two doors. The linear distance between door

5 and door 2, does not correctly represent the shortest travel distance because room K is blocking the linear path between the two doors, i.e. not all linear connections are valid.

To calculate the shortest travel distance, a geometric network graph is generated for each room respectively, using the doors and vertices (corners) of the room as nodes, and the linear distance between two nodes as the weight (figure 3.5 left, the length of each green line is the weight between the two points). If the linear line between two nodes intersects the boundary of the room, the weight is set to infinity. For example, the weight between door 5 and door 2 is set to infinity because the linear connection between the two doors passes room K. Using this information, we can generate the adjacency matrix of the network graph for each room (table 3.1).

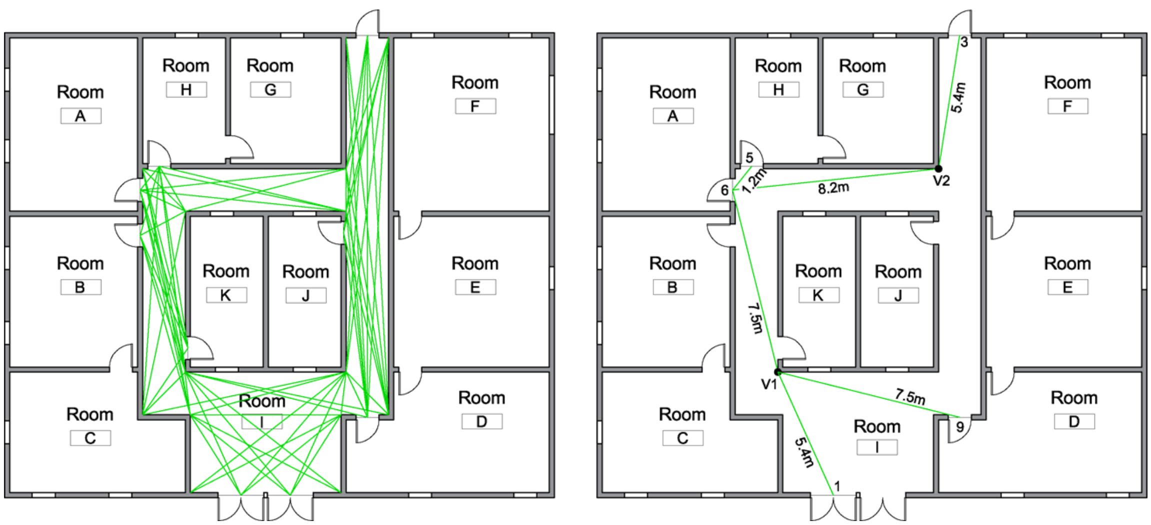


Figure 3.5: Geometric network graph of the room I using the doors and the vertices of the room as nodes (left). The shortest travel distance between door 6 and other four doors of the room I (right).

By running Dijkstra algorithm [54], a shortest path algorithm, the shortest path between any two nodes of the room can be easily calculated. In figure 3.5 (right), for example, the shortest path from door 6 to door 3 passes V2, and the shortest travel distance is 13.6 meters (8.2m + 5.4m). Similarly, the shortest path between door 6 and door 9 passes V1, and the distance is 15 meters. By combining the topological graph and the geometric network graphs of the rooms, the rooms can be sorted based on the shortest smoke travel distance from the room of fire origin, and extract the first 30 rooms for smoke propagation simulation. For example, assuming that the fire origin is room A, the next room that smoke propagates to is room I because room A and room I share door 6, (i.e. the distance is 0). Then the next is room H because door 5 is the next closest door to door 6, and so on. The whole selection process is automated by the algorithm and can be done within one mouse click.

	D1	D2	D3	D5	D6	D7	D9	D12	D13	V1	V2	...
D1	0											
D2	1.9	0										
D3	∞	∞	0									
D5	∞	∞	∞	0								
D6	∞	∞	∞	1.2	0							
D7	∞	∞	∞	2.9	1.8	0						
D9	∞	∞	15	∞	∞	∞	0					
D12	∞	∞	7.9	∞	∞	∞	7.4	0				
D13	∞	∞	∞	7.3	6.5	4.9	∞	∞	0			
V1	5.4	6.5	∞	8.3	7.5	5.8	7.5	∞	0.9	0		
V2	∞	∞	5.4	7.7	8.2	∞	9.9	2.5	∞	∞	0	
...												

Table 3.1: The adjacency matrix of room I. D stands for door, V stands for vertex. Room I contains 9 doors and 14 vertices. The matrix is symmetric.

3.4 Prototype of the Integrated System

A prototype application was developed using the described algorithms to demonstrate the integration of smoke propagation simulation and BIM. Revit was used as the BIM software, and CFAST was used as the smoke propagation simulation software. The prototype was developed using Revit API with C# programming language to extract data from the BIM and send it to CFAST. The system diagram is shown in figure 3.6. For easier reference in the following text, this prototype is given a name ToFAST (Converting Revit model to CFAST model).

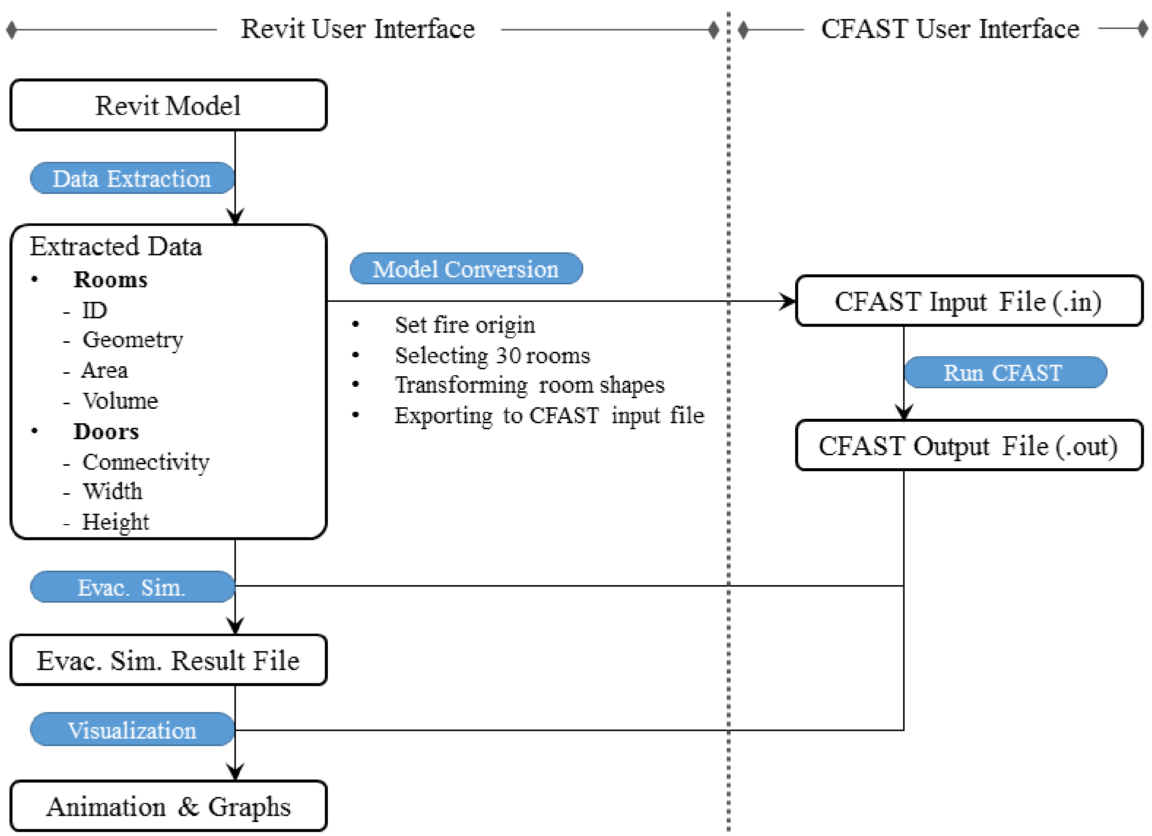


Figure 3.6: System diagram.

ToFAST retrieves the information of rooms and doors from a Revit model. The extracted room information includes ID, geometry, area, and volume of the room objects. The extracted door information includes height, width, and the rooms that each door connects. ToFAST then applies the transformation algorithms and the room selection algorithm to convert the model into a CFAST-compatible model for smoke propagation simulation, and export a CFAST input file (file extension .in). Using CFAST user interface, a user can open the input file and run smoke propagation simulation with a few clicks. At the end of the simulation, CFAST generates an output file (file extension .out) which contains the simulation results. An evacuation simulation model then uses the extracted BIM data and the CFAST output file to simulate occupant evacuation. The results of the evacuation simulation can be visualized with an animation and graphs. The details about the evacuation simulation and visualization are documented in the next section.

The following pseudo-code shows the main execution routine that ToFAST extracts data from a Revit model, convert it to a CFAST model, and export to a CFAST input file.

```
     Function GenerateCFASTmodel()
(1)       AccessCurrentRevitModel()
(2)       allRooms <- GetAllRooms()
(3)       roomOnFire <- GetFireOrigin()
(4)       allDoors <- GetAllDoors()
(5)       AssignDoorType()
(6)       CreateCompartments()
(7)       InitializeDoorGraph()
(8)       UpdateAdjacencyMatrix()
(9)       startNode <- roomOnFire
(10)      RunDijkstra()
(11)      SelectCompartmentsAndDoors()
(12)      WriteCFASTinput()
```

Line 1 accesses all the building elements in the current Revit model. Line 2 searches all the elements in the Revit model, apply filters to select all the room objects, and put them into the global variables named allRooms. Line 3 checks if the user has selected a room as the fire origin. If there is no room selected as the fire origin, the application terminates with an error message informing the user that a room needs to be selected as the fire origin to start the simulation. The ID of the room object is stored in a variable named roomOnFire. Line 4 searches all the elements in the Revit model, applies filters to select all the door objects, and put them into the global variables named allDoors. Line 5 iterates through all the doors and sets the type of each door to either exterior door or interior door, depending on whether the door connects two rooms or one room with the exterior. Line 6 creates compartment objects from the data of the room objects in the Revit model. Compartment class is a custom designed class which has variables and functions that are used for transforming the rooms in the Revit model into the compartments in CFAST model. Line 7 initializes an n by n identity matrix, where n is the number of the doors in the model. Line 8 creates adjacency matrix of the model. To create the adjacency matrix, the application first iterates through all the rooms and finds the rooms that have more than one door. Then the application calculates the shortest travel distance between the doors of the room and updates the matrix with corresponding data. Line 9 sets the room of fire origin as the start node of the network graph. Line 10 calculates the shortest distance from the start node to all the other nodes using Dijkstra algorithm which takes two input parameters, the adjacency matrix, and the index of the start node. Line 11 sorts the compartments by the shortest distance in ascending order and selects 30 rooms that are closest to the fire origin. In this process, it also selects all the doors that are connected to the selected 30 rooms. Line 12 exports the transformed model according to the format of CFAST input file. It first writes the header of the simulation input file with default values. The header information includes total simulation time, simulation interval, temperature, pressure, etc. Then the application writes the compartments, doors, mechanical vents, alarms, suppression system, and fire information according to the definition of CFAST input file.

3.5 Testing ToFAST

This subsection demonstrates the smoke propagation simulation on a test model using ToFAST. As the test model, a floor plan of a university building with 41 rooms is modeled in Revit as shown in figure 3.7. Before starting the simulation, a room must be selected and set as the fire origin. Two sofas were set on fire at the simulation time step of 0 second and 60 seconds respectively. The HRR and the gas yield of a sofa are stored in CFAST database. Because smoke propagation simulation results vary depending on which room is the fire origin, it is necessary to simulate multiple runs by setting the fire origin to different rooms. Once the room of fire origin is set, the Revit model is ready to be converted into a CFAST model. At the end of the conversion, ToFAST outputs a file that CFAST can read in and simulate. Information of smoke alarms, suppression systems, and mechanical vents can be added to the model prior to the model conversion if desired.

As shown in figure 3.8, there are a total of six commands in ToFAST. 1) Assign fire origin, 2) set mechanical vents, 3) set alarms, 4) set suppression system, 5) generate simulation model, and 6) visualize simulation results. Visualizing simulation results is documented in section 4.

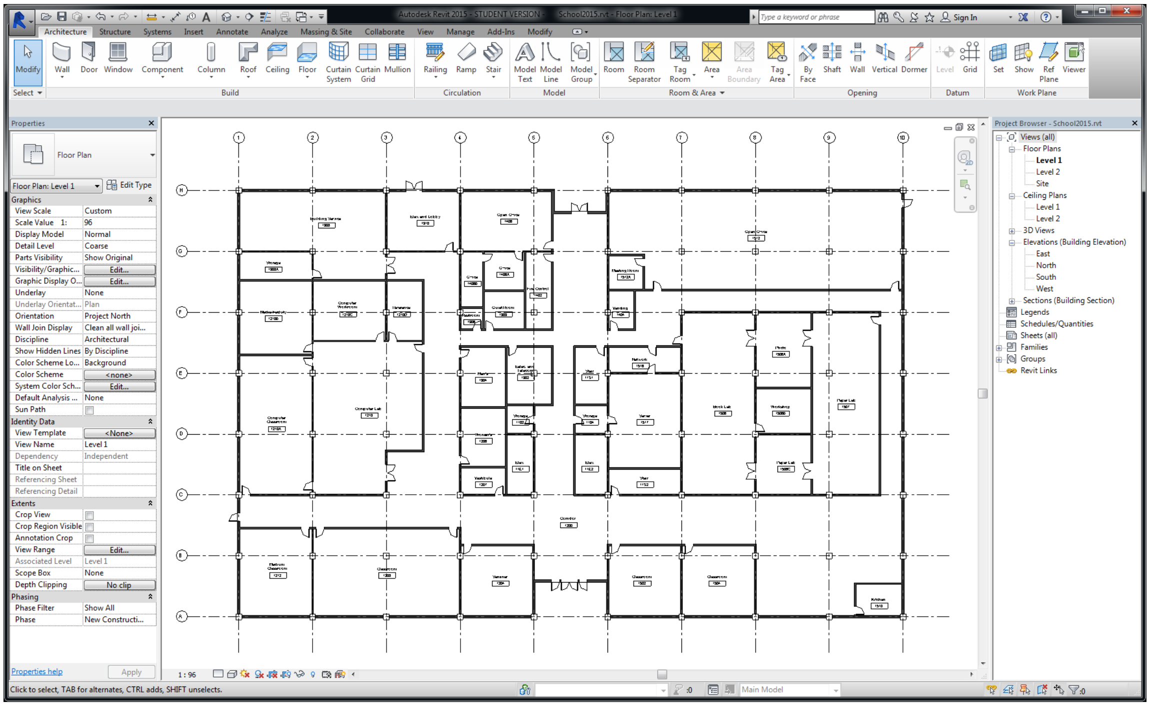


Figure 3.7: Revit model of a floor of an existing building.

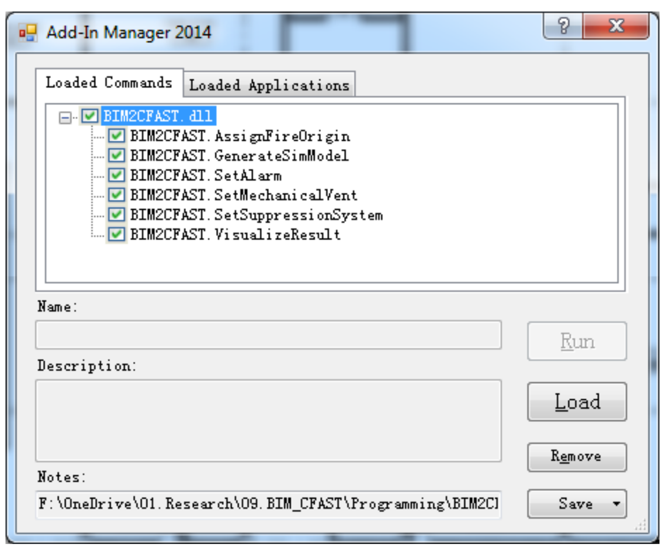


Figure 3.8: Commands in ToFAST, for conversion of a Revit model to a CFAST model and the visualization of the simulation results.

3.5.1 Converting a BIM model to a CFAST model

All rooms in the Revit model must be represented as Room objects. Before converting the model, a room has to be selected as the fire origin, which can be done by selecting a room and running AssignFireOrigin command (figure 3.9). The BIM model then can be converted into CFAST model by running GenerateSimModel command. A CFAST input file (extension .in) is saved at a user-specified location. The input file of CFAST model is in ASCII text format which can be open with any text editor (figure 3.10).

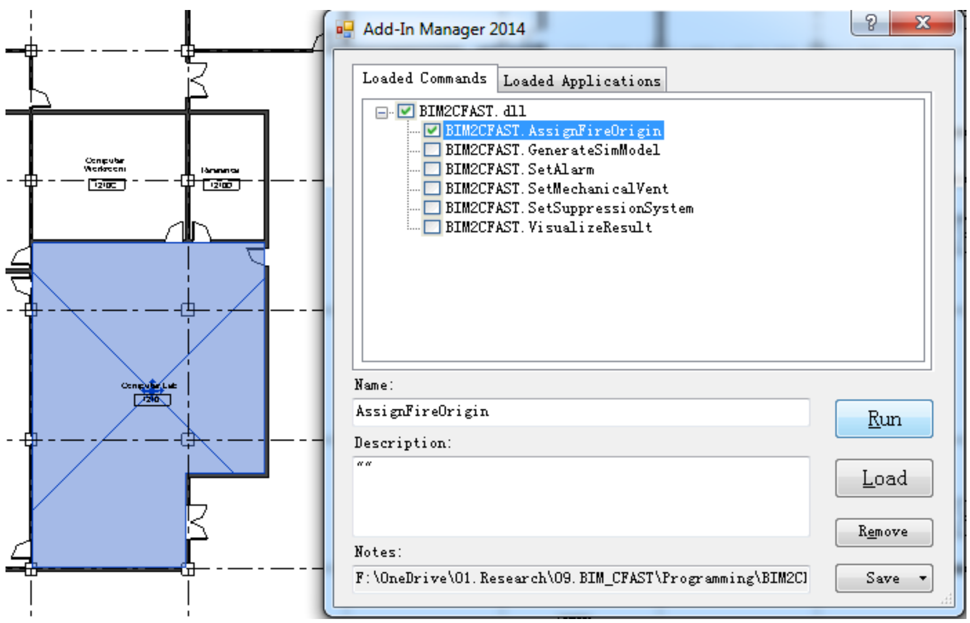
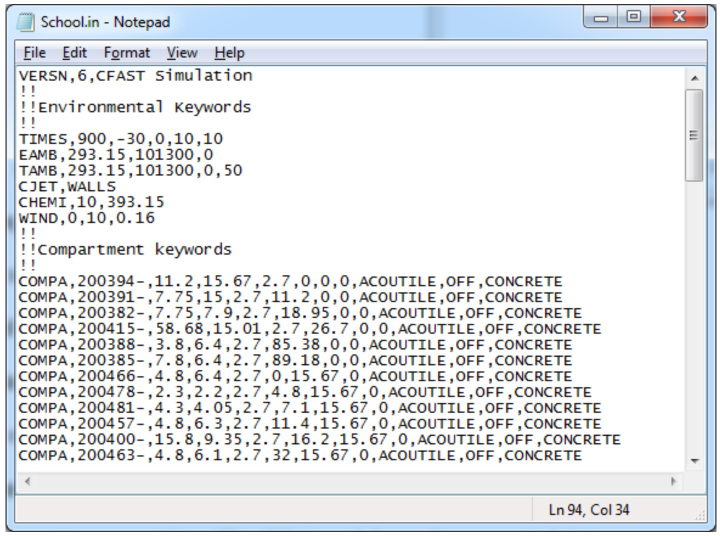


Figure 3.9: Setting the room of fire origin.

When converting a Revit model into a CFAST model, all rooms are converted into cuboids and located next to one another, ordered by the travel distance from the fire origin (figure 3.11). The relative position between any two connected rooms does not influence the simulation results because smoke propagation in CFAST model relies on the topological connectivity of the rooms rather than their geometric location.




```
VERSN,6,CFAST Simulation
!!
!!Environmental Keywords
!!
TIMES,900,-30,0,10,10
EAMB,293.15,101300,0
TAMB,293.15,101300,0,50
CJET,WALLS
CHEMI,10,393.15
WIND,0,10,0.16
!!
!!Compartment keywords
!!
COMPA,200394-,11.2,15.67,2.7,0,0,0,ACOUTILE,OFF,CONCRETE
COMPA,200391-,7.75,15,2.7,11.2,0,0,ACOUTILE,OFF,CONCRETE
COMPA,200382-,7.75,7.9,2.7,18.95,0,0,ACOUTILE,OFF,CONCRETE
COMPA,200415-,58.68,15.01,2.7,26.7,0,0,ACOUTILE,OFF,CONCRETE
COMPA,200388-,3.8,6.4,2.7,85.38,0,0,ACOUTILE,OFF,CONCRETE
COMPA,200385-,7.8,6.4,2.7,89.18,0,0,ACOUTILE,OFF,CONCRETE
COMPA,200466-,4.8,6.4,2.7,0,15.67,0,ACOUTILE,OFF,CONCRETE
COMPA,200478-,2.3,2.2,2.7,4.8,15.67,0,ACOUTILE,OFF,CONCRETE
COMPA,200481-,4.3,4.05,2.7,7.1,15.67,0,ACOUTILE,OFF,CONCRETE
COMPA,200457-,4.8,6.3,2.7,11.4,15.67,0,ACOUTILE,OFF,CONCRETE
COMPA,200400-,15.8,9.35,2.7,16.2,15.67,0,ACOUTILE,OFF,CONCRETE
COMPA,200463-,4.8,6.1,2.7,32,15.67,0,ACOUTILE,OFF,CONCRETE
```

Figure 3.10: CFAST input file generated by ToFAST.

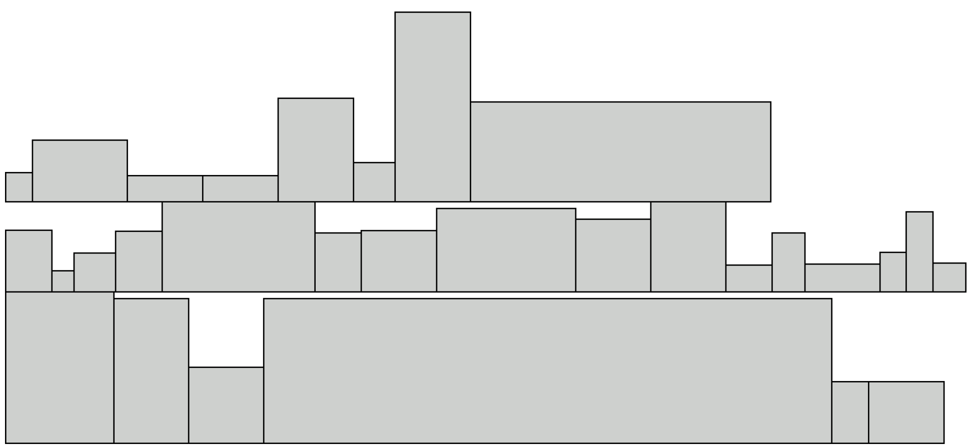


Figure 3.11: Floor plan of the CFAST model that is converted from the Revit model. All rooms are converted to cuboids.

3.5.2 Adding Systems

Alarms, suppression systems, and mechanical vents can be added to the model. Although adding alarms in CFAST does not directly affect the simulation results, the timing that the alarms are triggered is recorded in the simulation output file and can be used as the start time in the evacuation simulation for more accurate simulation results. Adding suppression system in CFAST dramatically slows down smoke propagation speed by suppressing the fire and the generation of smoke from the fire origin. Mechanical vents, on the other hand, increase smoke propagation speed between the rooms that are connected with the vents.

To add alarms, first select one or multiple rooms and run SetAlarm command. In the popup window select alarm type (smoke alarm or heat alarm), set the activation temperature of the alarm (^oC), and set response time index (figure 3.12). To add suppression system, first select one or multiple rooms and run SetSuppressionSystem command. In the popup window set the activation temperature (^oC) of the suppression system, response time index, and spray density (figure 3.13). To add mechanical vents, first select two of the rooms that are linked by a vent and run SetMechanicalVent command. Then set the properties of the mechanical vents between the two rooms which include vent area, height, orientation, air flow parameters, opening fraction, and filter efficiency (figure 3.14).

Alarms, suppression systems, and mechanical vents require position information. The position information can be extracted from the Revit model. By default, they are set to 0.1m under the center points of the ceilings. Due to the nature of zone models, the horizontal location of alarms and suppression systems does not affect simulation results. Height is the only parameter that determines the timing to trigger the alarms and the suppression systems.

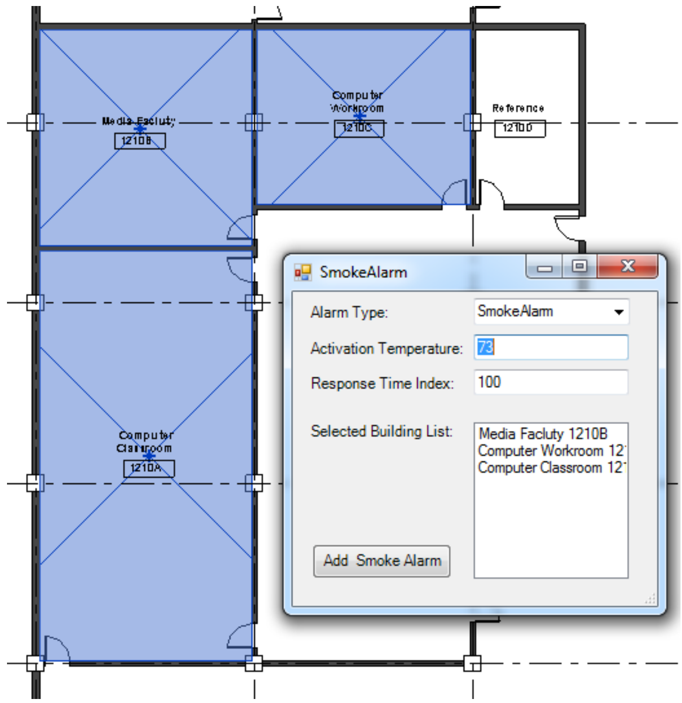


Figure 3.12: Adding alarms.

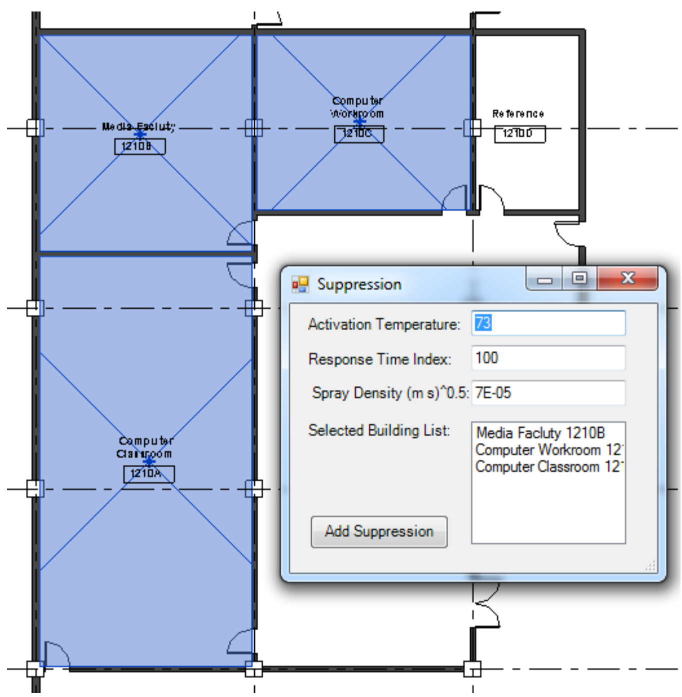


Figure 3.13: Adding suppression system.

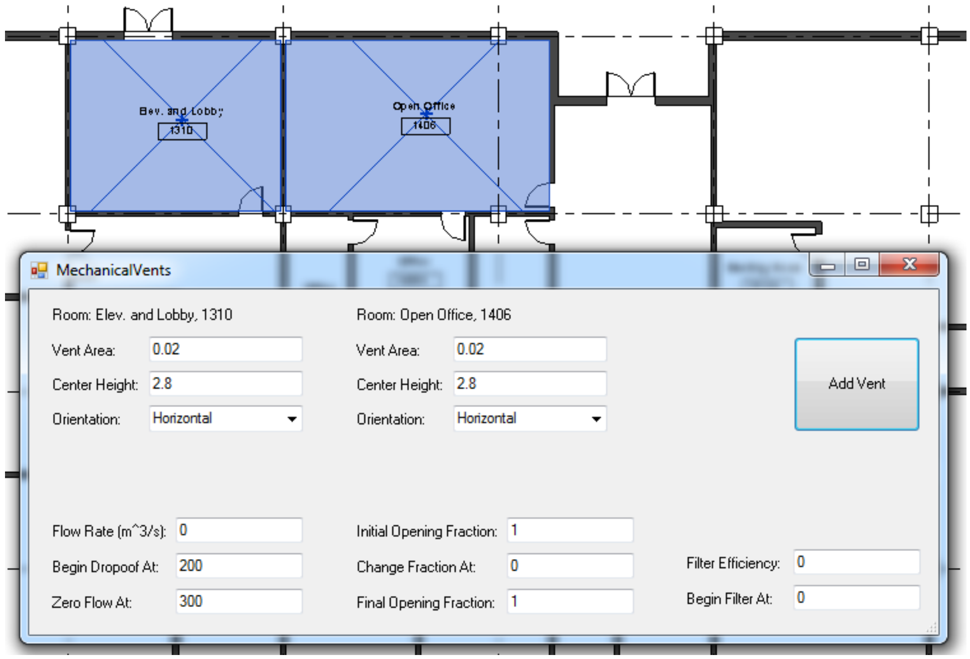


Figure 3.14: Adding mechanical vents.

After adding systems information, the Revit model can be converted into a CFAST model to run the simulation. Systems information can be added either in Revit or CEDIT (the graphic user interface for CFAST) which have no difference in the simulation results. The advantage of entering systems information using ToFAST interface is that it is easier for designers to enter the information by visually looking at the floor plan rather than reading text-based input file.

3.5.3 Performing Simulation in CFAST

After converting the Revit model into the CFAST-compatible format, smoke propagation simulation can be easily launched by opening the input file from CEDIT user interface and clicking on the Run button (figure 3.15). The simulation for this test case took less than 20 seconds (figure 3.16).

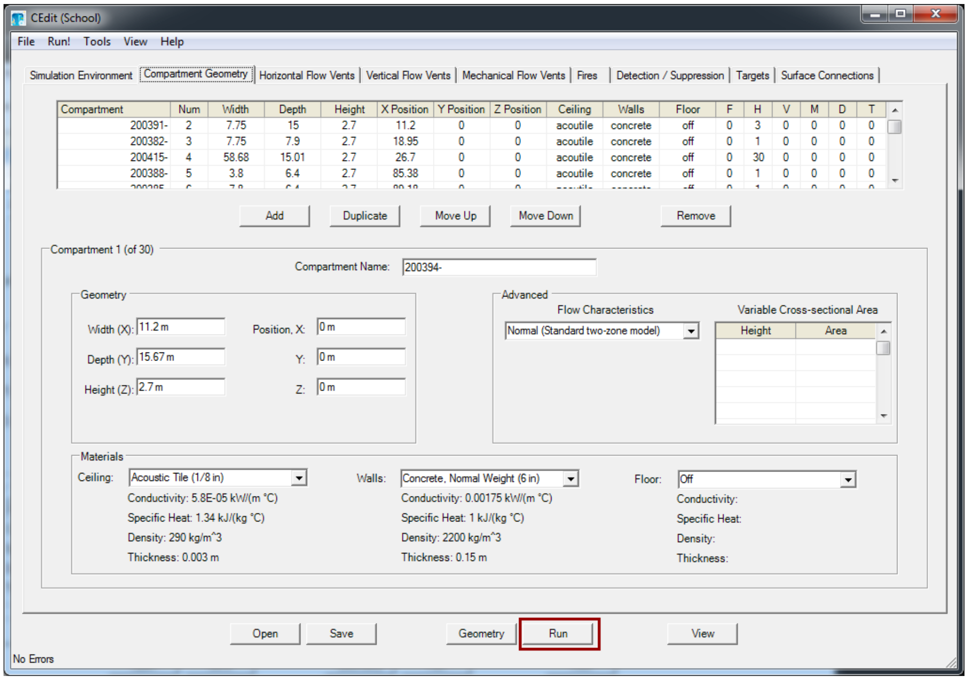


Figure 3.15: Running simulation from CFAST interface.

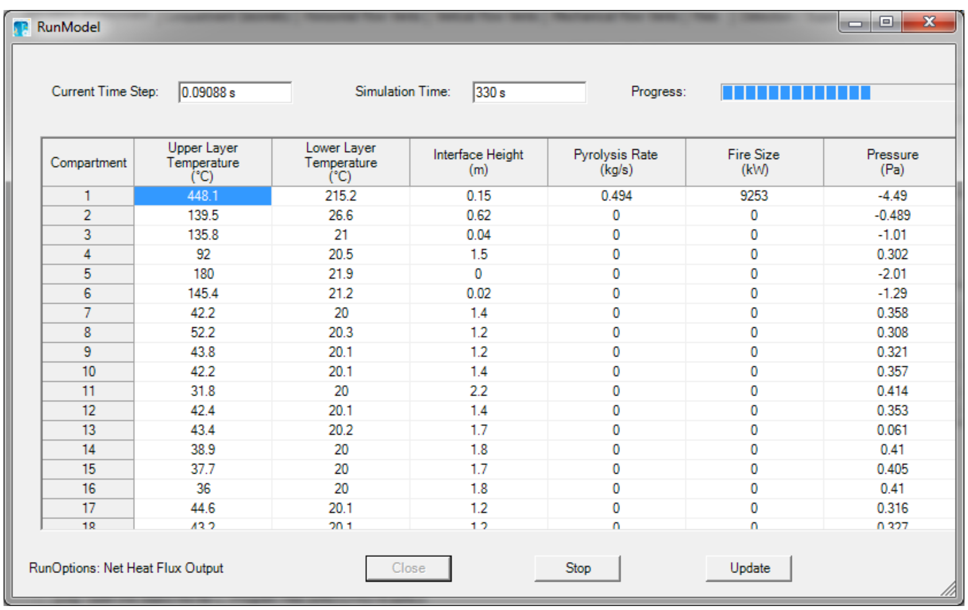


Figure 3.16: Simulation for the test case in progress.

When the simulation finishes, CFAST generates a text-based output file as the simulation results. The output file contains three blocks of data for each simulation time step, which are 1) the temperature of the upper zone and the lower zone, and the smoke height between the two zones, 2) the concentration of each gas species in the upper layer, 3) the concentration of each gas species in the lower layer. Figure 3.17 shows the simulation results at time step 510 seconds.

3.5.4 Testing on Multiple Buildings

To Test the generalizability of ToFAST, a one-story convenience store and two floors of a four-story hotel are tested with ToFAST. The floor plans are shown as in figure 3.18 - 3.20. The fire source is respectively set to the merchandise room (101) in the convenience store, room 117 on the first floor of the hotel, and room 321 on the third floor of the hotel.

In the floor plan of the convenience store, merchandise room (101) and sales room (102) are divided by a room separator, a virtual boundary in space denoted with a red line in figure 3.18. Currently, ToFAST does not recognize Room Separator objects as a type of connection between two rooms. As the result, ToFAST did not simulate three of the rooms, sales room (102), back room (103), and office (106), mistreating the rooms as if they are disconnected from the room of fire origin. This is because the functional definition of room in Revit is spatially different with the definition of compartment in CFAST. Two rooms in a Revit model can be spatially connected but separated by their functions. However, a compartment in CFAST needs to be spatially closed. If the floor plan is adjusted such that merchandise room and sales room are one compartment as shown in figure 3.21 (blue region), ToFAST was able to correctly generate a CFAST input file.

In the hotel building, ToFAST did not recognize the door openings of the lobby (100) as the connection between the lobby and the corridor. In the future, the functions of ToFAST needs to be expanded by including other types of room connections, such as

Time = 510.0 seconds.

Compartment	Upper Temp. (C)	Lower Temp. (C)	Inter. Height (m)	Upper Vol. (m^3)	Upper Absorb (m^-1)	Lower Absorb (m^-1)	Pressure (Pa)	Ambient Target (W/m^2)	Floor Target (W/m^2)
200394-	394.5	174.2	0.4073	4.02E+02(85%)	3.53	0.524	-5.52	8.243E+03	5.444E+03
200391-	186.9	48.63	0.4823	2.58E+02(82%)	0.500	1.000E-02	-2.93	1.558E+03	1.245E+03
200382-	159.6	23.84	1.3556E-03	1.65E+02(100%)	0.500	1.000E-02	-3.86	1.174E+03	1.142E+03
200415-	107.5	22.52	1.256	1.27E+03(53%)	0.500	1.000E-02	-0.426	444.	422.
200388-	191.6	27.43	2.7000E-04	66. (100%)	0.500	1.000E-02	-4.32	1.570E+03	1.504E+03
200385-	167.2	24.47	3.7053E-04	1.35E+02(100%)	0.500	1.000E-02	-3.98	1.272E+03	1.234E+03
200466-	52.67	20.90	0.8370	57. (69%)	0.500	1.000E-02	-0.395	112.	104.
200478-	70.57	21.87	1.043	8.4 (61%)	0.500	1.000E-02	-0.412	125.	109.
200481-	58.44	21.37	0.9171	31. (66%)	0.500	1.000E-02	-0.403	120.	109.
200457-	52.82	20.92	0.8390	56. (69%)	0.500	1.000E-02	-0.396	112.	104.
200400-	49.07	20.25	0.9036	2.65E+02(67%)	0.500	1.000E-02	-0.344	111.	109.
200463-	53.12	20.95	0.8433	54. (69%)	0.500	1.000E-02	-0.396	113.	105.
200469-	60.80	20.66	1.533	58. (43%)	0.500	1.000E-02	-8.438E-02	114.	108.
200376-	50.86	20.29	0.9416	2.18E+02(65%)	0.500	1.000E-02	-0.341	117.	115.
200403-	48.56	20.32	0.8334	1.09E+02(69%)	0.500	1.000E-02	-0.366	104.	101.
200397-	47.64	20.25	0.8884	1.31E+02(67%)	0.500	1.000E-02	-0.343	99.9	97.7
200451-	60.77	21.51	0.9461	24. (65%)	0.500	1.000E-02	-0.405	120.	107.
200445-	56.18	21.24	0.8874	38. (67%)	0.500	1.000E-02	-0.401	115.	105.
200379-	33.08	20.08	0.5549	48. (79%)	0.500	1.000E-02	-0.301	40.3	39.6
200490-	62.92	21.60	0.9701	19. (64%)	0.500	1.000E-02	-0.407	123.	109.
200487-	54.05	21.14	0.8580	43. (68%)	0.500	1.000E-02	-0.400	107.	97.2
200442-	58.39	20.50	0.9694	18. (64%)	0.500	1.000E-02	-0.366	105.	101.
200460-	65.89	21.71	1.001	14. (63%)	0.500	1.000E-02	-0.409	125.	111.
200472-	47.92	20.26	0.9213	1.11E+02(66%)	0.500	1.000E-02	-0.333	98.2	95.9
200448-	54.90	20.39	0.9471	37. (65%)	0.500	1.000E-02	-0.357	103.	99.5
200436-	55.08	21.22	0.8729	38. (68%)	0.500	1.000E-02	-0.401	109.	98.3
200433-	36.60	20.13	0.6584	1.61E+02(76%)	0.500	1.000E-02	-0.304	61.4	60.3
200406-	48.56	20.32	0.8334	1.09E+02(69%)	0.500	1.000E-02	-0.366	104.	101.
200484-	32.91	20.09	0.5352	38. (80%)	0.500	1.000E-02	-0.308	40.2	39.4
200430-	43.15	20.15	1.306	2.13E+02(52%)	0.500	1.000E-02	-0.160	71.4	70.1

Upper Layer Species

Compartment	N2 (%)	O2 (%)	CO2 (%)	CO (ppm)	HCN (ppm)	HCL (ppm)	TUHC (%)	H2O (%)	OD (1/m)	CT (g-min/m3)
200394-	71.0	9.16	7.23	2.121E+03	0.00	0.00	0.00	8.93	29.0	181.
200391-	70.9	9.09	7.26	2.130E+03	0.00	0.00	0.00	9.06	42.4	169.
200382-	71.8	10.4	6.43	1.887E+03	0.00	0.00	0.00	8.16	39.8	152.
200415-	74.9	15.1	3.41	1.000E+03	0.00	0.00	0.00	4.83	23.7	102.
200388-	70.2	8.02	7.95	2.331E+03	0.00	0.00	0.00	9.79	46.0	195.
200385-	71.3	9.66	6.89	2.022E+03	0.00	0.00	0.00	8.66	42.0	162.
200466-	76.3	17.3	2.06	603.	0.00	0.00	0.00	3.40	16.7	56.3
200478-	75.1	15.4	3.21	943.	0.00	0.00	0.00	4.65	24.8	86.6
200481-	75.8	16.6	2.49	729.	0.00	0.00	0.00	3.87	19.8	65.7
200457-	76.2	17.2	2.07	606.	0.00	0.00	0.00	3.42	16.7	56.6
200400-	76.7	17.9	1.62	474.	0.00	0.00	0.00	2.93	13.2	45.1
200463-	76.2	17.2	2.09	613.	0.00	0.00	0.00	3.44	16.9	57.0
200469-	76.0	16.8	2.35	691.	0.00	0.00	0.00	3.69	18.6	59.1
200376-	76.6	17.7	1.75	512.	0.00	0.00	0.00	3.07	14.2	50.9
200403-	76.6	17.8	1.71	502.	0.00	0.00	0.00	3.03	14.0	48.1
200397-	76.7	17.9	1.63	479.	0.00	0.00	0.00	2.95	13.4	45.6
200451-	75.6	16.3	2.69	789.	0.00	0.00	0.00	4.09	21.3	70.5
200445-	76.0	16.8	2.35	690.	0.00	0.00	0.00	3.72	18.9	62.7
200379-	77.3	18.9	1.03	303.	0.00	0.00	0.00	2.30	8.88	21.1
200490-	75.5	16.0	2.83	829.	0.00	0.00	0.00	4.23	22.3	73.9
200487-	76.0	16.9	2.27	666.	0.00	0.00	0.00	3.64	18.3	61.1
200442-	76.1	17.1	2.17	637.	0.00	0.00	0.00	3.52	17.3	75.5
200460-	75.3	15.8	2.99	878.	0.00	0.00	0.00	4.41	23.4	78.7
200472-	76.7	17.9	1.66	487.	0.00	0.00	0.00	2.97	13.6	48.4
200448-	76.1	17.0	2.19	642.	0.00	0.00	0.00	3.54	17.6	67.4
200436-	76.0	16.8	2.35	689.	0.00	0.00	0.00	3.72	18.9	62.8
200433-	77.1	18.5	1.25	368.	0.00	0.00	0.00	2.54	10.7	31.2
200406-	76.6	17.8	1.71	502.	0.00	0.00	0.00	3.03	14.0	48.1
200484-	77.3	18.8	1.04	305.	0.00	0.00	0.00	2.30	8.94	21.4
200430-	77.0	18.4	1.34	392.	0.00	0.00	0.00	2.62	11.1	36.7

Lower Layer Species

Compartment	N2 (%)	O2 (%)	CO2 (%)	CO (ppm)	HCN (ppm)	HCL (ppm)	TUHC (%)	H2O (%)	OD (1/m)	CT (g-min/m3)
200394-	77.7	19.2	0.831	244.	0.00	0.00	0.00	1.81	4.88	27.4
200391-	77.4	18.8	1.08	317.	0.00	0.00	0.00	2.16	8.83	29.9
200382-	78.4	20.5	0.00	0.00	0.00	0.00	0.00	1.17	0.00	0.00
200415-	78.6	20.5	5.801E-02	17.0	0.00	0.00	0.00	0.897	0.514	0.784
200388-	78.4	20.5	0.00	0.00	0.00	0.00	0.00	1.17	0.00	0.00
200385-	78.4	20.5	0.00	0.00	0.00	0.00	0.00	1.17	0.00	0.00
200466-	78.3	20.4	2.667E-02	7.82	0.00	0.00	0.00	1.18	0.238	0.221
200478-	78.4	20.4	6.514E-02	19.1	0.00	0.00	0.00	1.16	0.579	1.35
200481-	78.3	20.4	4.487E-02	13.2	0.00	0.00	0.00	1.18	0.400	0.596
200457-	78.3	20.4	2.728E-02	8.00	0.00	0.00	0.00	1.18	0.243	0.229
200400-	78.4	20.5	2.866E-08	8.408E-06	0.00	0.00	0.00	1.17	2.564E-07	2.011E-06
200463-	78.3	20.4	2.855E-02	8.37	0.00	0.00	0.00	1.18	0.255	0.248
200469-	78.8	20.6	2.249E-02	6.60	0.00	0.00	0.00	0.552	0.200	0.229
200376-	78.4	20.5	8.723E-04	0.256	0.00	0.00	0.00	1.17	7.801E-03	2.771E-02
200403-	78.4	20.5	2.611E-03	0.766	0.00	0.00	0.00	1.17	2.335E-02	6.839E-03
200397-	78.4	20.5	2.922E-08	8.570E-06	0.00	0.00	0.00	1.17	2.613E-07	2.050E-06
200451-	78.3	20.4	5.120E-02	15.0	0.00	0.00	0.00	1.18	0.456	0.770
200445-	78.3	20.4	4.099E-02	12.0	0.00	0.00	0.00	1.18	0.365	0.484
200379-	78.4	20.5	1.371E-10	4.021E-08	0.00	0.00	0.00	1.17	1.227E-09	6.520E-09
200490-	78.3	20.4	5.428E-02	15.9	0.00	0.00	0.00	1.18	0.483	0.877
200487-	78.3	20.4	3.889E-02	11.4	0.00	0.00	0.00	1.19	0.347	0.415
200442-	78.3	20.5	1.146E-02	3.36	0.00	0.00	0.00	1.17	0.102	0.428
200460-	78.3	20.4	5.789E-02	17.0	0.00	0.00	0.00	1.17	0.515	1.02
200472-	78.4	20.5	6.380E-04	0.187	0.00	0.00	0.00	1.17	5.706E-03	2.402E-02
200448-	78.3	20.5	5.607E-03	1.64	0.00	0.00	0.00	1.17	5.013E-02	0.235
200436-	78.3	20.4	4.215E-02	12.4	0.00	0.00	0.00	1.19	0.376	0.487
200433-	78.4	20.5	1.248E-10	3.660E-08	0.00	0.00	0.00	1.17	1.117E-09	7.710E-09
200406-	78.4	20.5	2.611E-03	0.766	0.00	0.00	0.00	1.17	2.335E-02	6.839E-03

Figure 3.17: Simulation results of the test case at time step 510 seconds.

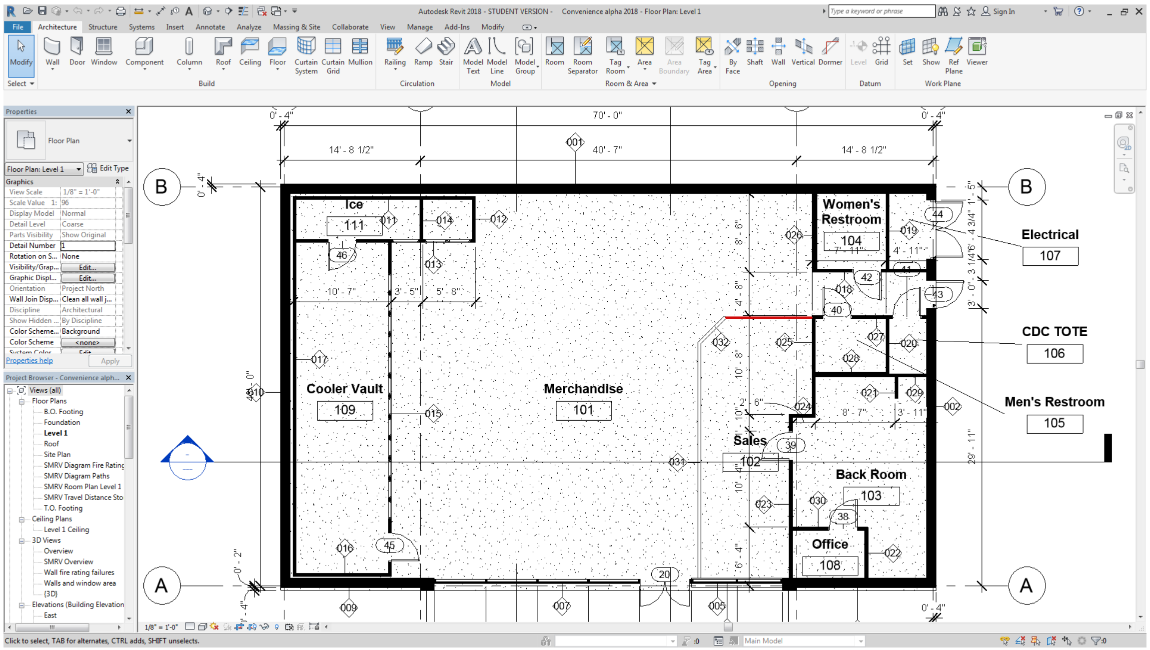


Figure 3.18: Floor plan of the one-story convenience store.

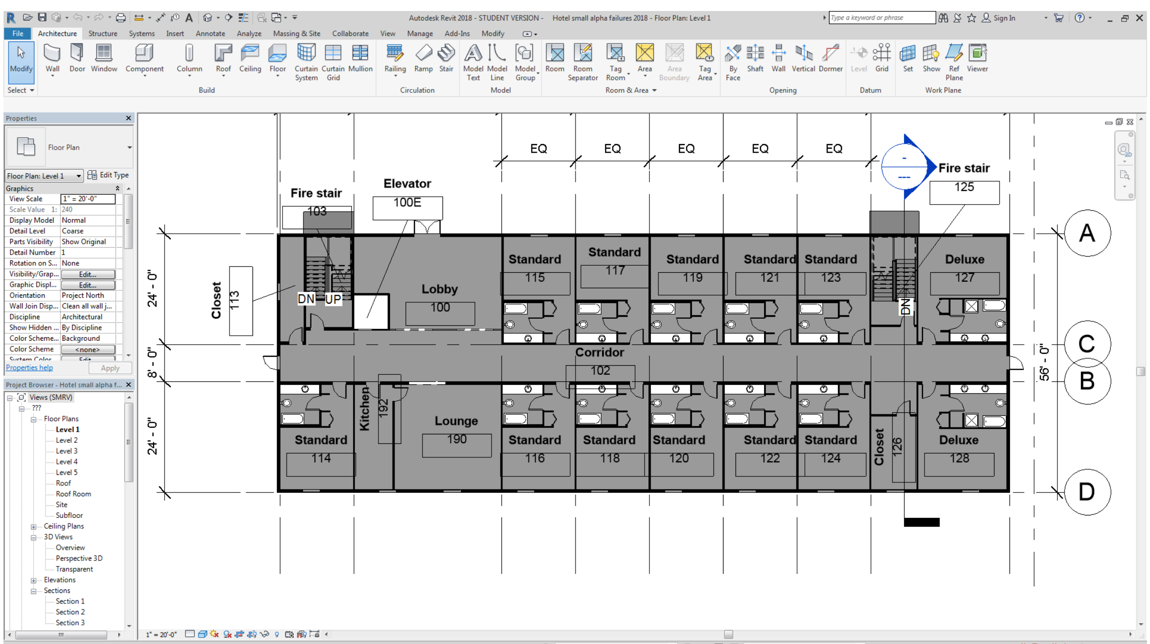


Figure 3.19: First floor plan of the four-story hotel.

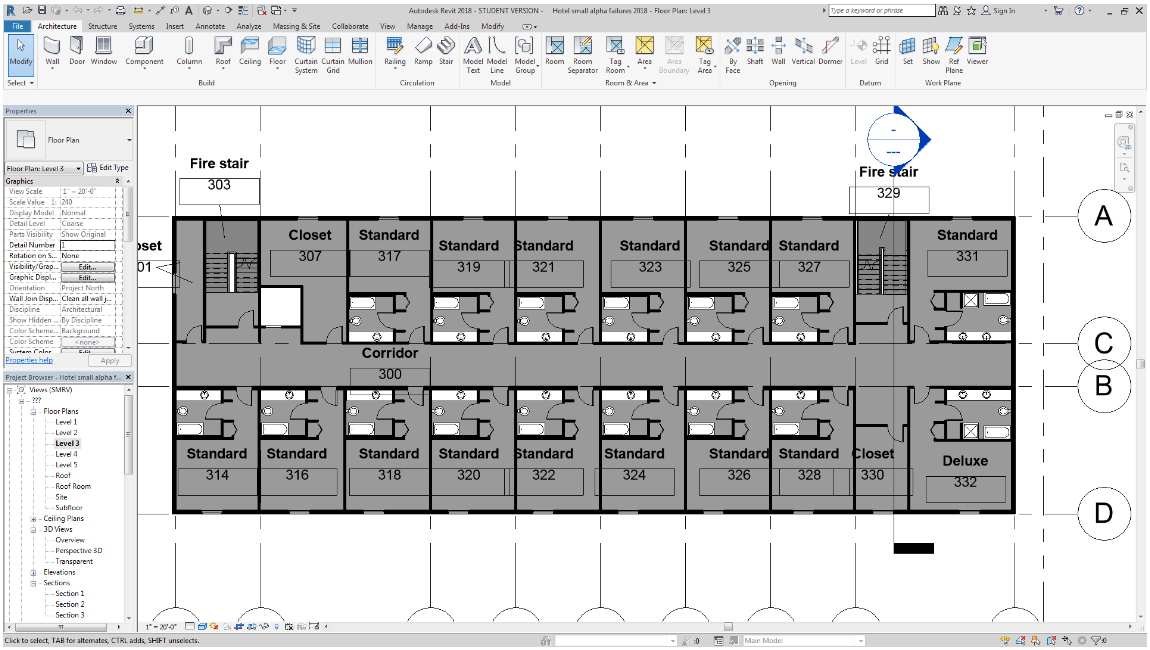


Figure 3.20: Third floor plan of the four-story hotel.

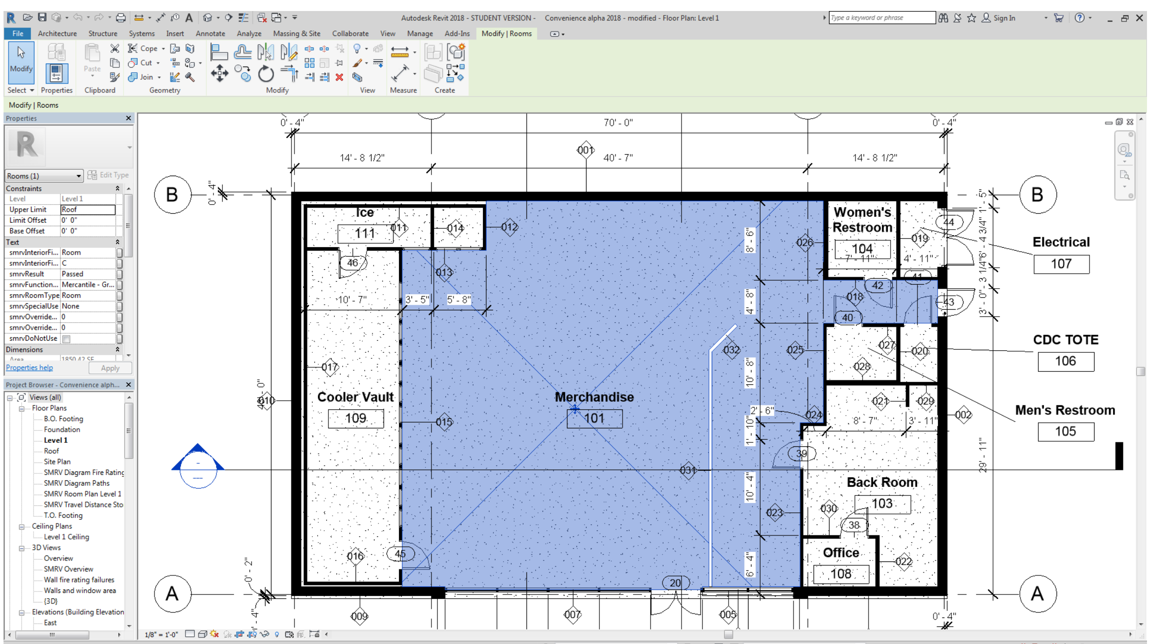


Figure 3.21: Treating merchandise room and sales room as one compartment.

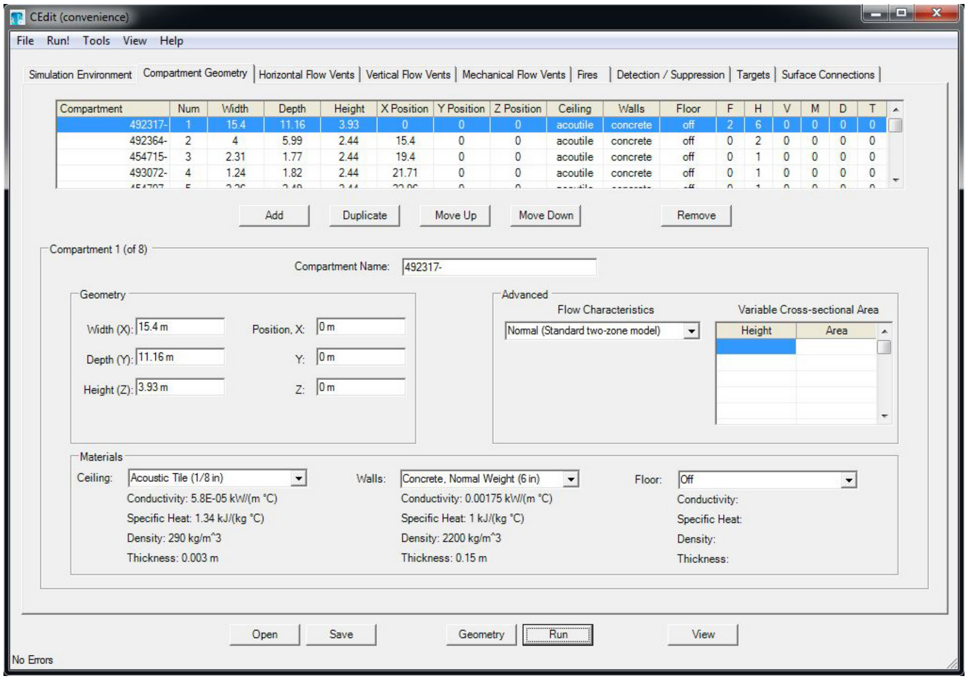


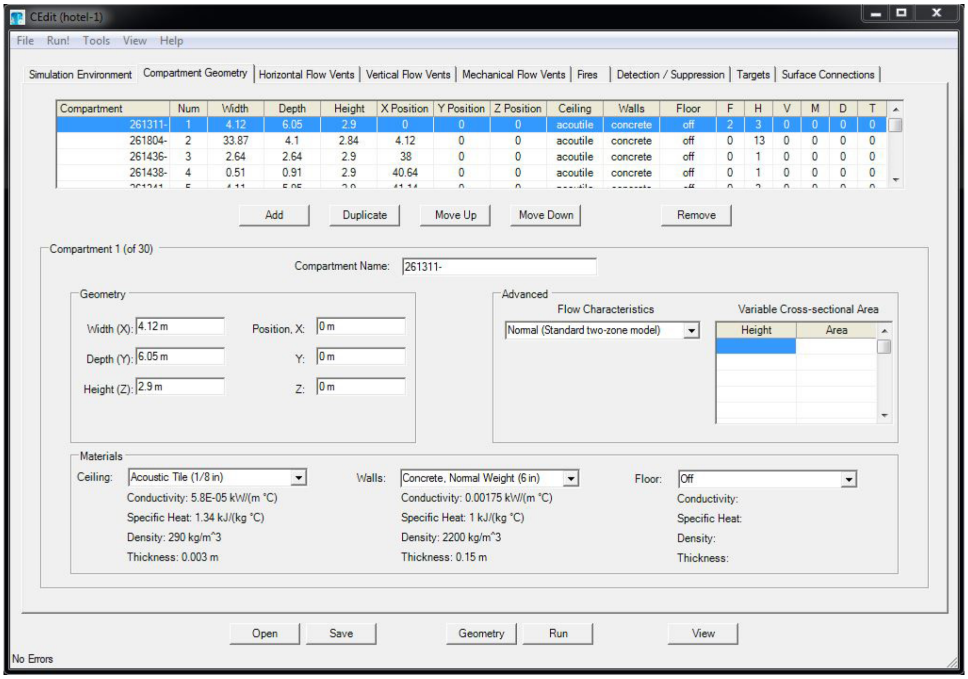
Figure 3.22: CFAST reads the input file of the convenience store that is generated by ToFAST.

room separators and wall openings, in additions to doors. This can solve the problems shown in the simulation of the convenience store and the hotel above.

By defining the two rooms (merchandise room and sales room) of the convenience store as one compartment, ToFAST was able to correctly generate CFAST input files. Figure 3.22 - 3.24 show that the input files generated by ToFAST for the convenience store and the two floors of the hotel are correctly read into CFAST. Figure 3.25 - 3.27 show that the simulations are progressing without error.

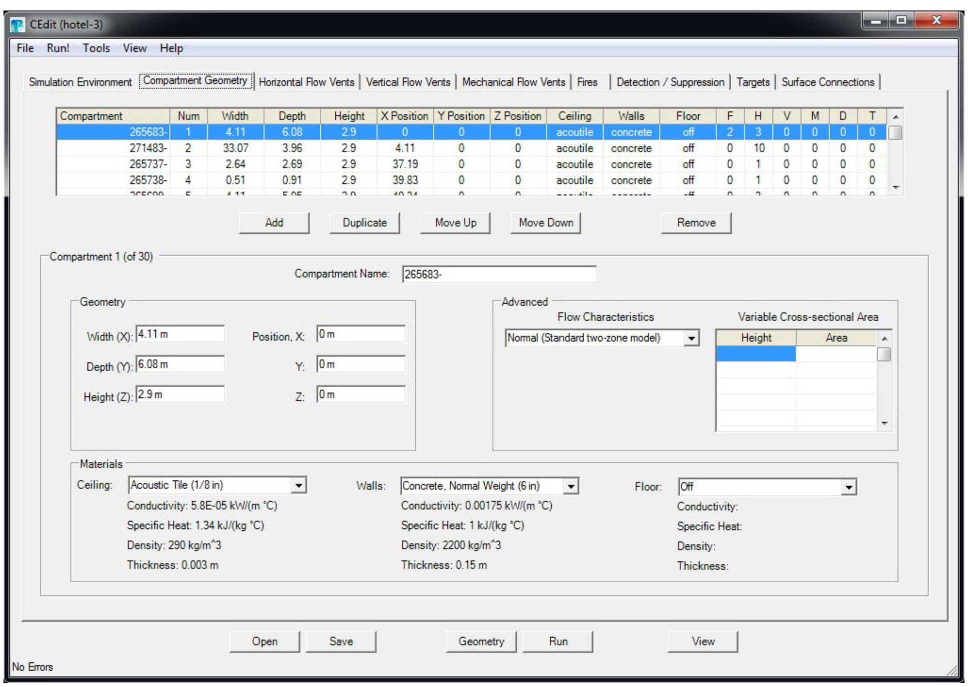
3.6 Comparing against Conventional Simulation Processes

Conventionally, to simulate smoke propagation in CFAST or FDS, a building design must be manually modeled using the text-based user interface of CFAST or FDS by a person reading the building information from 2D drawings and interpreting it as input to



Compartment	Num	Width	Depth	Height	X Position	Y Position	Z Position	Ceiling	Walls	Floor	F	H	V	M	D	T
261311-	1	4.12	6.05	2.9	0	0	0	acoutile	concrete	off	2	3	0	0	0	0
261804-	2	33.87	4.1	2.84	4.12	0	0	acoutile	concrete	off	0	13	0	0	0	0
261436-	3	2.64	2.64	2.9	38	0	0	acoutile	concrete	off	0	1	0	0	0	0
261438-	4	0.51	0.91	2.9	40.64	0	0	acoutile	concrete	off	0	1	0	0	0	0

Figure 3.23: CFAST reads the input file of the first floor of the hotel that is generated by ToFAST



Compartment	Num	Width	Depth	Height	X Position	Y Position	Z Position	Ceiling	Walls	Floor	F	H	V	M	D	T
265683-	1	4.11	6.08	2.9	0	0	0	acoutile	concrete	off	2	3	0	0	0	0
271483-	2	33.07	3.96	2.9	4.11	0	0	acoutile	concrete	off	0	10	0	0	0	0
265737-	3	2.64	2.69	2.9	37.19	0	0	acoutile	concrete	off	0	1	0	0	0	0
265738-	4	0.51	0.91	2.9	39.83	0	0	acoutile	concrete	off	0	1	0	0	0	0

Figure 3.24: CFAST reads the input file of the third floor of the hotel that is generated by ToFAST.

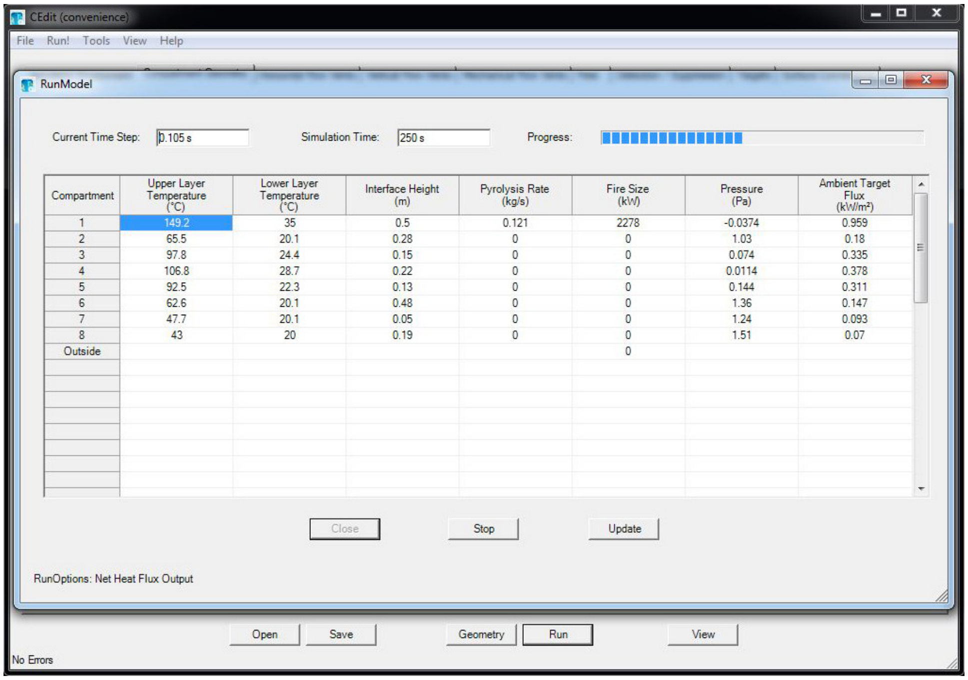


Figure 3.25: Running simulation of the convenience store in CFAST.

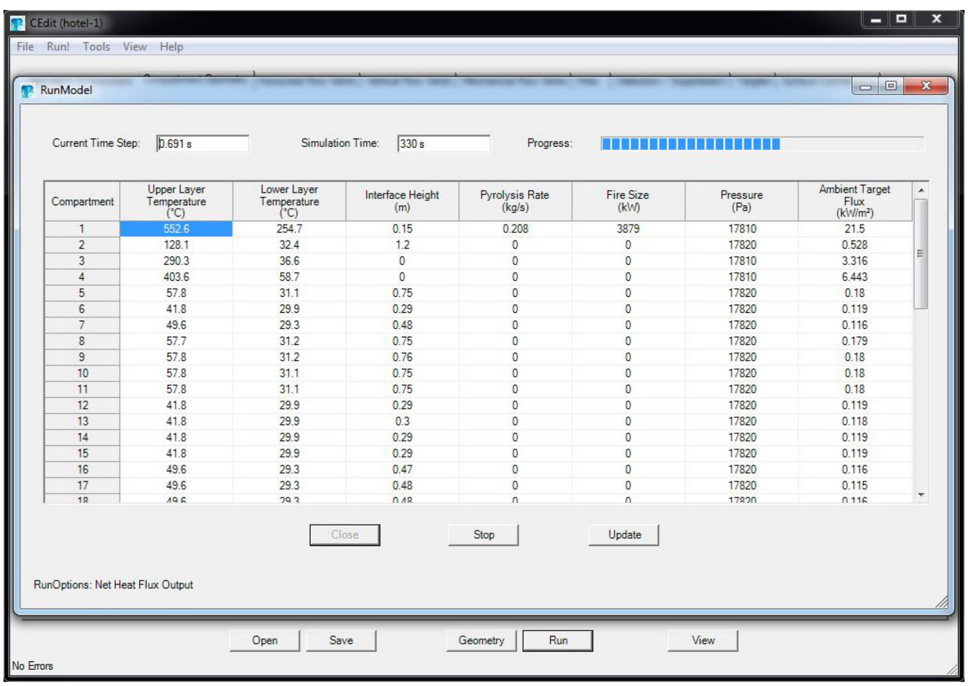


Figure 3.26: Running simulation of the first floor of the hotel in CFAST.

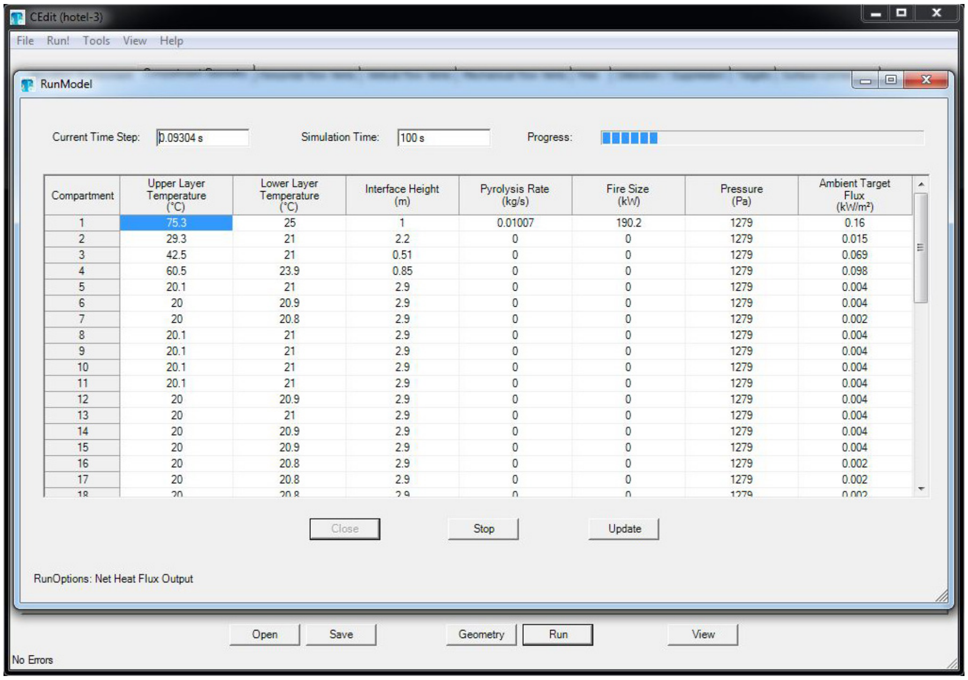


Figure 3.27: Running simulation of the third floor of the hotel in CFAST.

the simulation tool. This modeling process in CFAST or FDS is a duplication of effort requiring a great amount of time and expertise. Modeling for FDS in particular is an extremely painstaking process. ToFAST, the integrated simulation system developed in this research, utilizes BIM technology to generate simulation models automatically. This helps designers to simulate smoke propagation with great ease. To quantify how easy it is to simulate smoke propagation with ToFAST relative to the conventional methods of using CFAST or FDS with 2D CAAD, comparison tests have been performed on the same simulation task. The building design shown in figure 3.7 is used in the comparison tests.

The simulation process using ToFAST and BIM is demonstrated in subsection 3.3. The time used for generating the simulation model took less than two minutes, and the time used for running the simulation in CFAST took less than 30 seconds. The detailed process and the time needed for performing smoke propagation simulation using CFAST and FDS in the conventional way are documented in the following two subsections. To minimize the time to perform the simulations with the conventional methods, additional software applications were used. CFAST was grouped with AutoCAD and spreadsheets. AutoCAD was used to facilitate the calculation of room area and measuring bounding box dimensions. Spreadsheets were used to facilitate the numeric operations involved in the conversion of non-cuboid rooms to cuboids. FDS was grouped with PyroSim and SketchUp. PyroSim was a graphic user interface used for generating FDS simulation models. The 3D meshes needed in PyroSim were modeled in SketchUp, based on 2D drawings, to further reduce the overall modeling time.

The time required to perform the simulations is separated into modeling time and simulation running time. Modeling time measures the amount of efforts that a designer or an engineer put into the active modeling process. Therefore a day of modeling time is calculated by 8 hours/day, and a week of modeling time is defined as 5 days/week. Simulation running time, on the other hand, is calculated by 24 hours/day because it only requires computers to work without any active human involvement.

3.6.1 Simulating with CFAST + AutoCAD + Spreadsheets

Figure 3.28 shows the AutoCAD drawing of the floor plan of the same model shown in figure 3.7. To begin with, the room of fire origin was selected. Then the shortest travel paths were drawn and measured from the room of fire origin to the other rooms in AutoCAD (figure 3.29). The rooms were sorted based on the travel distance using a spreadsheet, and 30 of the rooms that are closest to the fire origin were selected for simulation. To be simulated in CFAST, the non-cuboid rooms were converted into the closest cuboid, using the same algorithm that was used in ToFAST. The area of the rooms and the dimensions of their bounding boxes are stored in a spreadsheet. The conversion process of the room dimensions was expedited by utilizing the functions of the spreadsheet

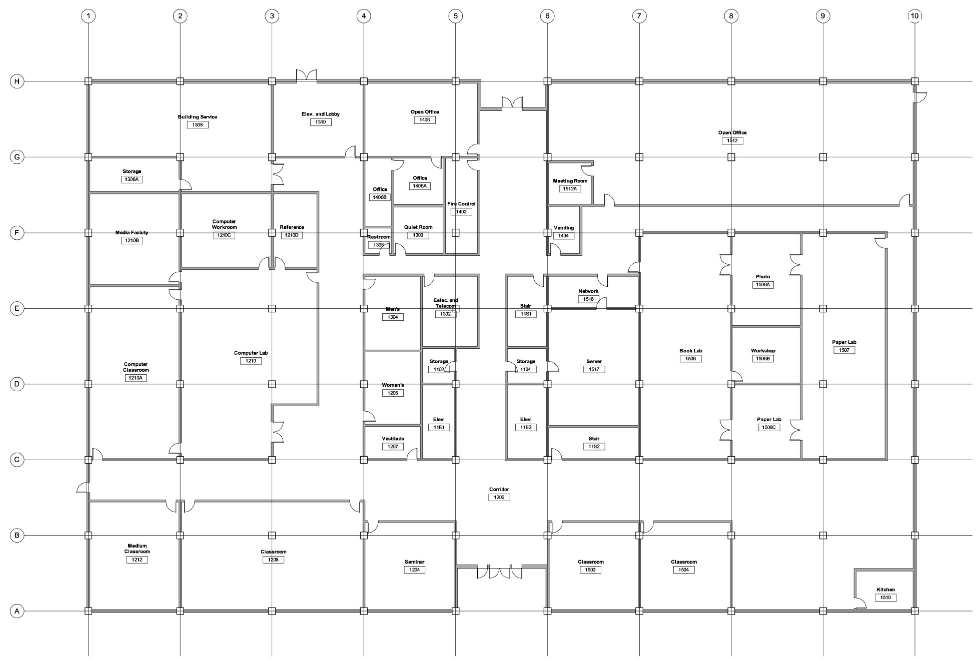


Figure 3.28: AutoCAD drawing of the floor plan.

(table 3.2). Lastly, a CFAST input file was generated by entering the room information shown in table 3.2 and the room-door connectivity information using CFAST modeling interface (CEdit).

The time used for each step of the modeling processes is shown below:

- Drawing travel paths, sorting and selecting 30 rooms: 92 minutes
- Converting to cuboids using spreadsheet: 54 minutes
- Entering the data using CEdit: 103 minutes
- Examine the input data: 43 minutes

The total time used to generate the simulation model was 292 minutes. This is the time to generate the simulation model with one of the rooms set as the fire origin. To better understand the fire safety of the design, multiple simulation runs need to be performed with

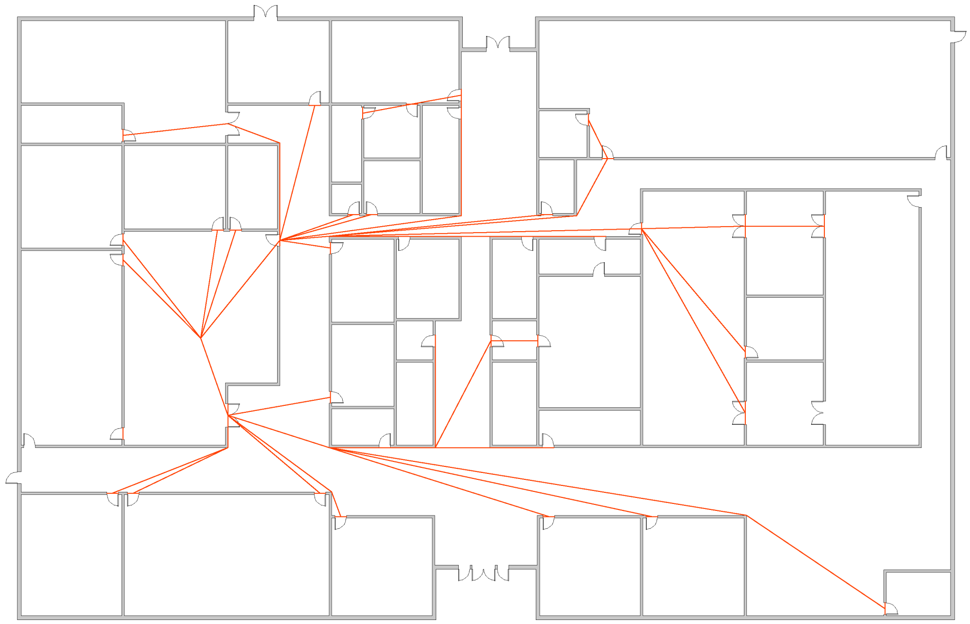


Figure 3.29: Measuring the distance from the room of fire origin to the other rooms.

the fire origin set to a different room each time. When changing the fire origin, the whole process needs to be restarted. To simulate 10 of the 40 rooms as the fire origins, the total time of 292 x 10 = 2920 minutes is required. Simulating different fire origin can be done in parallel. If 10 designers model different fire origins simultaneously, this can be done in 292 minutes. If there are two design changes based on the feedback of the simulation results, which requires three times of simulations, the total simulation modeling time of the project would be 2920 x 3 = 8760 minutes = two weeks and 4.25 days. Alternatively, if ten people work simultaneously, this can be done in approximately two days, if ignoring the overhead time needed for collaboration. The simulation running time on the computers would be 30 seconds/ run x 10 runs x 3 = 15 minutes, which is negligible compared to the modeling time.

Room Name	Area	AABB-length	AABB-width	Ratio	L	W
Building Services	124.19	15.75	9.45	1.67	14.39	8.63
Corridor	881	71.7	43.5	1.65	38.11	23.12
Storage 1308A	22.48	7.75	2.9	2.67	7.75	2.9
Media Faculty	61.23	7.75	7.9	0.98	7.75	7.9
Computer Workrm	49.92	7.8	6.4	1.22	7.8	6.4
Computer Classrm	116.25	7.75	15	0.52	7.75	15
Computer Lab	175.5	11.8	16.5	0.72	11.2	15.67
Reference	24.32	3.8	6.4	0.59	3.8	6.4
Lobby	49.53	7.8	6.35	1.23	7.8	6.35
Open Office 1406	62.23	9.8	6.35	1.54	9.8	6.35
Office 1406A	17.42	4.3	4.05	1.06	4.3	4.05
Quiet Room	17.42	4.3	4.05	1.06	4.3	4.05
Restroom	5.06	2.3	2.2	1.05	2.3	2.2
Fire Control	23.24	2.8	8.3	0.34	2.8	8.3
Vending	11.07	2.7	4.1	0.66	2.7	4.1
Medium Classroom	72.46	7.75	9.35	0.83	7.75	9.35
Classroom 1208	147.73	15.8	9.35	1.69	15.8	9.35
Seminar room	58.51	7.75	7.55	1.03	7.75	7.55
Classroom 1502	58.51	7.75	7.55	1.03	7.75	7.55
Men's room	30.72	4.8	6.4	0.75	4.8	6.4
Women's room	30.24	4.8	6.3	0.76	4.8	6.3
Vestibule	13.44	4.8	2.8	1.71	4.8	2.8
Storage 1102	8.4	2.8	3	0.93	2.8	3
Storage 1104	10.2	3.4	3	1.13	3.4	3
Elec. and Telecom	29.28	4.8	6.1	0.79	4.8	6.1
Stairs 1	20.74	3.4	6.1	0.56	3.4	6.1
Network	21.06	7.8	2.7	2.89	7.8	2.7
Server room	78.78	7.8	10.1	0.77	7.8	10.1
Stairs 2	21.06	7.8	2.7	2.89	7.8	2.7
Book Lab	152.88	7.8	19.6	0.4	7.8	19.6

Table 3.2: Converting non-cuboid rooms to cuboids. AABB-length field denotes the length of the axis-aligned bounding box, AABB-width field denotes the width of the bounding box, Ratio field is calculated by AABB-length / AABB-width, L field denotes the length of the transformed cuboid, and W field denotes the width of the transformed cuboid.

3.6.2 Simulating with FDS + PyroSim + SketchUp

Using the text-based user interface to model FDS input takes tremendous amount of time and efforts. To minimize the time and efforts for the modeling, SketchUp was used to generate the 3D mesh of the building and PyroSim was used to import the mesh and generate the FDS simulation model. The SketchUp model of the same building is shown in Figure 3.30. The model was exported as an obj file and imported into PyroSim as a

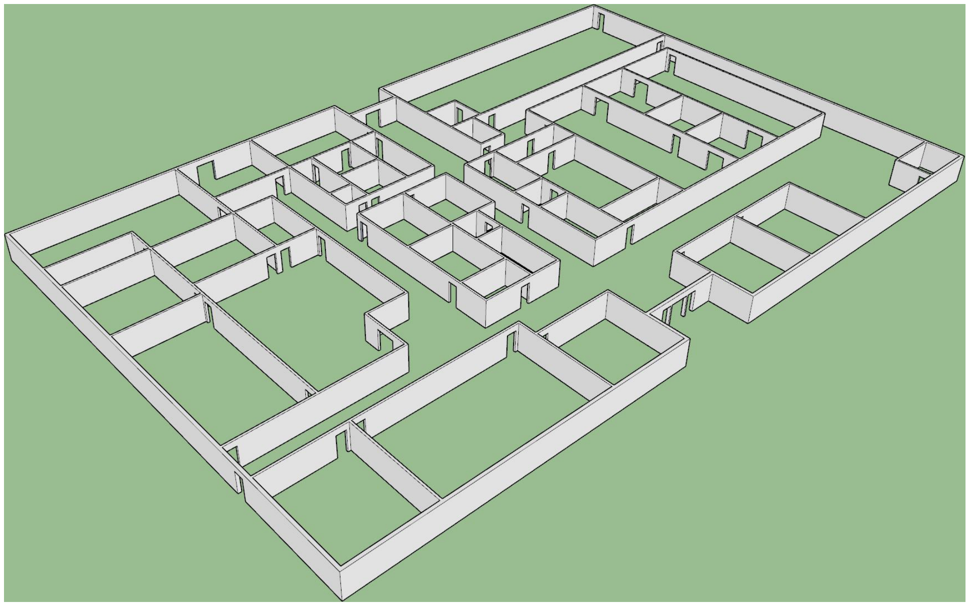


Figure 3.30: SketchUp model of the building design. The slabs and the ceilings are hidden for presentation purposes.

mesh (figure 3.31). Then the additional information that is necessary for FDS simulation was added, which includes fire settings, mesh subdivision, the connections to the exterior, and the total simulation time (15 minutes). The mesh and the spaces were discretized into 10cm x 10cm x 10cm cubes. The fire used the same setting as in subsubsection 5.1.3. Lastly, an FDS input file was exported from the PyroSim model.

The time used for each step of the modeling processes is shown below:

- SketchUp modeling: 75 minutes
- PyroSim modeling: 12 minutes

The total time needed to generate the simulation model was 87 minutes. Simulating 10 of the 40 rooms as fire origins does not require 10 folds of the time since no change is needed for the SketchUp model. Changing the location of the fire in PyroSim only takes 1-2 minutes to update. The time needed to generate 10 simulation models is approximately

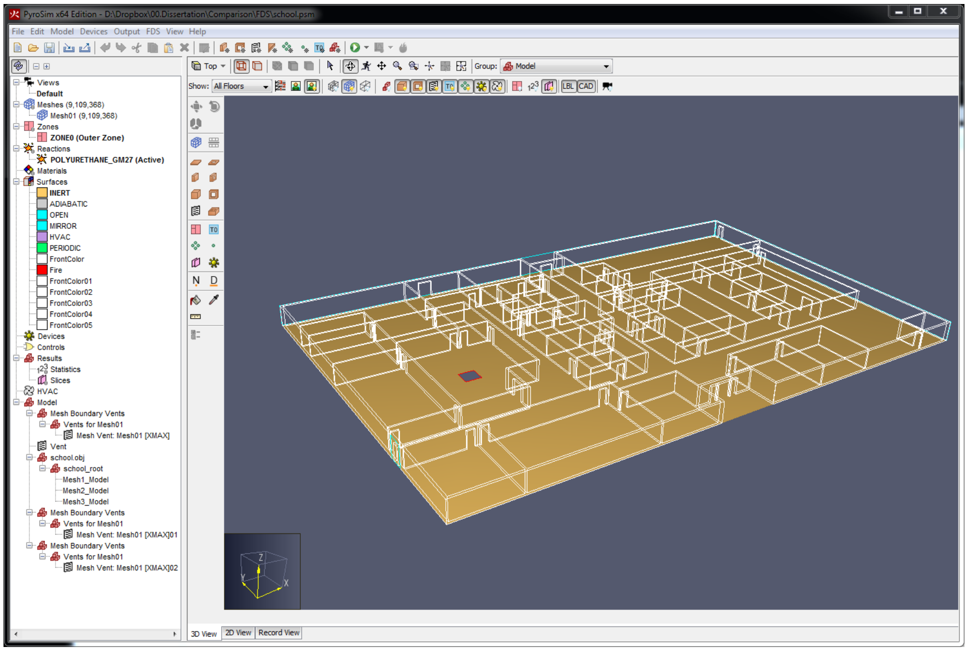


Figure 3.31: SketchUp model is imported into PyroSim as a mesh. Additional information such as fire, mesh subdivision, and so on, are added to the model.

100 minutes. However, if a design change ensues based on the feedback of the simulation results, the SketchUp model and PyroSim model may need to be updated or remodeled. Assuming two design changes in a project, the total time needed for modeling FDS input is between 100-200 minutes.

The simulation running time of one run took 55.3 days. Assuming that 10 of the 40 rooms are simulated as the fire origins, and there are two design changes, the total simulation running time would be 55.3 x 10 x 3 = 1659 days. Since the simulation runs with different fire origins can be performed with multiple computers in parallel, the total time can be shortened to 165.9 days if 10 computers operate simultaneously.

The specifications of the computer used for the simulation is shown below:

- CPU: Intel i7-3770, Quad-core, 8 thread, 3.4GH clock
- Memory: 16GB, DDR3

- Operating system: 64bit windows 7

3.6.3 Summary

This subsection compared the time and efforts required by the three different ways of performing smoke propagation simulation: ToFAST + BIM, CFAST + AutoCAD + spreadsheets, and FDS + PyroSim + SketchUp. The amount of effort required for each type of simulation is measured by the time that a designer was actively involved to generate the simulation input files. The simulation running time is recorded to compare overall time resources each type of simulation consumes. The comparison results showed that ToFAST + BIM requires significantly less time and efforts to simulate smoke propagation (table 3.3).

	ToFAST	Conventional CFAST	Conventional FDS
Modeling Time	60 minutes	8760 minutes	100-200 minutes
Simulation Running Time	15 minutes	15 minutes	1659 days
Total	75 minutes	2 weeks and 4.3 days	1659 days

Table 3.3: Comparison of the projected time to simulate smoke propagation.

4. VISUALIZATION AND INTERPRETATION OF SIMULATION RESULTS

ToFAST translates a BIM model into a simulation model and exports it to a CFAST-input file. After reading the file and running smoke propagation simulation, CFAST outputs an ASCII file that contains the simulation results as shown in figure 3.17. Because the simulation results are presented in thousands of lines of numbers, it is very difficult for designers to extract any meaningful information from the simulation data. SmokeView, a tool developed by NIST, is used for visualizing CFAST simulation results. However, SmokeView can correctly display the space configuration only if there are no non-cuboid rooms in the building. Figure 4.1 shows the CFAST simulation results of the university building using SmokeView. Because all the rooms are transformed into cuboids and are rearranged, it is not intuitive for designers to map the new layout to the original floor plan and extract useful information.

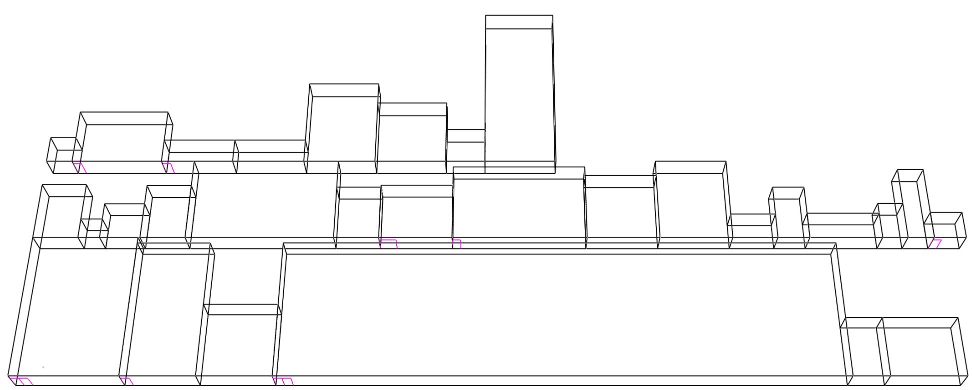


Figure 4.1: Visualization of the CFAST simulation results for the university building using SmokeView.

This demands for better visualization of the simulation results to provide designers with useful feedback in the decision making process. For this research, I developed a presentation module to extract information from the simulation results. With this module, designers can easily visualize smoke propagation, perform evacuation simulation, present the evacuation simulation results as graphs, and visually inspect the evacuation to get qualitative feedback.

4.1 Visualizing Smoke Simulation Results

A presentation module was developed with C# on WPF platform as a plug-in in Revit to visualize smoke propagation (figure 4.2). This module draws a simplified floor plan using the information retrieved from the Revit model. Then it reads the CFAST simulation results, extracts essential information such as smoke height and CO concentration, and prints each block of data for the corresponding room. Each room is color coded at each time step based on one of the parameters. By adjusting the slider on the top of the window, which controls the simulation time step, one can visually inspect how smoke propagates from room to room, and how the concentration of the toxic gases changes in each room (figure 4.3).

One of the purposes of visualizing smoke propagation is that designers can check whether a revised design scheme is better than the original one in terms of fire safety by just checking if the revised scheme delays smoke propagation. This information can be useful for rapid interpretation. If a certain spatial layout can reduce smoke propagation speed, it is likely to extend the time for occupants to safely evacuate in case of a building fire.

4.2 Simulating Occupant Evacuation

Fire safety is closely related to both the speed of smoke propagation and the speed of occupant evacuation. Occupants are safe if they can evacuate before smoke reaches the height of the human head. In this sense, visualizing smoke propagation is only half of the picture to understand building fire safety. Simulating occupant evacuation based on

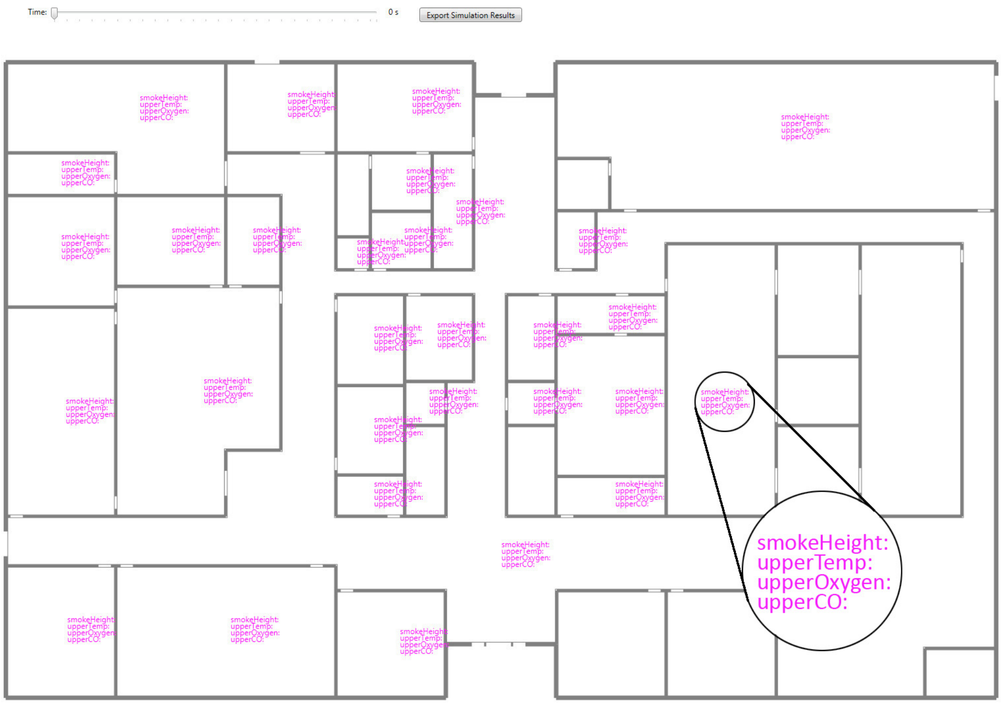


Figure 4.2: Reading the CFAST simulation results, extracting essential information, and locating each set of data at the corresponding location for easier visualization.

Figure 4.3: Color-coded floor plan to show smoke propagation and the information about the toxic gases.

smoke propagation simulation results can provide designers more informative feedback about their design. A simulation helps designers to identify bottlenecks in egress paths, the quality of circulation design, the capacity of egress routes, and so on. To provide more informative feedback, I developed a simple BIM-based multi-agent evacuation model and incorporated it into the visualization module. The multi-agent evacuation model interacts with the smoke information, which is generated from CFAST simulation, to report the safety of each agent at the end of the simulation. The multi-agent model used in the evacuation simulation is not yet validated and needs further investigation.

4.2.1 Initializing Evacuation Simulation Environment

To begin with, a number of agents are generated based on user-prescribed density and are randomly placed in the scene without overlap (figure 4.4). Each agent is assigned initial properties, including shoulder width, chest to back depth, height, normal speed, and max speed.

4.2.2 Calculating Exit Paths

Accurately modeling occupant evacuation is extremely complicated and is an active research topic [55]. The evacuation model used in this research is simplified to three basic rules: 1) all agents are familiar with the building floor plan; 2) each agent evacuates through the nearest exit measured by walking distance; 3) each agent can detect the velocity (speed and direction) of the near-by agents and adjust its velocity accordingly to avoid collisions.

The shortest egress path of an agent is represented by the connection between a sequence of target points. Target points are either concave corners of the rooms or the center points of the doors. The shortest egress paths are calculated with the same algorithm used for the room selection algorithm in the previous section, only with a few minor adjustments. When the algorithm is used without any adjustment, the agents tend

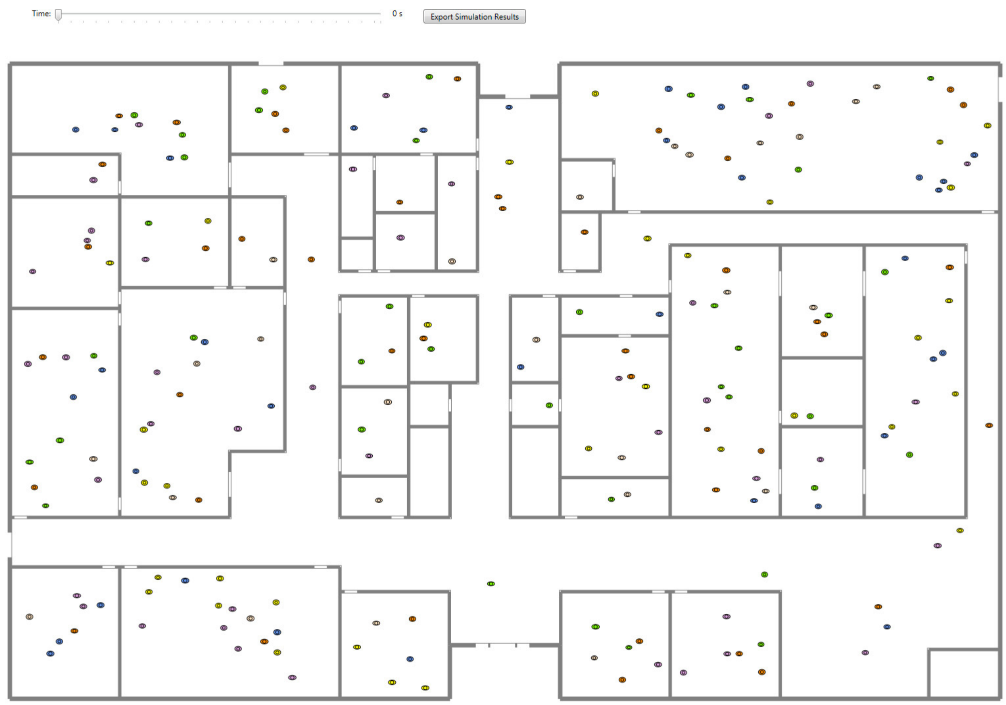


Figure 4.4: Randomly generating agents in the scene.

to get very close to the corners and the center of the doors as shown in figure 4.5. This causes unnatural turns when agents reach each target points. Two minor adjustments were made to alleviate this problem:

- When reaching the center of a door, agents keep walking along the direction that is perpendicular to the door, instead of turning right away at the center of the door. After passing the door by certain threshold, the agents then turn their walking direction to the next target point;

- Floor boundaries of the rooms are offset inwards by a certain threshold (green lines in figure 4.6) to keep agents away from walls.

The polygon offset functionality is implemented with an open source clipper library developed by Johnson [56]. Calculating egress paths using the offset floor boundaries

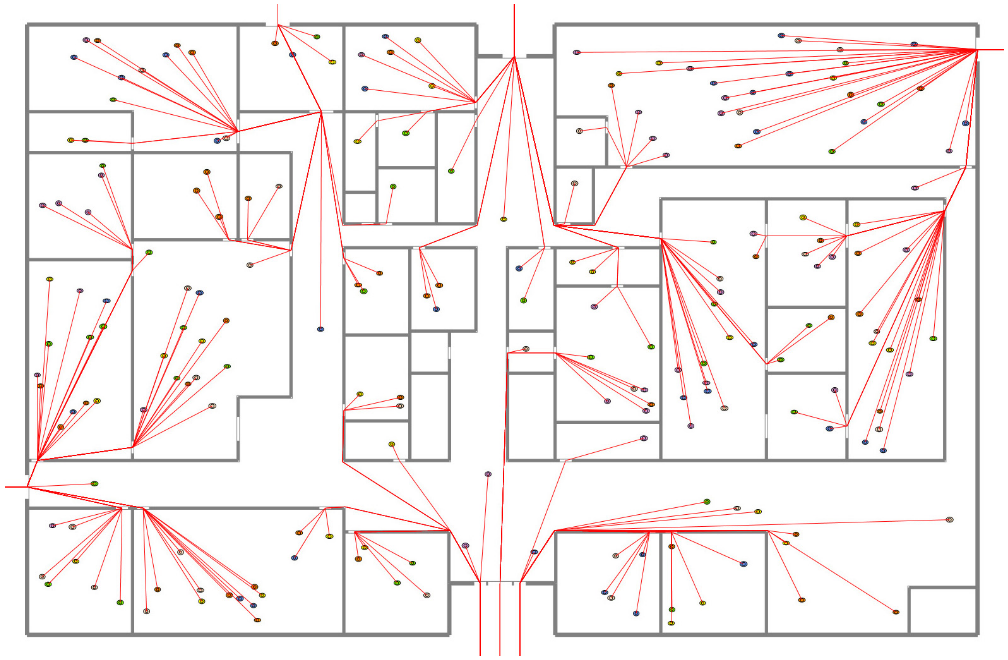


Figure 4.5: Calculating the egress path of each agent using the same algorithm used for selecting 30 rooms without any adjustment.

(green lines) allows agents to turn more naturally at corners. The egress paths of the agents after these adjustments are shown in figure 4.7. These paths are the planned paths for each agent, not the actual evacuation paths. During evacuation simulation process, agents are likely to deviate slightly from the planned paths to avoid collision with other agents. However, the target points of each agent remain unchanged in order to guide the agent to the nearest exit door.

4.2.3 Simulating Evacuation

After the egress paths are calculated, the simulation progresses each agent towards the nearest target point on its planned egress path. During evacuation process, each agent may deviate slightly from the preferred path to avoid collision with nearby agents. The functionality of collision avoidance is implemented with an open source library developed by a research team at the University of North Carolina at Chapel Hill [57].

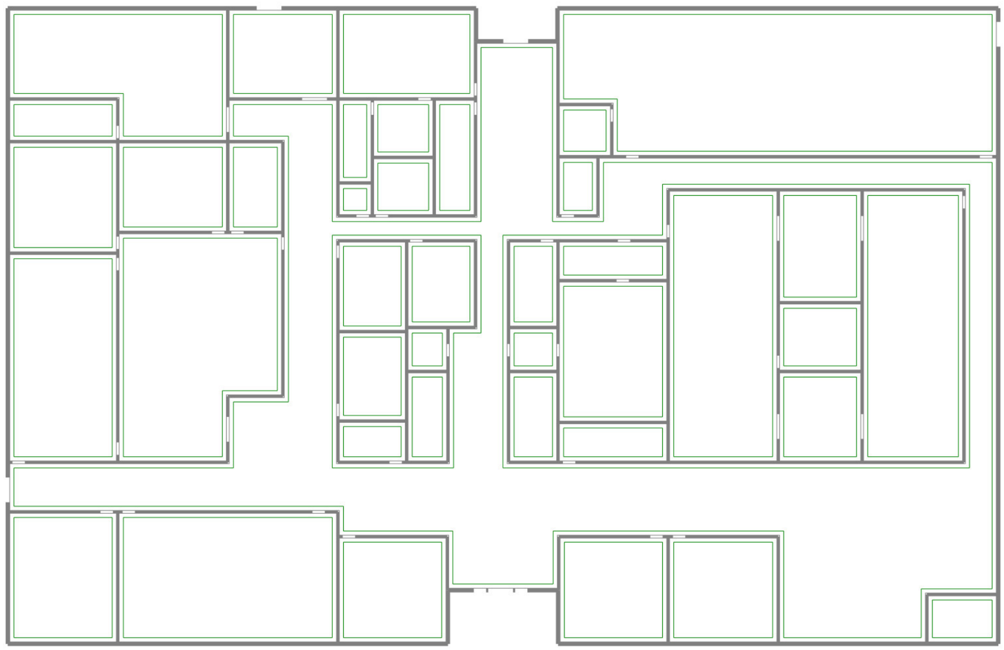


Figure 4.6: Offsetting the floor boundaries inwards.

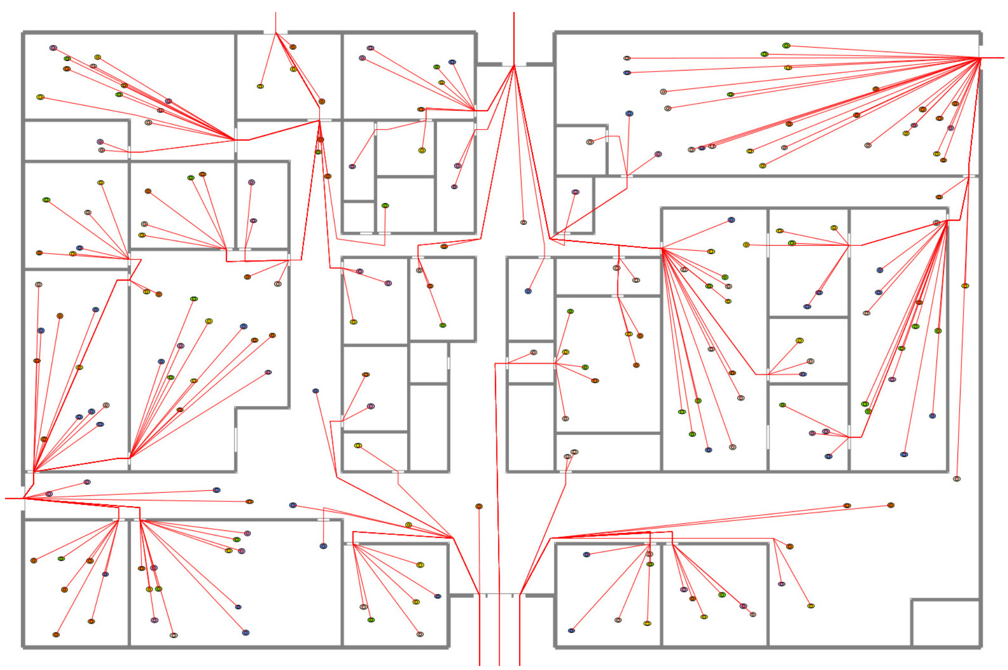


Figure 4.7: Adjusting the algorithm to make agents walk past the doors and turn the corner with a buffering threshold.

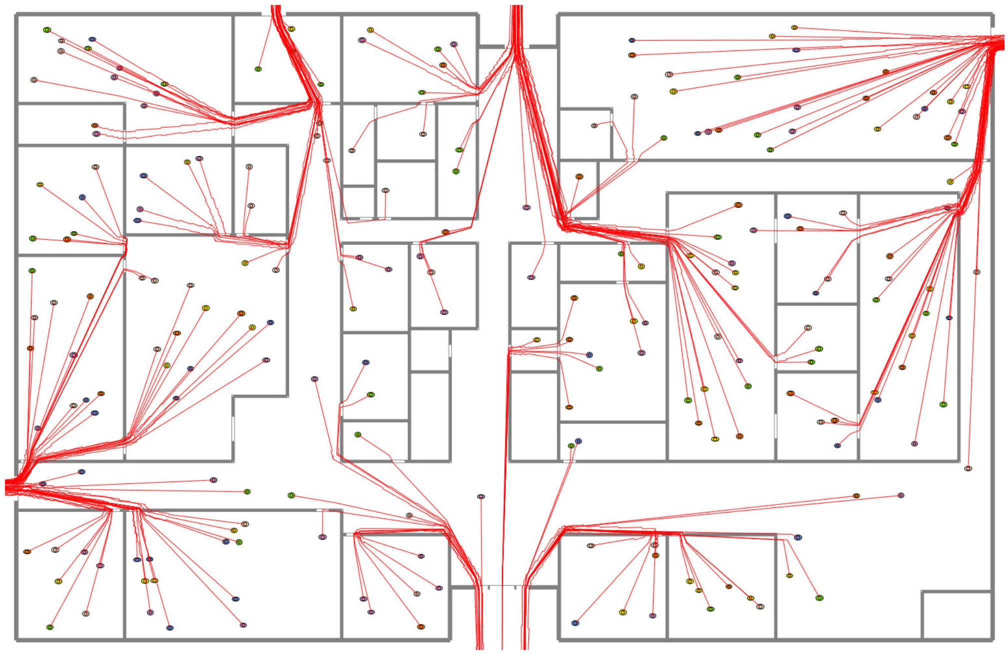


Figure 4.8: Agents' actual evacuation trails. The zigzag paths show the efforts from the agents tried to avoid collision with their neighbouring agents. The zigzag paths can be smoothened by increasing the number of simulation steps per second.

At each simulation time step each agent identifies the room it is in, and records the smoke height, CO concentration, and temperature of the room, which are retrieved from CFAST simulation results. This information is used for safety analysis described in the next subsection. Each agent also records its evacuation trail at each time step as shown in figure 4.8. Agents' trails are exported as a CSV file at the end of the simulation.

4.3 Reporting Simulation Results

At the end of the simulation, the information generated by each agent is reported so that designers can quantitatively examine the fire safety of the design. In addition, the raw data from the simulation is summarized and analyzed to provide more informative characterizations of the effect of the fire event on the agents.

Figure 4.9 shows the duration of time that each agent spent in smoke. X axis lists all

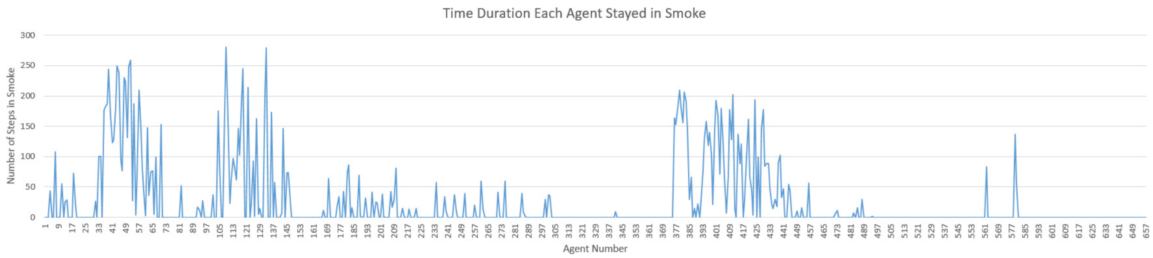


Figure 4.9: Duration of time that each agent spent in smoke.

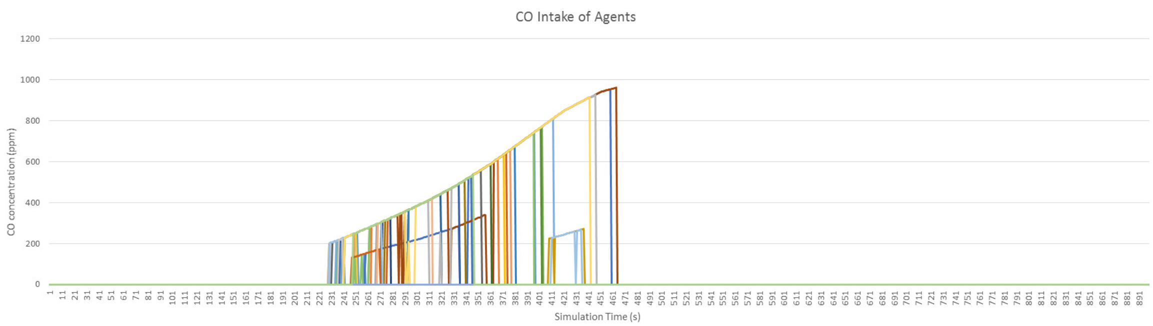


Figure 4.10: CO intake of each agent.

the agents, and Y axis denotes the duration of time in seconds that the agents spent in smoke during evacuation.

Figure 4.10 shows CO intake of each agent. X axis denotes time in seconds, and Y axis denotes CO concentration in ppm. Each color line in the graph denotes an agent.

Figure 4.11 shows the ambient temperature of each agent. X axis denotes time in seconds, and Y axis denotes the upper layer temperature of the rooms each agent is in. Each color line denotes an agent. The tip of each color line infers the time that the agent walked out of a smoky room.

4.4 Animating Evacuation Simulation Results

When the evacuation simulation finishes, the results can be animated for visual examination. This helps designers to conduct a qualitative evaluation of the fire safety of

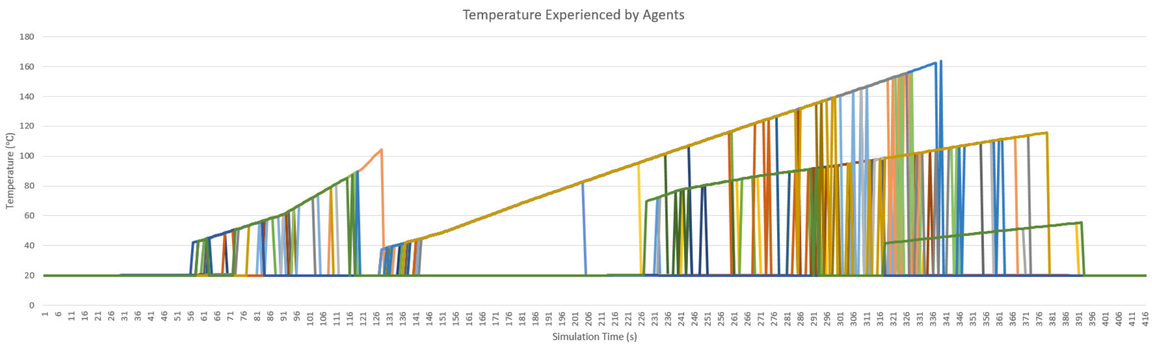


Figure 4.11: The ambient temperature of each agent.

their design, such as identifying bottle necks and inefficient circulation of the floor plan. Figure 4.12 shows that all agents are safe from smoke 60 seconds after the simulation started. At time step 145 seconds, smoke reaches the agents' height in four of the rooms before some of agents have left the rooms (figure 4.13).

The evacuation model used in this research does not necessarily reflect the reality due to the simplification of the model. However, the system architecture developed in this research, the seamless data transfer from BIM to CFAST to evacuation model, can be easily applied to other evacuation models. Plugging in a more refined evacuation model to this system is expected to generate more accurate and informative feedback for designers.

In short, the visualization module developed in this research helps designers to visually inspect smoke propagation and assess evacuation simulation results quantitatively and qualitatively with graphs and animations.

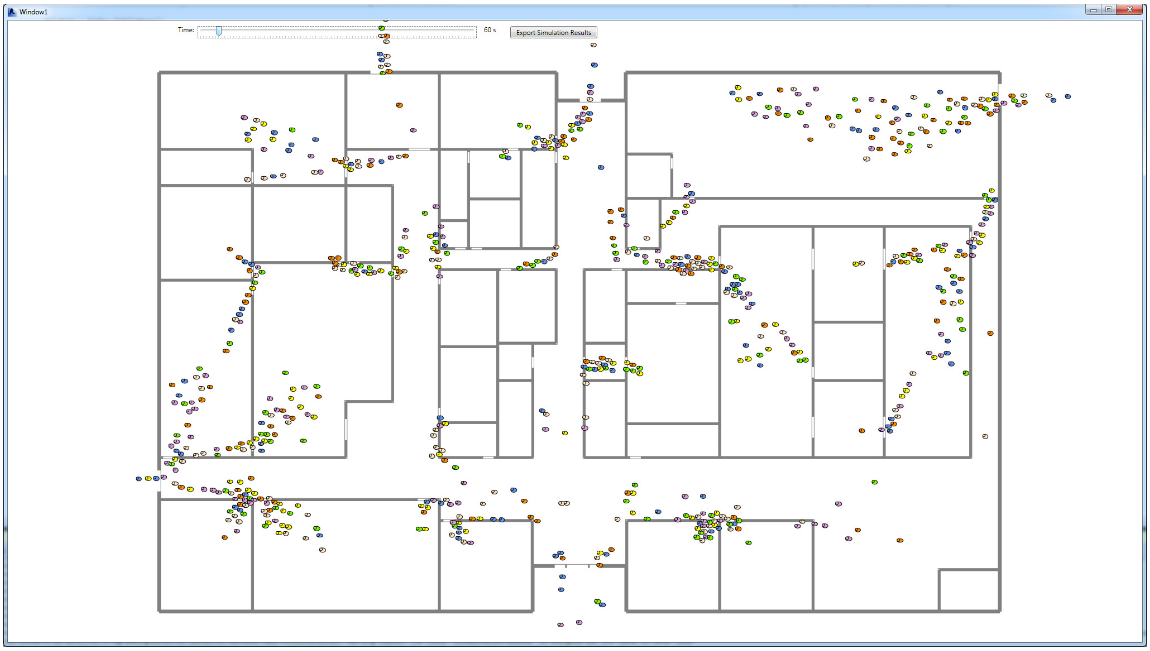


Figure 4.12: Agents are safe from smoke at the time step of 60 seconds.

Figure 4.13: At time step 145, some agents are walking in smoke regions which are denoted with grey.

5. VALIDATION OF THE ALGORITHMS

Two major obstacles to simulate smoke propagation using CFAST are that CFAST requires all rooms to take the shape of cuboids and the total number of the rooms must not exceed 30. In the real-world, rooms take various shapes other than cuboids, and many buildings have more than 30 rooms. CFAST is useful to architects in practice only if it can easily simulate real-world buildings, not just toy examples, with acceptable accuracy. To easily simulate real-world buildings in CFAST, I used transformation algorithms and a room selection algorithm to convert BIM models to CFAST models. The transformation algorithms convert rooms of all shapes to the closest cuboid shape while maintaining floor area, width/length proportion, and volume constant. The room selection algorithm selects 30 rooms that are closest to the fire source by smoke travel distance. This allows architects to simulate 30 of the most critical rooms. With these algorithms implemented in BIM, architects can perform smoke propagation simulation with a few mouse clicks in very short time, usually under a few minutes.

The issue triggered by these algorithms is that the accuracy of the simulation results is dependent on how accurately the original building is represented after applying the algorithms. To investigate how much error is introduced by the transformation algorithms and the room selection algorithm, I have conducted validation tests of the algorithms by comparing the simulation results of the simplified models to the simulation results of the original models using FDS, which is capable of handling the complexity of the original design.

5.1 Validation of the Transformation Algorithms

The transformation algorithms transform rooms of all shapes to the closest cuboid shape while maintaining floor area, width/length proportion, and volume. Transforming rooms to cuboid shape may cause errors compared to the simulation results of the original rooms. To find out the amount of the errors introduced by the transformation algorithms, I conducted a series of validation tests using FDS. Unlike CFAST, FDS can simulate rooms of any shape by discretizing a room into a myriad of tiny cubic cells of spaces. For each validation test, a building model containing non-cuboid shaped rooms was modeled and simulated in FDS. Then the model was transformed into cuboids using the transformation algorithms and was simulated using FDS. The simulation results of the models before and after the transformation were compared with each other to determine error.

The transformation algorithms transform general rooms and corridors differently. Therefore, the validation tests for general rooms and corridors were also modeled differently. For the validation of general rooms, as shown in figure 5.1, each model contains four rooms representing four different room conditions by the relative location to the fire source: room A contains the fire source; room B represents the rooms that smoke passes by; room C represents the rooms that only have incoming smoke flow but no outgoing smoke flow; room D represents the rooms that are directly connected to the exterior. Room A, B, C, and D are identical in shape but oriented differently. There are nine evenly distributed smoke sensors in each room except for room A, which has eight sensors. This is because placing a sensor at the center of room A, overlapping with the fire source, generates inaccurate sensor data. The smoke line of each room was calculated by averaging the smoke height that was detected by all of the smoke sensors in each room. Figure 5.2 shows the model after the transformation.

For the validation of corridors, a room of fire source and a corridor were modeled such that the corridor is directly connected to the room (figure 5.3). The corridor was then transformed using the transformation algorithm (figure 5.4). Smoke sensors are evenly distributed in the corridors of both models, before and after the transformation.

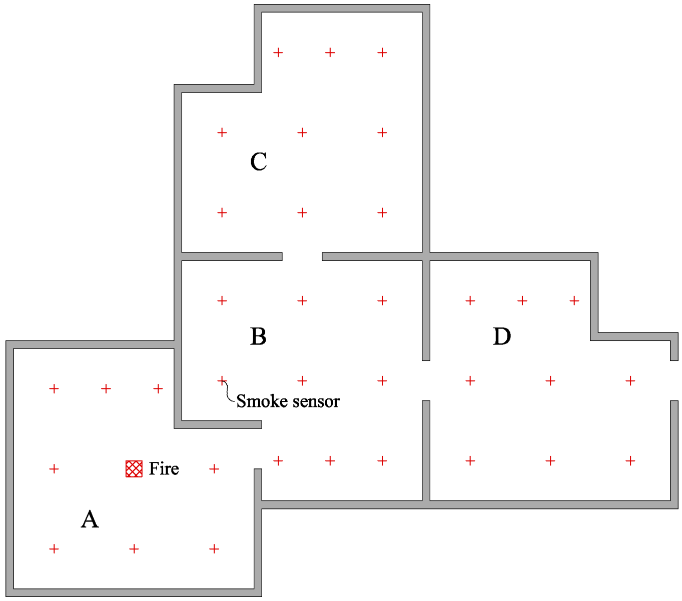


Figure 5.1: An example of a validation test model for general rooms. Room A, B, C, and D are identical in shape but oriented differently. Red crosses denote smoke sensors. Fire source is placed at the center of room A.

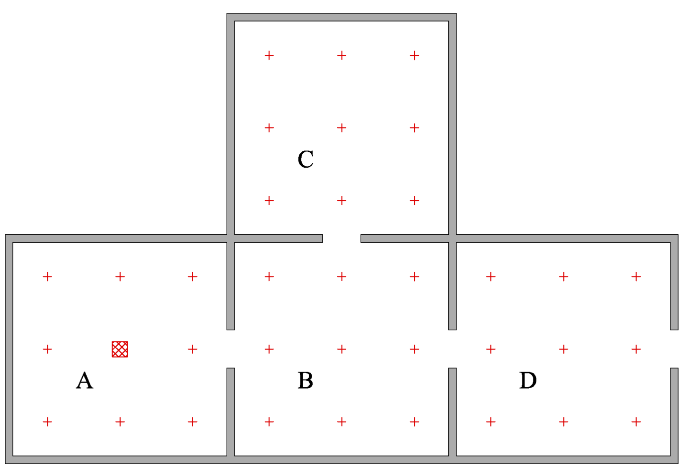


Figure 5.2: The transformed model using the transformation algorithm.

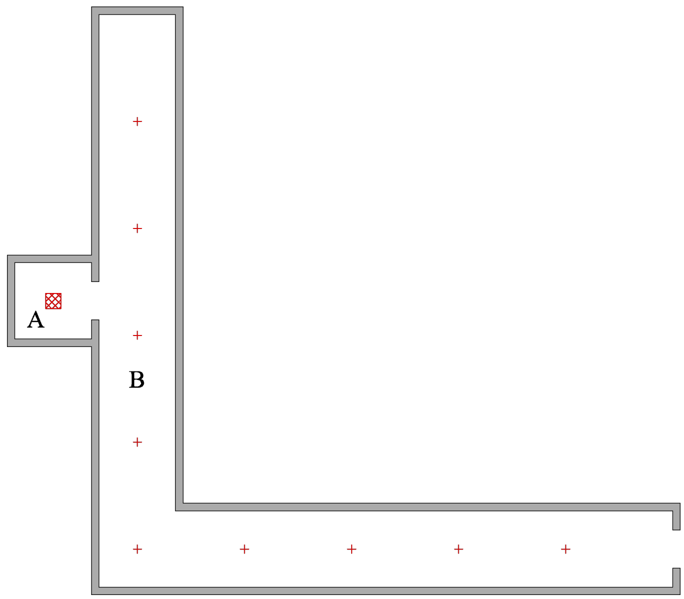


Figure 5.3: An example of a validation test model for T-shape corridor.

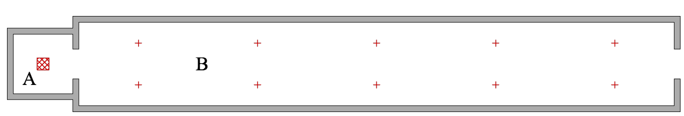


Figure 5.4: The transformed model of the corridor using the transformation algorithm.

5.1.1 Resolution Tests

FDS is a CFD-based model for simulating fire-driven air flow. FDS discretizes a continuous space into a myriad of small cuboids. The concentration of each gas species and the temperature of each cuboid are simulated by solving the Navier-Stokes equation. The accuracy of FDS simulation is closely related to the size of the cuboids, i.e. the resolution of space discretization. Generally speaking, the higher the resolution (the smaller the cuboids), the more accurate the simulation results. The downside of higher resolution is that simulation time grows as a cubic function of the resolution. For example, setting the size of the cube to 10cm per side takes eight times longer compared to the size of 20cm cubes. To balance the accuracy-time tradeoff, a set of resolution tests were conducted to determine the optimal resolution for the follow-up FDS simulations.

As shown in figure 5.5, the resolution test models have four 6m x 6m rooms, representing four different conditions relative to the location of the fire source. Seven runs of simulations are performed with the resolution set to 5cm, 6cm, 10cm, 20cm, 30cm, 40cm, and 60cm respectively. The thickness of the walls is set to 60cm to accommodate the lowest resolution. The model with the resolution of 5cm exceeded the memory capacity of the desktop computer that was used for the simulation, and consequently used hard drive for the simulation. Because hard drive is extremely slow compared to DRAM, the 5cm-model was expected to take approximately four years to finish. Therefore the 5cm-model was excluded from the options.

Figure 5.6 to 5.9 show the results of the resolution tests. In the graphs, X axis denotes the simulation time in seconds, and Y axis denotes the smoke height in meters. The ceiling height is set to 3m. The color lines are the individual runs with different resolutions.

The graphs show that 60cm-model and 40cm-model generated irrational results with large fluctuation. The lines of 30cm, 20cm, and 10cm models show a rather consistent

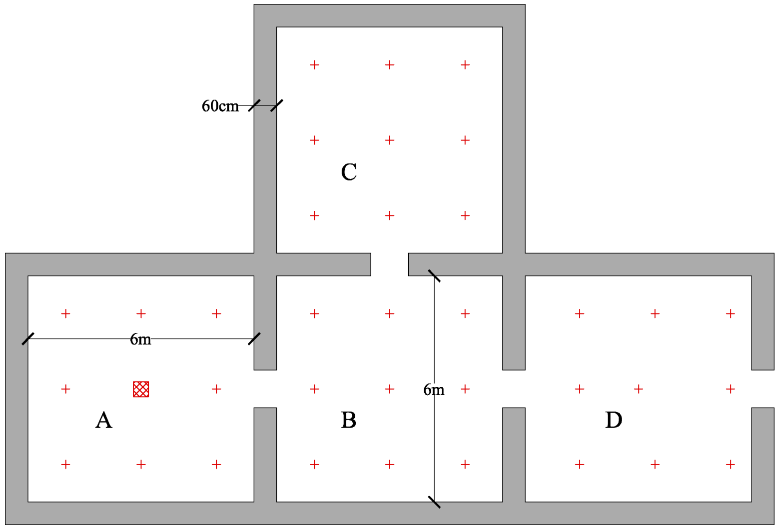


Figure 5.5: The model used in the resolution tests.

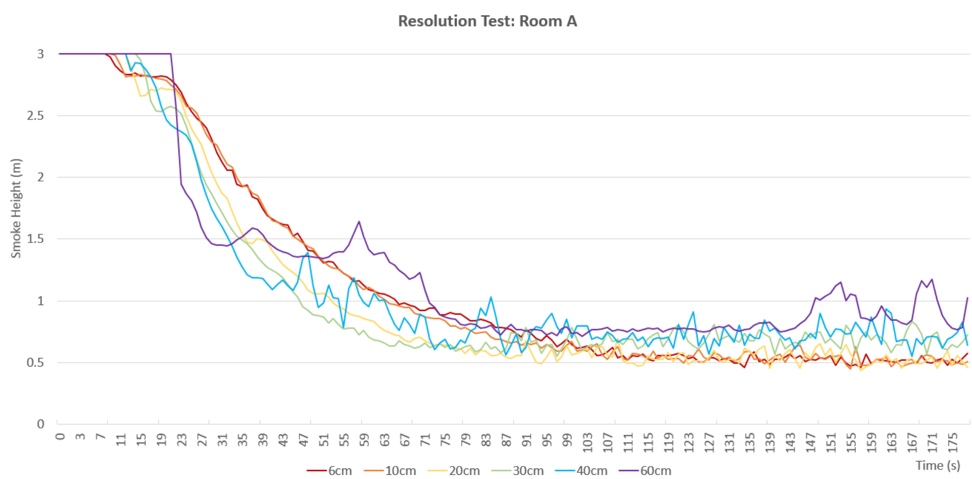


Figure 5.6: Simulation results of room A.

gap with the line of the 6cm model. The magnitude of the gaps with the 6cm-model also reduce as the resolution becomes higher, e.g. the gap between 10cm and 6cm lines is much smaller than the gap between 30cm and 6cm lines.

FDS generates more accurate simulation results with higher resolution. Due to the limited time and physical memory space, the resolution cannot be set to infinitely high.

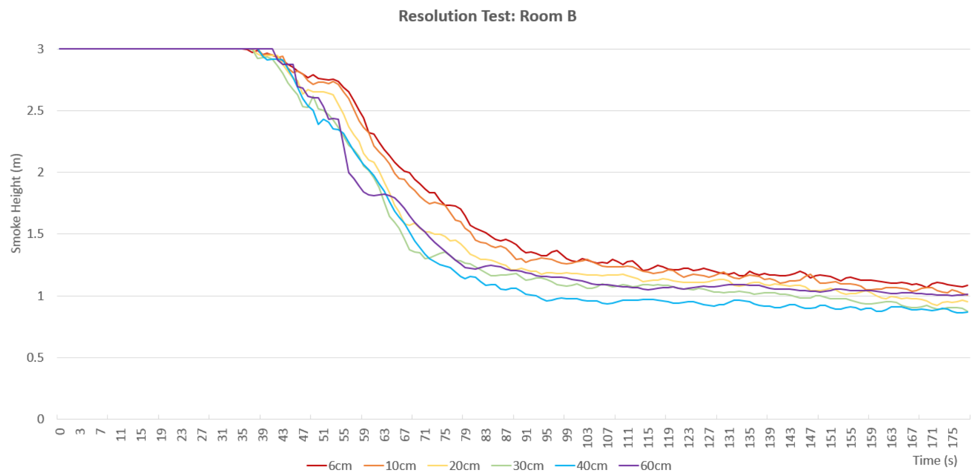


Figure 5.7: Simulation results of room B

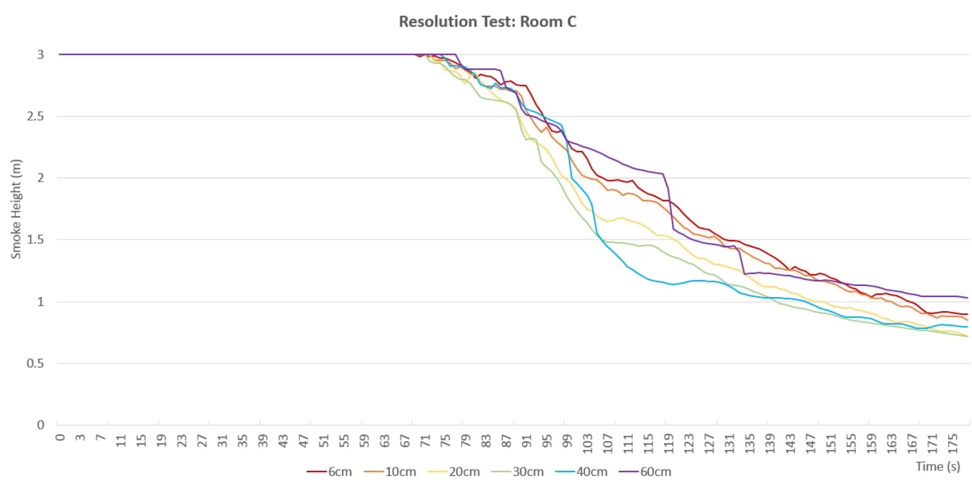


Figure 5.8: Simulation results of room C.

In this research, 6cm-model is the highest resolution that the computer can run. Thus, the resolution of all the FDS simulation tests in this research will be set to the highest resolution possible, up to 6cm, if the tests can be finished in a reasonable timeframe. The total time to finish all runs of simulations needed for this dissertation research using three desktop computers is estimated in the table 5.1. The specifications of the computer used for the simulation is shown below:

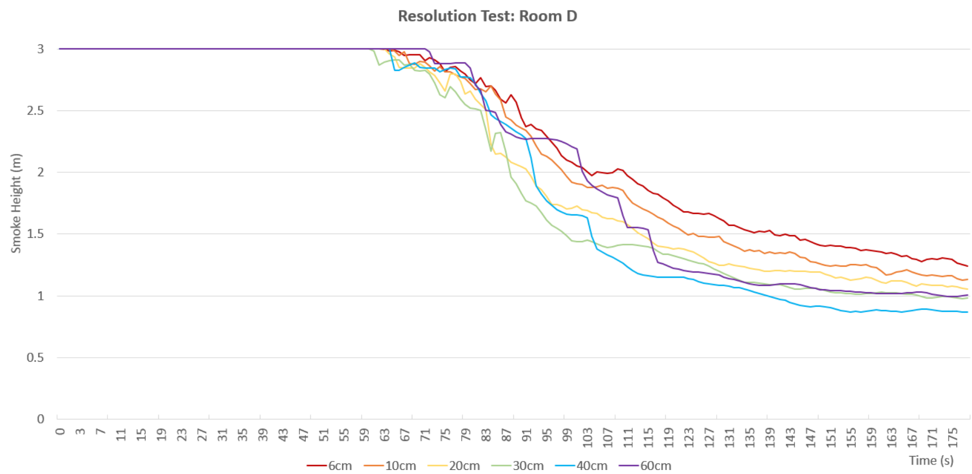


Figure 5.9: Simulation results of room D.

- CPU: Intel i7-3770, Quad-core, 8 thread, 3.4GH clock
- Memory: 16GB, DDR3
- Operating system: 64bit windows 7

Resolution	Time to finish all simulations
6cm	18 months
10cm	3 months
20cm	2 weeks
30cm	4 days
40cm	1.5 days
60cm	10 hours

Table 5.1: Projected time to finish all simulations.

The resolution simulation results (figure 5.6 - 5.9) and the expected finish time (table 5.1) show that 6cm-model does not offer significantly accurate results compared to the 10-cm model, but requires 13 months more simulation running time. Therefore, the resolution of all FDS simulations in this research is set to 10cm.

5.1.2 Test Cases

To investigate how shape and size affect the transformation algorithms, test models are built with a variety of shapes and sizes. The transformation algorithm transforms general rooms in two steps. If the room is not rectangular in floor plan, it is transformed into a rectangle with the same area and length/width proportion. Then if the room is not a rectangle in section, it is transformed into a cuboid with the same floor area and the same volume. Three common non-rectangular floor plans were selected as the test cases (figure 5.10). A name was given to each of them for easier referencing: shoe shape, SIM card shape, and circular shape.

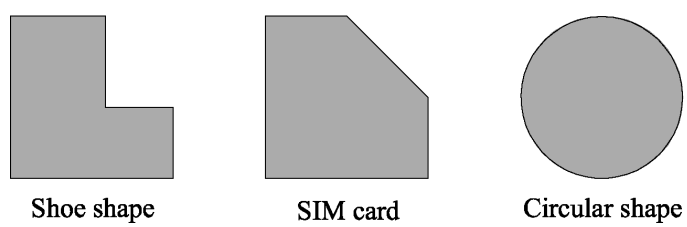


Figure 5.10: Three commonly seen non-rectangular floor plans.

Three commonly seen non-rectangular sections were selected as the test cases as shown in figure 5.11. They are named gable, shed, and vault respectively based on how they look in sections.

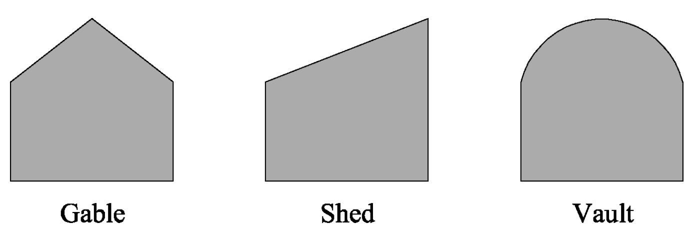


Figure 5.11: Three commonly seen non-rectangular sections.

The transformation algorithm transforms non-rectangular corridors to rectangular shape based on smoke travel distance. Three most commonly seen non-rectangular corridors were selected as the test cases: T-shape, L-shape, and O-shape (figure 5.12).

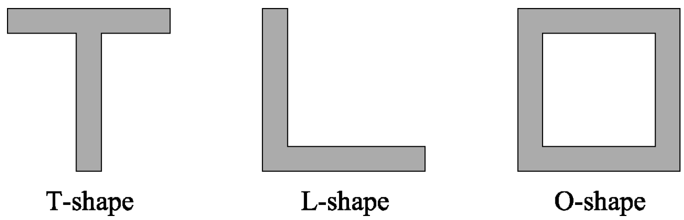


Figure 5.12: Three commonly seen non-rectangular corridors.

All types of rooms and corridors were simulated with various sizes and additional parameters if any are needed. This is to investigate whether the size and the parameters of the shapes are correlated with the magnitude of the error that is induced by the transformation algorithms.

5.1.2.1 Shoe Shape Rooms

The size of shoe shape rooms in floor plan can be defined by the size of the bounding box (L x W) subtracting the size of the void space (VL x VW) as shown in figure 5.13.

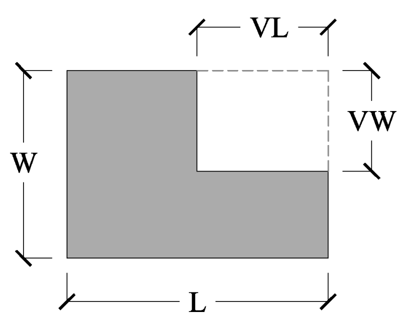


Figure 5.13: Parameters to define the size of a shoe shape rooms in the floor plan.

There are many potential factors that affect the accuracy of the shape transformation, such as room area, L/W ratio, void/room area ratio, VL/VW ratio and so on. To investigate how these parameters affect the transformation algorithm, rooms with various combination of bounding box sizes and void sizes were modeled as listed in table 5.2. The non-rectangular floor plans were transformed into a rectangular shape with similar proportion and minimum area difference, which is constrained by the allowable simulation resolution. For example, the first model in table 5.2 shows 0.3% area difference between the original shoe shape model and the transformed rectangle model because the resolution is set to 0.1m. For most models, the area difference is under 1%. Each model contains four identical rooms as shown in figure 5.1 (original model) and figure 5.2 (transformed model). The ceiling height of each room was set to 3m.

L x W (m)	VL x VW (m)	Transformed size (m)	Area difference (%)
4x2	2.2x1	3.4x1.7	0.3
4x4	2x1.9	3.5x3.5	0.4
6x2	3.3x1	5.1x1.7	0.3
6x4	2x1.2	5.7x3.8	0.3
6x4	3x2.2	5.1x3.4	0.3
6x4	4.1x3	4.2x2.8	0.5
6x6	3x3	5.2x5.2	0.1
8x4	3.8x2	7x3.5	0.4
8x6	2.3x2	7.6x5.7	0.2
8x6	4x3.3	6.8x5.1	0.3
8x6	6.1x4	5.6x4.2	0.3
8x8	4x4.1	6.9x6.9	0
10x4	5x2.2	8.5x3.4	0.3
10x6	5.5x3	8.5x5.1	0.3
10x8	5x4.4	8.5x6.8	0.3
10x10	2x2	9.8x9.8	0
10x10	4x2	9.6x9.6	0.2
10x10	5x3	9.2x9.2	0.4
10x10	5x4.9	8.7x8.7	0.3
10x10	6x6	8x8	0

Table 5.2: Various size of shoe shape models.

5.1.2.2 SIM Card Shape Rooms

The size of SIM card shape can be defined by the size of the bounding box (L x W) and the size of the triangular void space (VL x VW / 2) as shown in Figure 5.14.

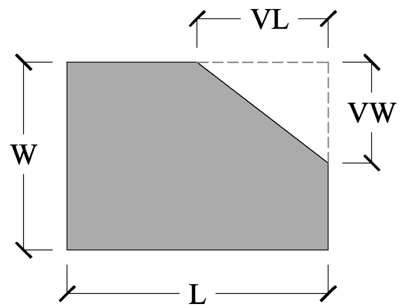


Figure 5.14: Parameters to define the size of a SIM card shape room in floor plan.

Various sizes of SIM card shape rooms were modeled (table 5.3) to validate the transformation algorithm for the similar reason to the shoe shape models.

L x W (m)	VL x VW (m)	Transformed size (m)	Area difference (%)
6x4	3x1.7	5.7x3.8	1
6x4	4.5x3	5.1x3.4	0.5
6x4	1.5x3	5.7x3.8	0.4
6x4	4.5x1	5.7x3.8	0.4
8x6	4x3	7.5x5.6	0
8x6	6x4.5	6.8x5.1	0.5
8x6	2x4.5	7.6x5.7	0.4
8x6	6x1.5	7.6x5.7	0.4
10x10	2.5x2.5	9.8x9.8	0.9
10x10	5x5	9.4x9.4	1
10x10	7.5x7.5	8.5x8.5	0.5
10x10	2.5x7.5	9.5x9.5	0.4

Table 5.3: Various size of SIM card shape models.

5.1.2.3 Circular Rooms

For circular rooms, five different sizes are tested which are shown in table 5.4.

Diameter (m)	Transformed size (m)	Area difference (%)
4	3.5x3.6	0.3
6	5.3x5.3	0.6
8	7.1x7.1	0.3
10	8.8x8.9	0.3
12	10.6x10.7	0.3

Table 5.4: Various size of circular models.

5.1.2.4 Gable / Shed / Vault

The parameters of the gable, shed, and vault models are shown in figure 5.15. L, W, and H are the length, width, and height of the bounding box. Length L is the magnitude of the extrusion of the polygons which is not explicitly denoted in the figure. The height of the rectangular base is set to 3m for all models. The slope of the ceiling S is calculated by S = 2h/W in the gable models, and S = h/W in the shed models. The lists of the models with different parameters are shown in table 5.5 to 5.7.

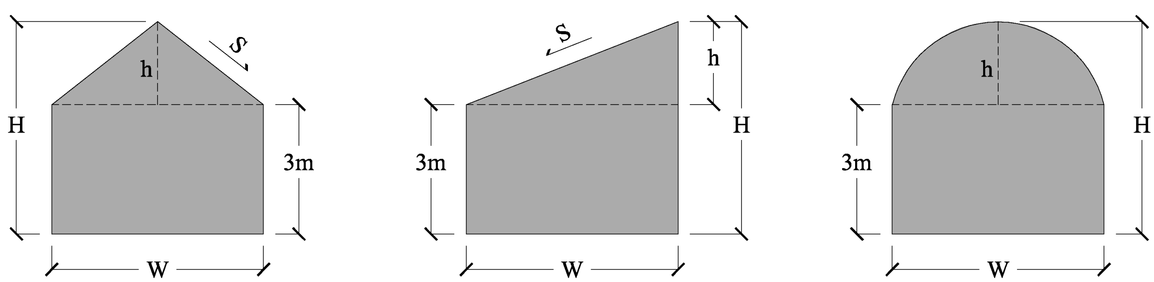


Figure 5.15: Parameters of the gable (left), shed (middle) and vault (right) models. Length L is the magnitude of the extrusion of the polygons, perpendicular to the polygons. Length L is not explicitly denoted in the figure above.

L x W (m)	H (m)	Slope	Transformed height (m)	Area difference (%)
6x4	4	0.5	3.5	0
6x4	5	1	4	0
6x4	7	2	5	0
8x6	4.6	0.5	3.8	0
8x6	7	1	4.5	0
8x6	9	2	6	0
10x10	5.6	0.5	4.3	0
10x10	8	1	5.5	0

Table 5.5: Gable models with different parameters.

L x W (m)	H (m)	Slope	Transformed height (m)	Area difference (%)
6x4	4	0.25	3.5	0
6x4	5	0.5	4	0
6x4	7	1	5	0
8x6	4.6	0.25	3.8	0
8x6	7	0.5	4.5	0
8x6	9	1	6	0
10x10	5.6	0.25	4.3	0
10x10	8	0.5	5.5	0

Table 5.6: Shed models with different parameters.

L x W (m)	H (m)	Transformed height (m)	Area difference (%)
6x4	3.5	3.3	1.1
6x4	4	3.7	0
6x4	5	4.6	0.7
8x6	3.8	3.5	1.1
8x6	4.5	4	1.2
8x6	6	5.4	0.8
10x10	4.2	3.8	0.3
10x10	5.5	4.8	1.1
10x10	8	6.9	0.4

Table 5.7: Vault models with different parameters.

5.1.2.5 T-shape / L-shape / O-shape Corridors

The length L of the T-shape, L-shape, O-shape corridors represents the length of one side of the corridors as shown in figure 5.16. The width of all corridors is set to 2m. The detailed dimensions of the models are listed in table 5.8 to 5.10.

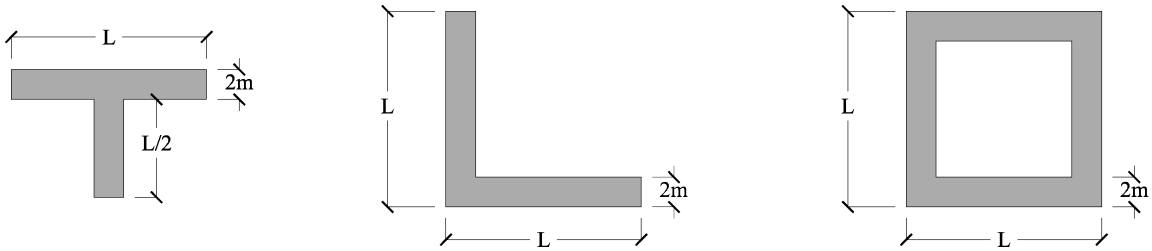


Figure 5.16: Parameters of the corridors.

L (m)	Transformed size (m)	Area difference (%)
10	8.2x3.7	1.1
15	11.8x3.8	0.4
20	15.6x3.8	1.2
30	23.0x3.9	0.3
40	30.0x4.0	0

Table 5.8: Various size of T-shape corridors.

L (m)	Transformed size (m)	Area difference (%)
10	13.0x2.8	1.1
15	20.0x2.8	0
20	27.0x2.8	0.5
30	42x2.8	1.4
40	57.0x2.7	1.3

Table 5.9: Various size of L-shape corridors.

L (m)	Transformed size (m)	Area difference (%)
10	16.0x4.0	0
15	25.0x4.2	1
20	35.0x4.1	0.3
30	55x4.1	0.7
40	75x4.1	1.2

Table 5.10: Various size of O-shape corridors.

5.1.3 Fire Parameter Settings

To investigate the accuracy of the transformation algorithms by isolating the shape transformation as the only varying factor, all fire parameters were set to default values in all of the simulation tests. In FDS, the fire source is mainly controlled by four parameters: chemical composition, max heat release ratio (HRR) per unit area, time to reach max HRR, and the surface area of the fire source. The chemical composition determines how much toxic gases and soot is produced per unit mass of fuel (fuel could be furniture, building material, books, and so on). The fire used in the simulations was set to reach the max HRR of 1000 from 0 in 60 seconds as a square function of time, which is typically known as T-square fire [58]. The surface area of the fire was set to 60cm x 60cm in each model. The details of the fire parameters used in the FDS input files are shown below:

```
&REAC ID='POLYURETHANE_GM27',
      FYI='SFPE Handbook, GM27',
      FUEL='REAC_FUEL',
      C=1.0, H=1.7, O=0.3, N=0.08,
      CO_YIELD=0.042,
      SOOT_YIELD=0.198/
&SURF ID='Fire',
      COLOR='RED',
      HRRPUA=1000.0,
      TAU_Q=-60.0/
```

5.1.4 Test Results

The FDS simulation tests produced 1000+ pages of data which are visualized with 200+ charts. To make the main text concise, only four of the charts are presented in this subsection as an example. The rest of the charts are presented in Appendix A. Figure 5.17 shows the simulation results of an 8m x 4m shoe shape model. In the graphs, X axis is the simulation time in seconds and Y axis is the smoke height in meters. The ceiling height of the models is set to 3m. Cyan lines show the simulation results of the original model, and the orange lines show the simulation results of the transformed model. The magnitude of the gaps between the lines denotes the amount of error introduced by the transformation algorithm.

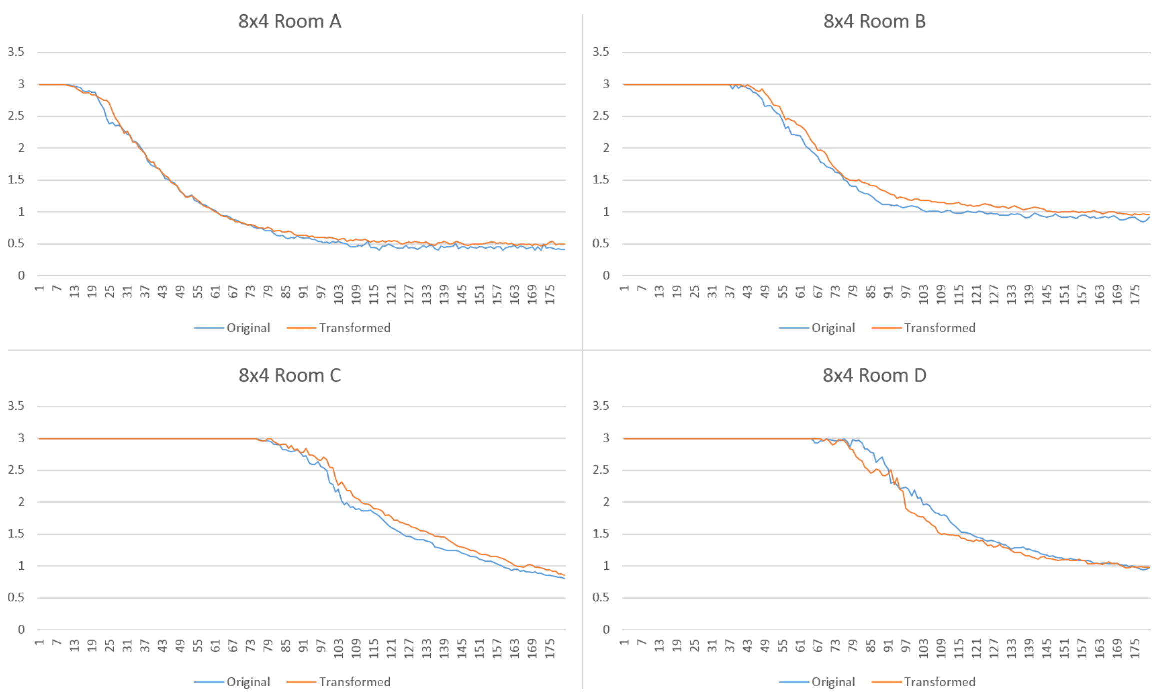


Figure 5.17: Simulation results of an 8m x 4m shoe shape model.

The simulation results of the entire 154 models (see Appendix A) show that the proposed transformation algorithm introduced very limited amount of error into the simulation process, except for some of the shed models. While the precise reasons for the large error in the shed models are unknown, it is likely to be caused by the irrationally high ceilings (up to 6m) and the acute angle (up to 45 degrees) of the ceilings which impedes natural smoke propagation.

To better examine if the error shows any noticeable patterns, the entire simulation results were visualized with seven error graphs as shown in figure 5.18 to 5.24. X axis shows the models with different parameters, and Y axis shows the percentage of the error introduced by transforming the model using the transformation algorithm. The error ϵ is calculated by: $\epsilon = (o_t - t_t)/o_t * 100\%$ where o_t and t_t are the average time that smoke reaches the 2m-1.5m zone in the original models and the transformed models respectively, i.e. ϵ shows the percentage of the error introduced by the transformation algorithm. The reason for using 2m-1.5m zone to calculate the average time is that people's lives are threatened when smoke reaches this zone. This generates more meaningful ϵ values. If the average time is calculated using every datum points, the value of ϵ will be much smaller. However, when the smoke line is very close to the ceiling or slab, the error between the original model and the transformed model makes no practical difference.

The simulation results of the validation tests show that:

- most of the models showed 5-10% error, except for some of the shed models.
- there is no discernable pattern associated with the change of the parameters of the models or the size of the model.
- the distance from the fire origin does not have notable influence, i.e. room A, B, C, and D show similar amount of error in each model.

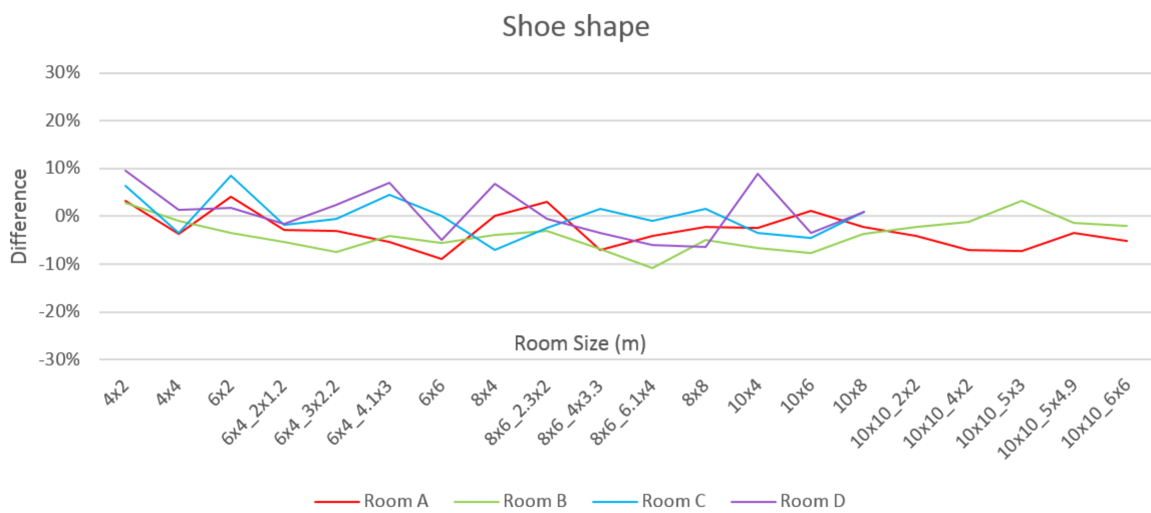


Figure 5.18: Error graph of the shoe shape models. X axis shows the models with different parameters. For example, 6x4-2x1.2 denotes a model with a bounding box of 6m x 4m, and a void of 2m x 1.2m. Y axis shows the percentage of the error introduced by transforming the model using the transformation algorithm.

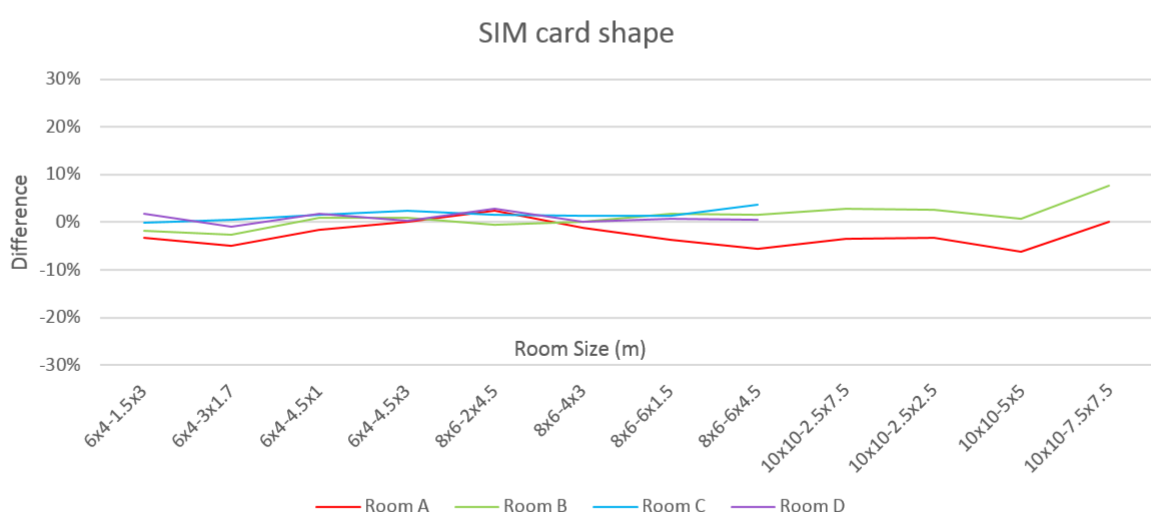


Figure 5.19: Error graph of the SIM card shape models.

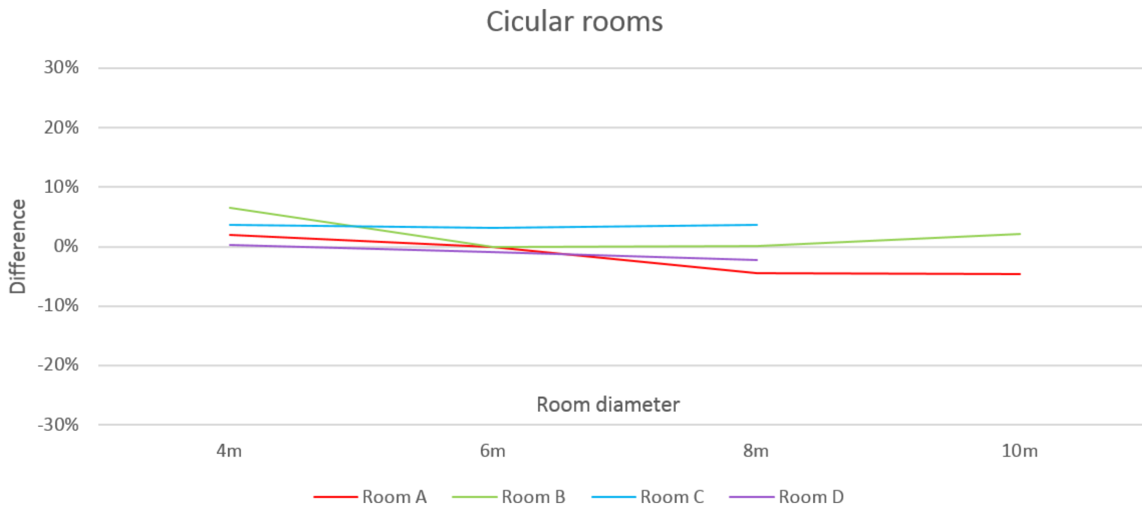


Figure 5.20: Error graph of the circular models. X axis shows the models with different diameters.

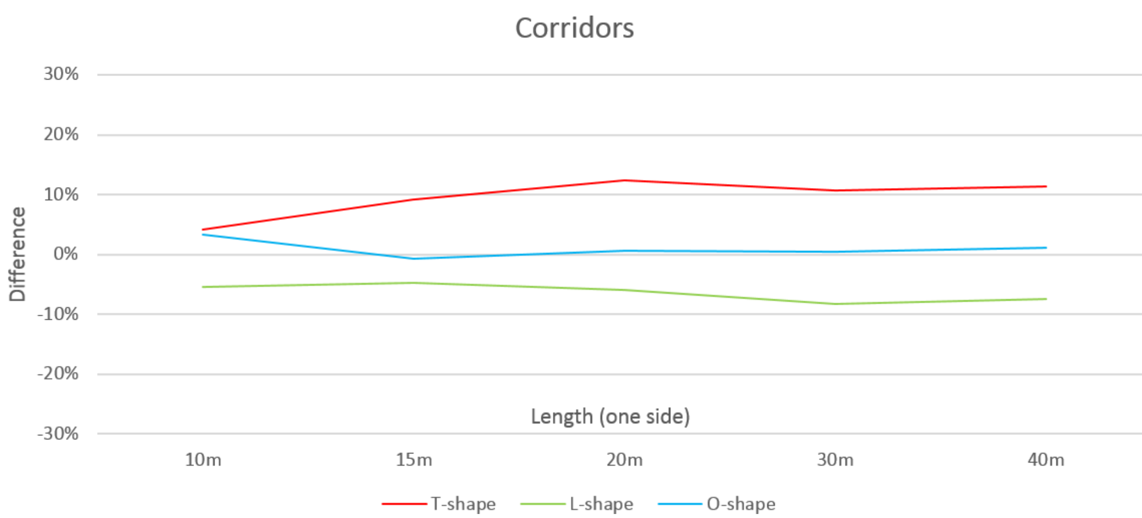


Figure 5.21: Error graph of the corridor models.

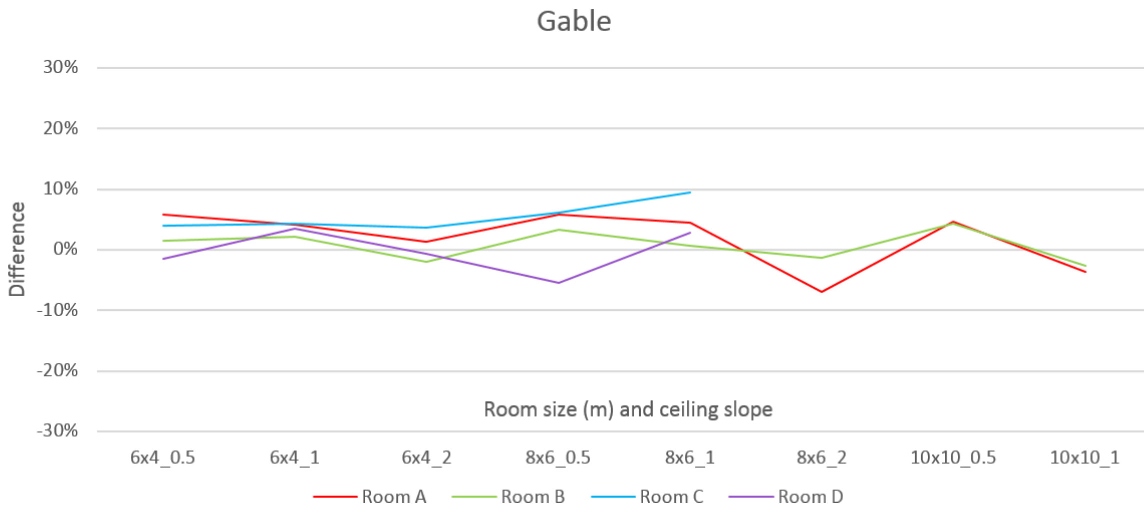


Figure 5.22: Error graph of the gable models. X axis shows the models with different parameters. For example, 6x4-0.5 denotes a model with a bounding box of 6m x 4m, and a ceiling slope of 0.5.

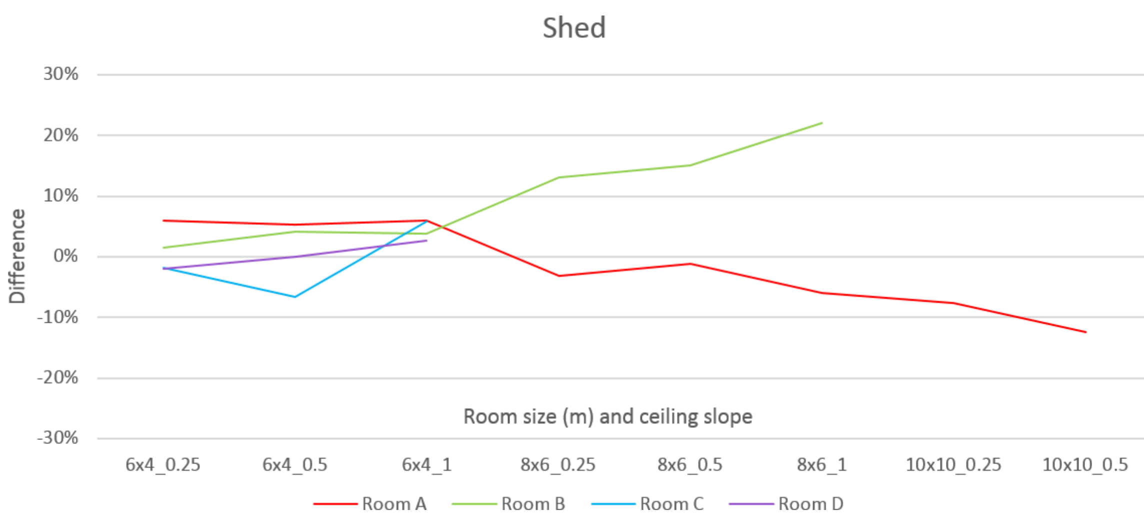


Figure 5.23: Error graph of the shed models.

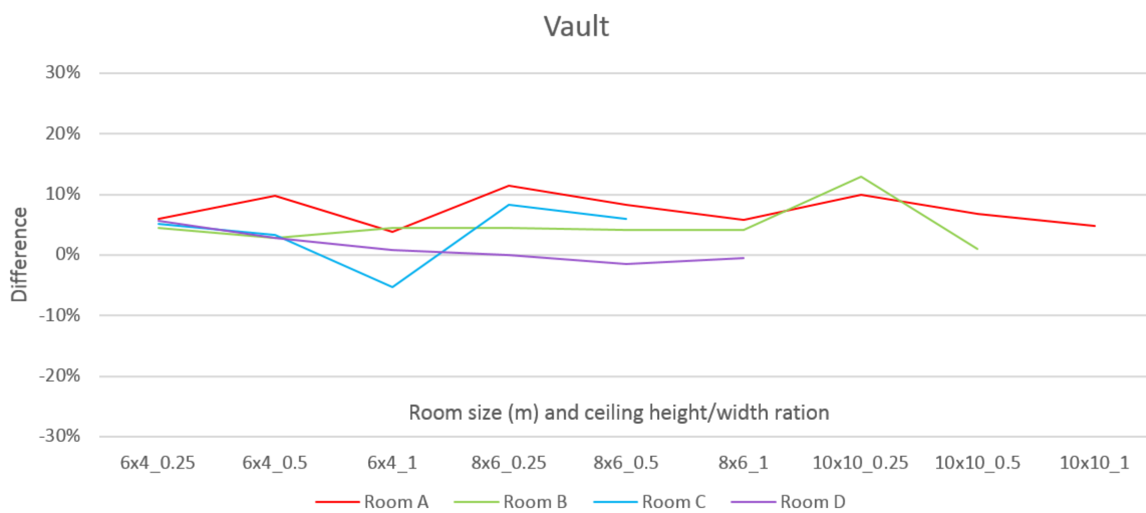


Figure 5.24: Error graph of the vault models.

5.2 Validation of the Room Selection Algorithm *

CFAST can only simulate buildings with a maximum of 30 rooms. To simulate a building with more than 30 rooms using CFAST, I proposed an algorithm in section 3 to select 30 rooms that have the shortest smoke travel distance from the fire origin. The tests of the validity for the room selection algorithm are discussed in this subsection. If the room selection algorithm is valid, one can simulate at least 30 of the most critical rooms of a building.

The room selection algorithm selects and simulates 30 of the most critical rooms. However, ignoring the rest of the rooms may affect the accuracy of the simulation results. The question is *"how consistent are the simulation results of the selected 30 rooms compared to the same 30 rooms of the original model assuming that CFAST could simulate the entire building of more than 30 rooms?"* In other words, "what is the amount of the error introduced by the room selection algorithm?" To answer this question, a

*Reprinted with permission from "Fire Propagation Simulation for Large Buildings in CFAST: Using BIM to Facilitate Simulation Process" by Wu et al., 2016. 13th International Conference on Design and Decision Support Systems in Architecture and Urban Planning, pp. 503-516. [59]

number of validation simulations were performed to find out the scalability of smoke propagation simulation.

5.2.1 Test Cases

The basic model for the scalability test is a single story building in BIM with exactly 30 rooms (elevator shafts are not counted into the 30 rooms) so that CFAST can run the entire building without any modification (figure 5.25). The whole model is then simulated in CFAST (figure 5.26A). The simulation results were set as the baseline for comparison of all of the following simulations.

I then simulated 25 of the rooms, which were selected using the room selection algorithm (figure 5.26B). Comparing with the simulation results of the same 25 rooms in the baseline can reveal how consistent the simulation results of the selected 25 rooms are. Scalability in this study refers to a concept such that "if the simulation results of the selected 25 rooms are similar to the simulation results of the same 25 rooms in the 30-room-simulation (the baseline model), selecting 30 rooms from a 35-room building would produce reasonably accurate simulation results, i.e. smoke propagation simulation in CFAST is scalable." It turned out that the smoke height in the selected 25 rooms is often slightly lower than the same 25 rooms in the baseline. Four more simulation tests were performed which include first 20 rooms (figure 5.26C), 15 rooms (figure 5.26D), 10 rooms, and 5 rooms, selected using the room selection algorithm. The simulation results were compared to the baseline respectively to test the scalability. The fewer number of rooms selected, the more discrepancy occurred between the simulation results of the selected rooms and the baseline.

A hypothesis is that selecting N number of rooms and merging the rest of the rooms to the Nth room (figure 5.27, right) to keep the overall volume unchanged would get more consistent simulation results of the first N-1 rooms, compared to ignoring the rest of the

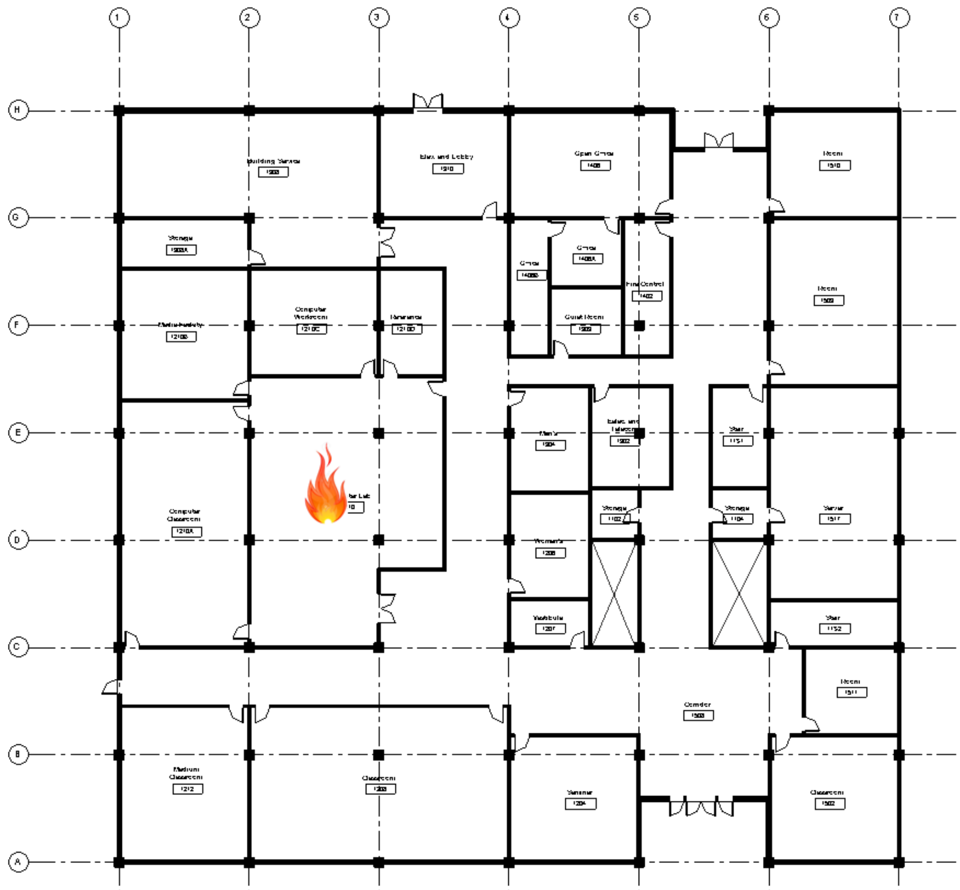


Figure 5.25: A floor plan with 30 rooms used in the test cases. Two elevator shafts are excluded from the 30 rooms assuming that elevators are not used during building fire evacuation. The flame icon denotes where the fire started.

rooms (figure 5.27, left). For easier reference, the two selection schemes are named as "merging scheme" and "ignoring scheme". Ignoring scheme may generate less consistent simulation results because when the overall volume of the building becomes smaller, the smoke line between the upper and lower zone moves downward faster given the same smoke producing rate of the fire source. This hypothesis is later proved to be true.

Another hypothesis is that the accuracy of the room selection algorithm is affected by whether the simulated floor is directly connected to the exterior (i.e. the floor has exterior doors). It turned out that the simulation results are more consistent when the floor is not

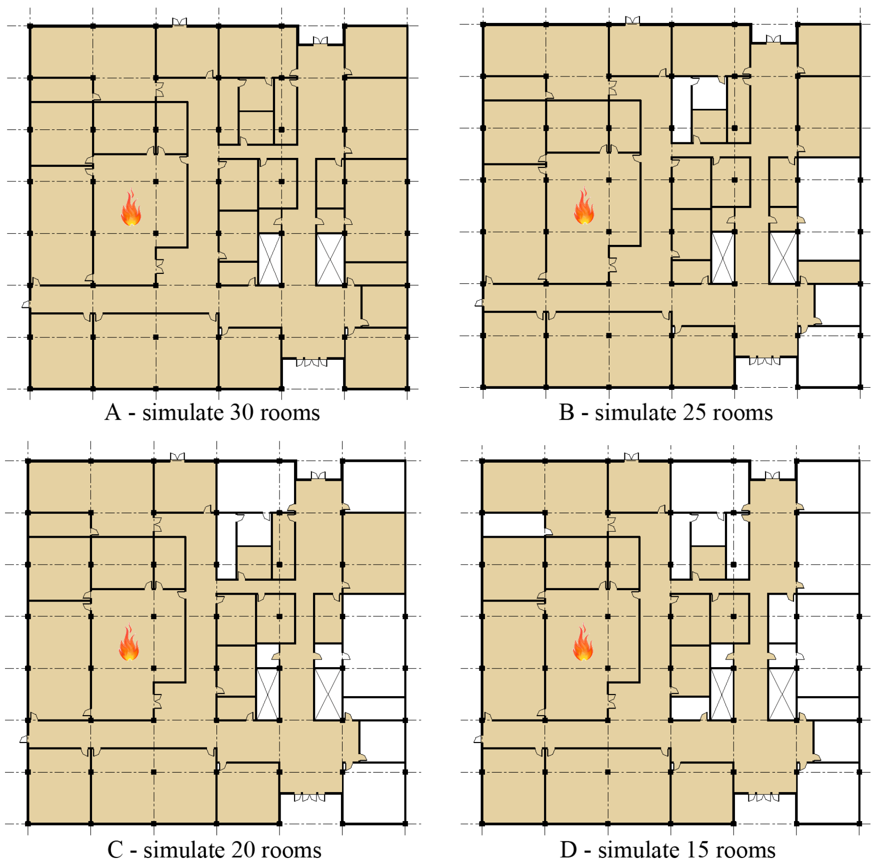


Figure 5.26: Selecting different numbers of rooms using the proposed algorithm.

directly connected to the exterior.

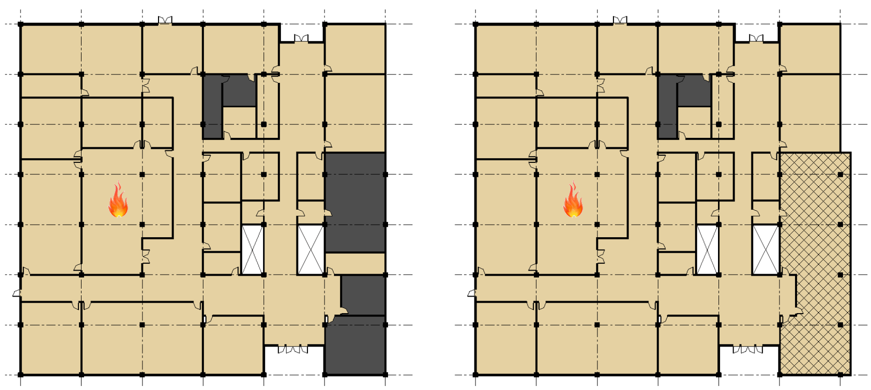


Figure 5.27: Merging spaces. In the left figure, the five rooms (in grey) that are furthest from the fire origin are ignored in the simulation. In the right figure, the volume of the last five rooms is merged into the next last room (in checker pattern). The volume of the two rooms in grey is also merged into the big room which resulted the wall protruded from the column grid. The two rooms in white are elevator shafts.

5.2.2 Test Results

The simulation results of the 30 rooms of the baseline model are visualized in a 3D graph (figure 5.28). It is easy to notice how smoke propagates from the room of the fire origin to all the other rooms, and how smoke height changes as the simulation progresses.

I then selected 25, 20, 15, 10, and 5 rooms respectively using the room selection algorithm and ran simulations using ignoring scheme and merging scheme. The model used in this set of simulations is directly connected to the exterior through several exterior doors. In the simulation results, two of the most critical indicators are selected for comparison: smoke height and CO concentration. The simulation results are presented in figure 5.29 to 5.32. The duration of each simulation was set to 600 seconds. The time step of the simulation was set to every 30 seconds which produced overall 168 graphs. To make the main text concise, only the graphs at the end of the simulation are presented in this subsection. The rest of the graphs are presented in Appendix B in 60 second interval.

In the figures, the green line is the baseline that all the others are compared to. X axis

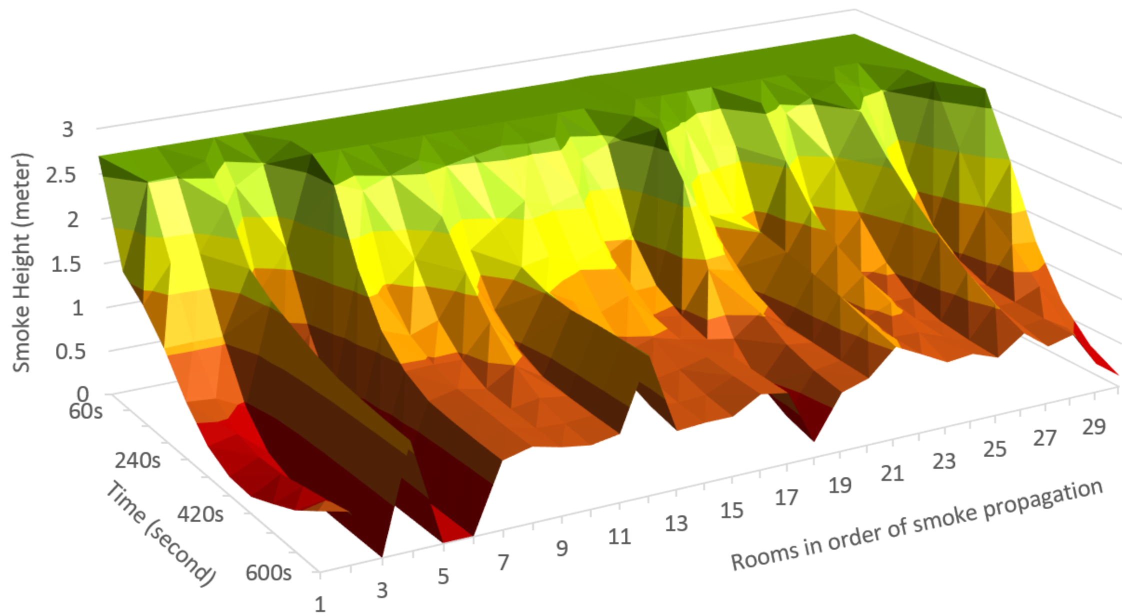


Figure 5.28: Visualized simulation results showing smoke propagation through time. Room 1 is the fire origin. The rest of the rooms are sorted by the smoke travel distance from Room 1. Ceiling height of the rooms is all set to 2.7 meters.

denotes the rooms sorted by smoke propagation distance from Room 1, the fire origin. Y axis denotes the smoke height of each room in meters. Lines with different colors denote the simulations with different number of rooms. The smaller the gap from the green line, the more consistent the simulation results are.

As for the interpretation of CO concentration, the dash lines are the results for the upper layers, and the continuous lines are the results for the lower layers. The green lines (the longest) are the baseline that the other simulations are compared to. X axis denotes the rooms sorted by smoke travel distance, and Y axis denotes CO concentration in ppm.

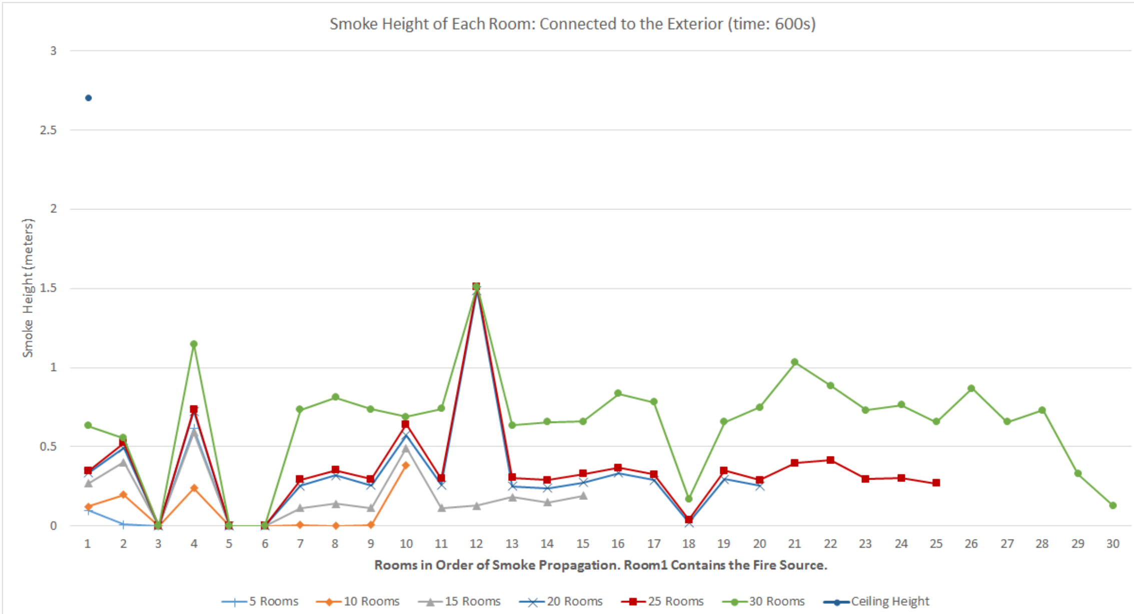


Figure 5.29: Smoke height with ignoring scheme.

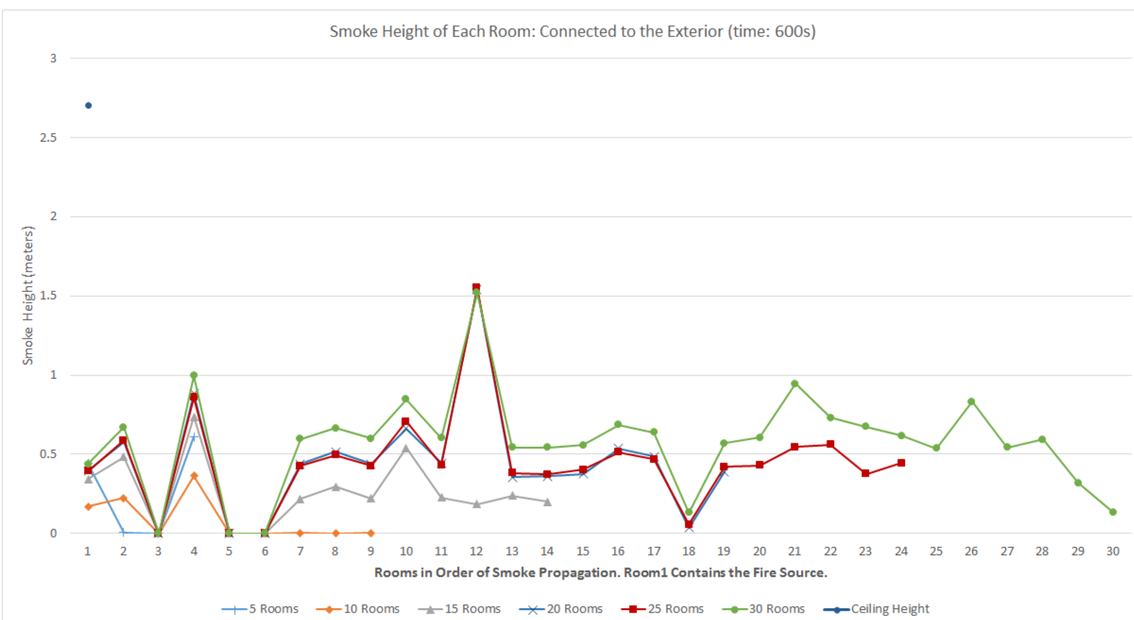


Figure 5.30: Smoke height with merging scheme.

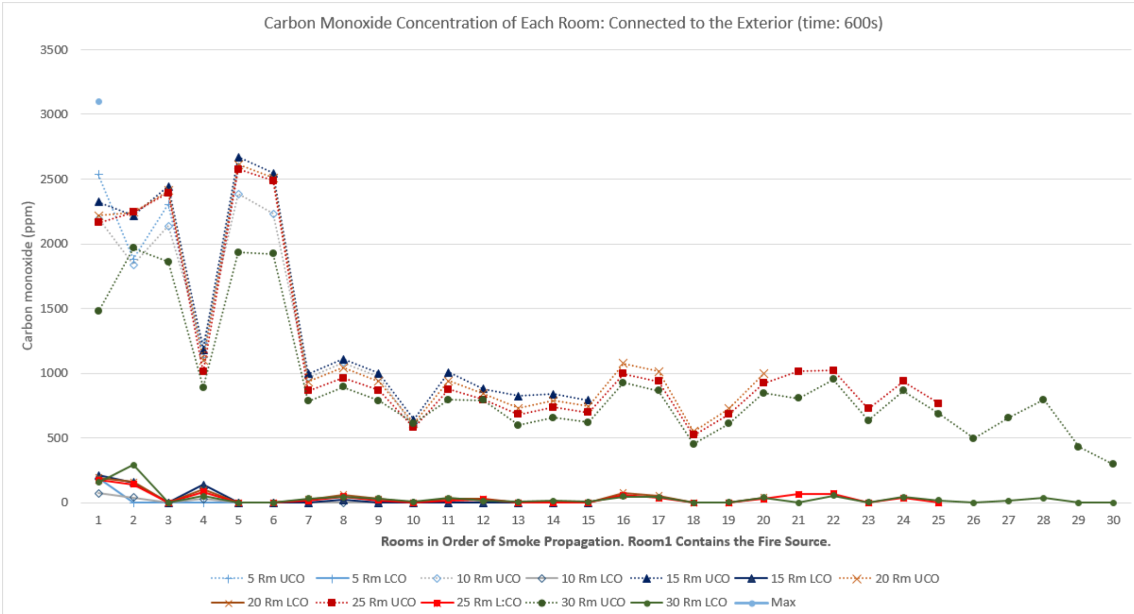


Figure 5.31: CO concentration with ignoring scheme.

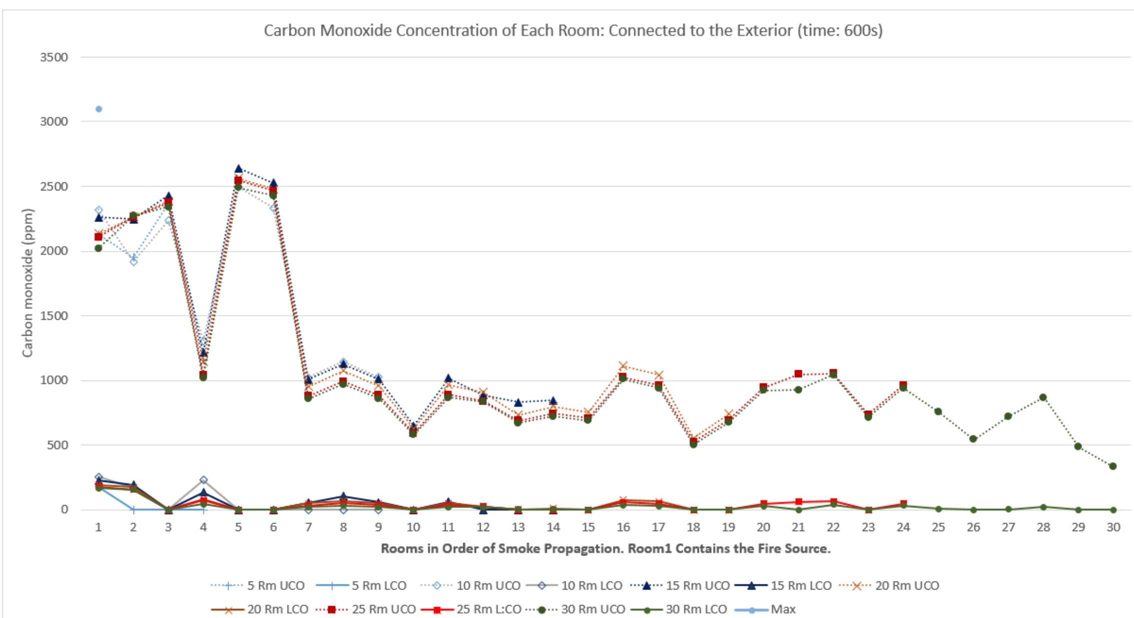


Figure 5.32: CO concentration with merging scheme.

To test how direct connection to the exterior affects simulation results, the models were modified such that the exterior doors are replaced with walls, i.e. none of the rooms are directly connected to the exterior. The occupants of the building are assumed to evacuate through staircases. I then selected 25, 20, 15, 10, and 5 rooms respectively using the room selection algorithm and ran simulations using both ignoring scheme and merging scheme for the modified models. The simulation results are presented in figure 5.33 to 5.36.

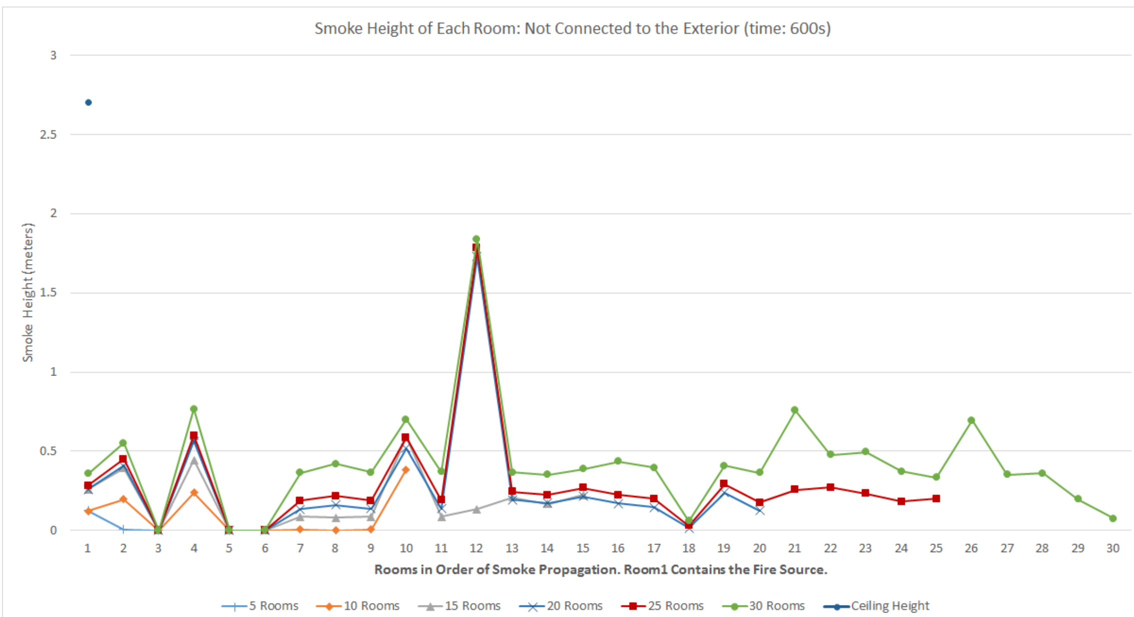


Figure 5.33: Smoke height with ignoring scheme.

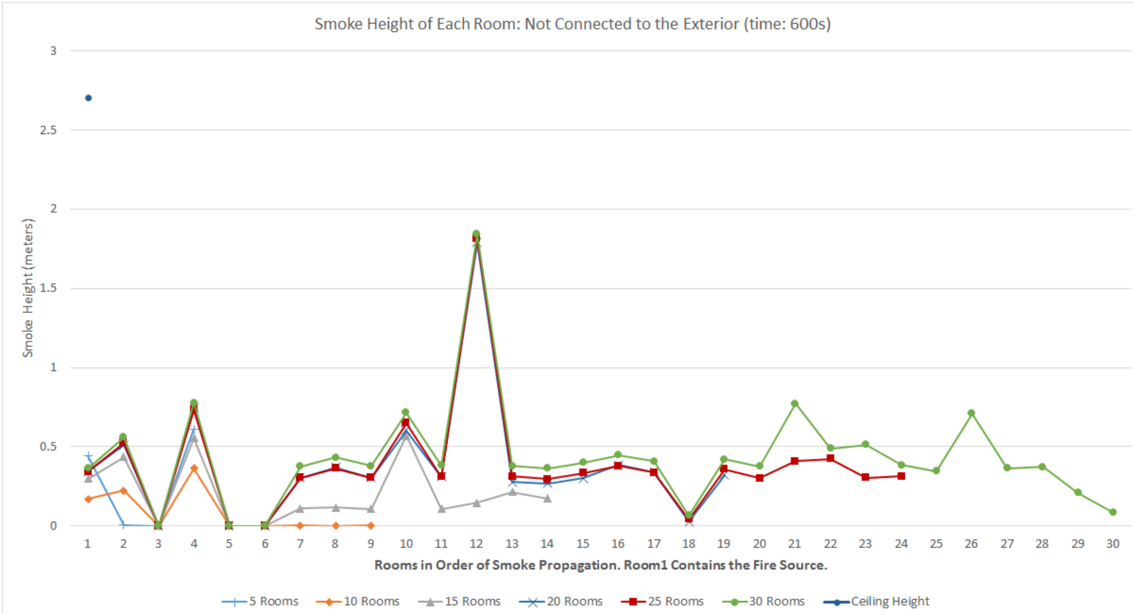


Figure 5.34: Smoke height with merging scheme.

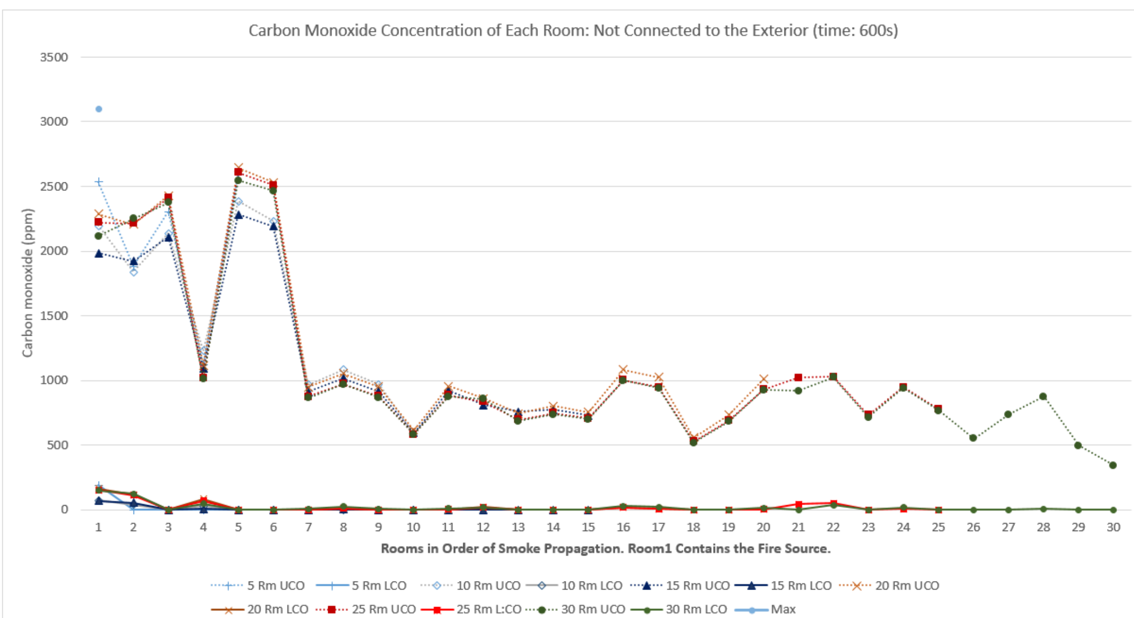


Figure 5.35: CO concentration with ignoring scheme.

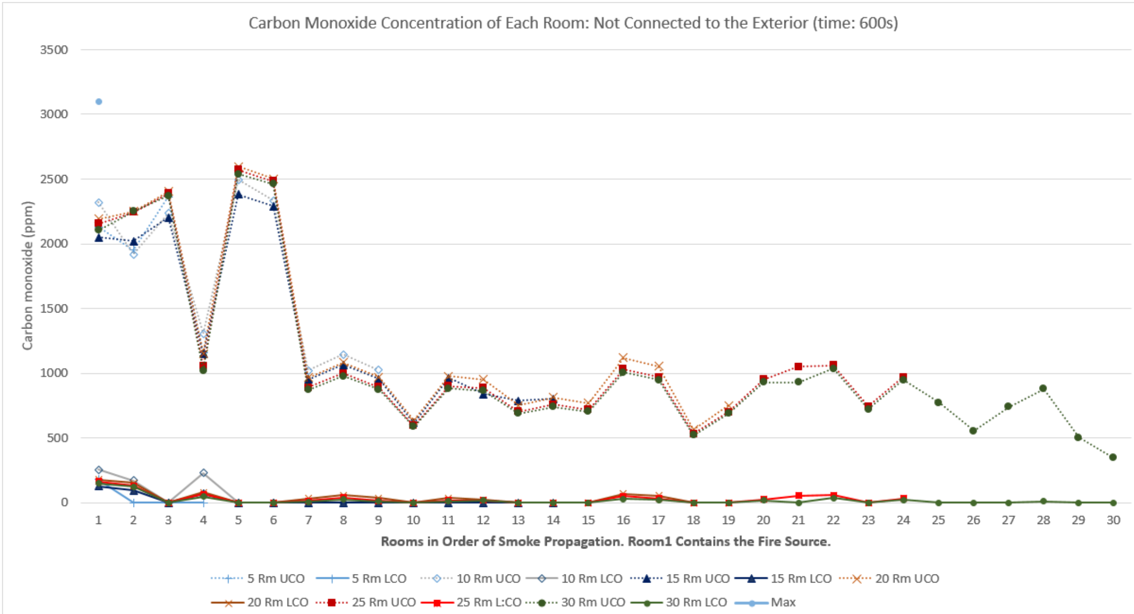


Figure 5.36: CO concentration with merging scheme.

All simulation tests showed negligible difference in CO concentration compared to the baseline, i.e. different selection schemes or connection to the exterior does not have much influence on CO concentration. In addition, the CO concentration of lower layer is very low compared to the upper layer, even for the room of fire origin.

Merging scheme showed better consistency in terms of smoke height. With the model directly connected to the exterior, ignoring scheme showed approximately 40cm difference in smoke height while merging scheme showed roughly 20cm. With the model that is not directly connected to the exterior, ignoring scheme showed roughly 20cm difference in smoke height while merging only showed approximately 5cm. This shows that the algorithm introduces less error when the model is not connected to the exterior.

In short, when using merging scheme, the simulation of selected 20 or 25 rooms showed 5-20 cm difference in smoke height compared to the baseline. This is approximately 2-7% error considering the ceiling height is 2.7meters.

6. NEW KNOWLEDGE DISCOVERY

In the typical architectural design process, building fire safety relies solely on the compliance of building fire codes. Although code-based design can achieve a high level of fire safety, simulation-based design has additional advantages in comparison to code-based design. One of the advantages is the potential to discover new knowledge that is not yet expressed by building codes.

The nature of building codes is to prevent similar disasters from happening again based on lessons learned in the previous incidents. This means that building codes come after accidents or disasters. There are countless examples of new building codes enacted after a disaster. Emperor Nero implemented building codes to enhance fire safety after the Burning of the Rome in AD64 [60]. The Great Fire of London in 1666 which burned more than half of London to the ground led to the London Building Act in 1667 [61]. The Chicago Fire in 1871 and other numerous building fires led to new building codes to reinforce fire safety [62]. On the other hand, the nature of simulation is to predict consequences beforehand based on the laws of physics or the laws of nature. Because of this fundamental difference, simulation-based design has the potential to discover new knowledge that building codes have not yet captured.

While performing smoke propagation simulations using CFAST, I have discovered several pieces of new knowledge that are not yet captured by building codes. ***Ceiling design and door design can affect building fire safety in several ways***. Since the majority of building fire deaths are caused by smoke, delaying smoke propagation has the effect of improving building fire safety. In a building fire, hot smoke moves downwards from the ceiling as building fire develops. Smoke eventually threatens people's lives when it reaches human height. Studying this phenomenon as simulated led to a design idea to increase the time for smoke to reach human height. Utilizing plenum space between ceiling and slab can delay smoke propagation by increasing the volume of the room. One could open up part of the ceiling or install grilles to allow smoke to move higher than the danger zone. This can delay smoke propagation and give occupants more time to safely evacuate in case of a building fire.

Two CFAST simulation runs were performed with the building shown in figure 6.1, one run with ceilings and the other without ceilings to utilize the plenum space. Because plenum space is not defined in CFAST, the two models were simulated with different room height, 2.8m and 3.4m respectively. There are four 6m x 6m rooms in the model, room A, B, C, and D. Room A contains the fire source (red square). Simulation results showed noticeable smoke delaying effect in all four rooms (figure 6.2). The average time that smoke reaches 2m - 1.5m zone above the floor increased approximately 20% by opening up the ceilings (table 6.1).

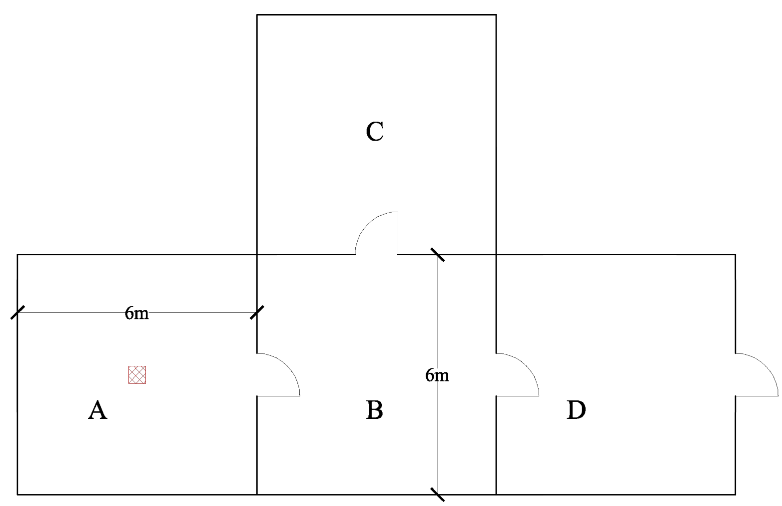


Figure 6.1: CFAST model for testing how opening ceiling affects smoke propagation. Ceiling height is set to 2.8m, and plenum height is set to 60cm.

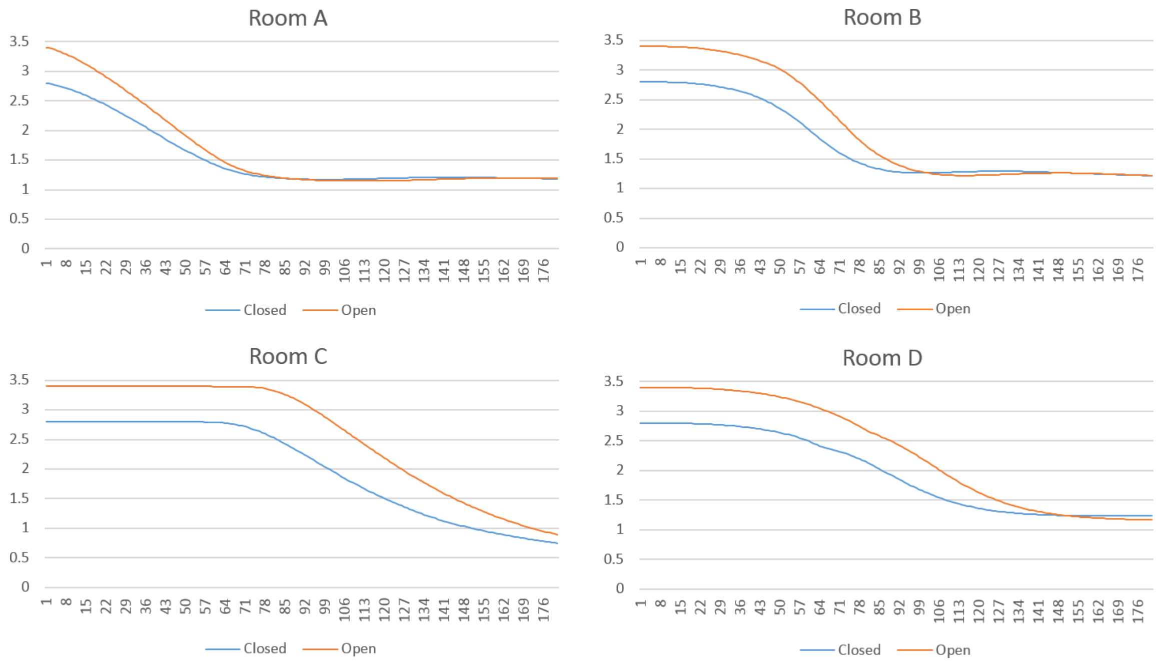


Figure 6.2: Comparison of the simulation results. Blue lines denote the simulation results of the model with ceilings, and the orange lines denote the simulation results of the model without ceilings. X axis denotes simulation time in seconds, and Y axis denotes smoke height in meters.

	Room A	Room B	Room C	Room D
Closed	47	67.5	110.5	97.5
Open	55	81	135	116.5
Increase	17%	20%	22%	19%

Table 6.1: Comparison of the time (in seconds) that smoke reaches 2-1.5m zone.

Door design also affects building fire safety. Doors are exits for occupants and pathways for smoke. Wider doors allow people to evacuate faster by widening the bottlenecks, and at the same time increase the speed of smoke propagation. Higher doors, on the other hand, only increases the speed of the smoke propagation while having no effect on the speed of occupant evacuation. Distance D in figure 6.3 determines the valid volume that can hold smoke before it propagates to the next room. With the same ceiling height, the higher the doors, the quicker smoke propagates to the adjacent rooms. If a designer chooses higher doors merely because its slender proportion fits better to the overall appearance of the building design, which subsequently threatens the safety of the occupants, extra fire safety features should be installed as the compensation.

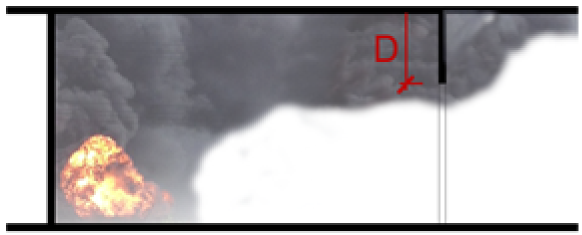


Figure 6.3: Valid volume for stalling smoke propagation to the next room.

To cross-validate the discovery that ceiling design and door design affect smoke propagation, and to more accurately codify how they affect smoke propagation, I conducted a series of simulation tests in FDS with various parameters. Tested parameters include opening ratio, opening size, opening distribution, plenum height, and door height.

6.1 Simulation Settings

Ceiling and door design can affect smoke propagation in many ways. In this study, I selected five of the parameters to investigate their impact on smoke propagation. To isolate the impact of each parameter, a model is built as the base model, and every time only one parameter was changed while the others remained untouched.

As shown in figure 6.4, the base model has four rooms. In the perspective drawing (figure 6.4, left) the slabs at the top and the bottom are hidden for presentation purposes. The only way for smoke to propagate from one room to the next is through the doors. Room A contains the fire source at its center, and room D is connected to the exterior.

Each room has nine evenly distributed sensors (red cross signs) except for room A which has eight sensors. The size of each room is set to 6m x 6m.

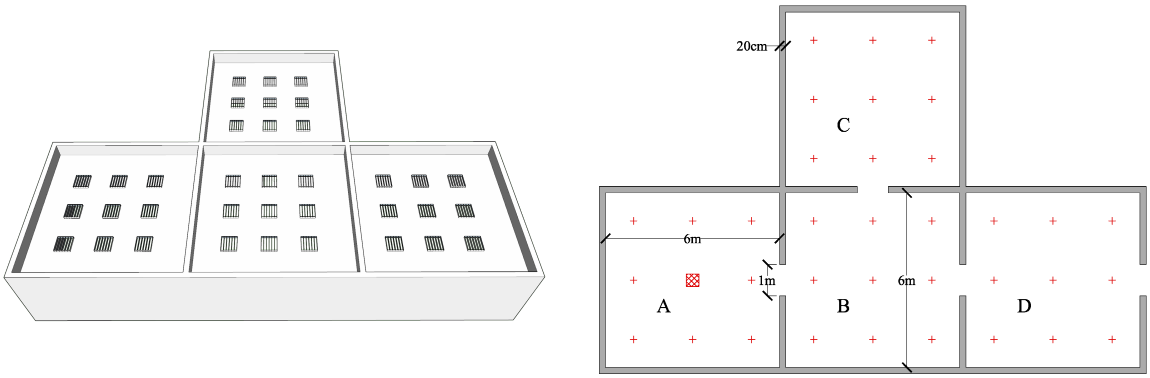


Figure 6.4: Perspective (left) and the floor plan (right) of the base model for the simulations.

Ceiling height of each room for the base model was set to 2.8m, and the floor height was set to 3.6m (figure 6.5). The size of each door was set to 1m x 2m (W x H).

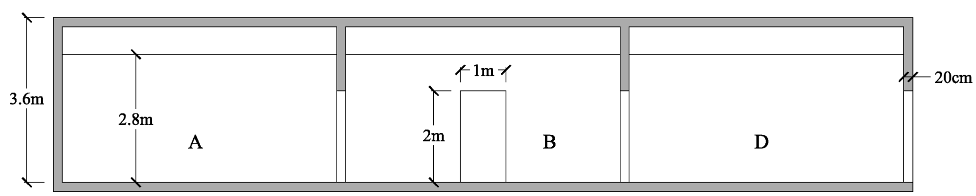


Figure 6.5: Section of the base model.

The resolution of all FDS simulations was set to 10cm. This restricts the dimensions of the smallest geometries in the model to be greater or equal to 10cm. Thus, the height of the grilles and the spacing of the grilles were set to 10cm. Each grille fin is represented using one surface without thickness. The length and the width of the grilles were set to 60cm (figure 6.6).

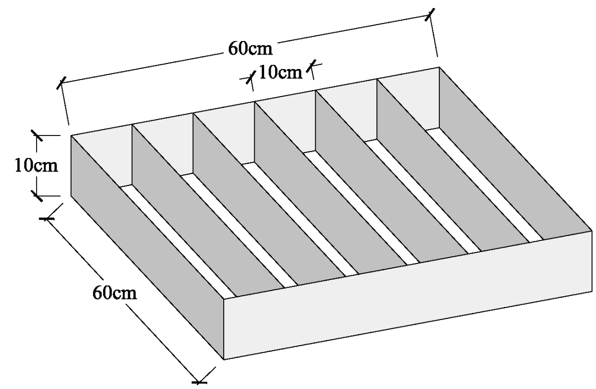


Figure 6.6: Grille dimensions of the base model.

6.2 Simulations and the Results

6.2.1 Opening Ratio

Putting openings on ceiling induces smoke into plenum space and subsequently delay smoke propagation. How effectively openings delay smoke propagation is likely to be affected by the ratio between the total opening area and the ceiling area. To investigate precisely how opening ratio affects smoke propagation, a set of models with different opening ratios were simulated using FDS. Figure 6.7 shows the ceiling plan of the models. Each model has nine identical square openings with varying size L. The sizes of the openings of each model are listed in table 6.2.

The openings of the models are evenly distributed with the center points of the openings of each model unchanged. The model with 100% opening ratio does not have a ceiling. The average time to reach 2m-1.5m zone was extracted from the simulation results (figure 6.8).

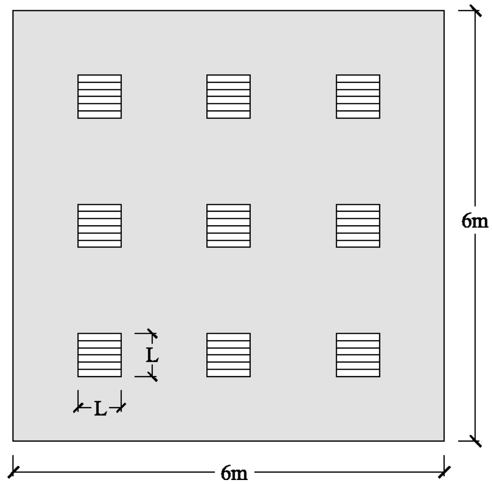


Figure 6.7: Ceiling plan of the rooms.

Grill Size L (m)	Opening Ratio (%)
0.2	1
0.4	4
0.6	9
0.8	16
1	25
1.2	36
1.4	49
1.6	64
1.8	81
open	100

Table 6.2: List of grill sizes

The simulation results are very interesting. When gradually opening up the ceiling from 0% to 16%, the time delay of smoke propagation increases dramatically. The time delay increases in much slower speed from 16% to 50%, and starts to decrease from 50% to 100%. Room A, which contains the fire source, showed up to 20% increase in time delay while room C and D, which are far away from the fire source, showed up to 60% of increase in time delay. The exact reason why opening up more than 50% of the ceiling diminishes smoke delaying effect is unknown. The simulation results for 0% and 100% opening, except for room A (fire origin), are similar to the simulation results using CFAST

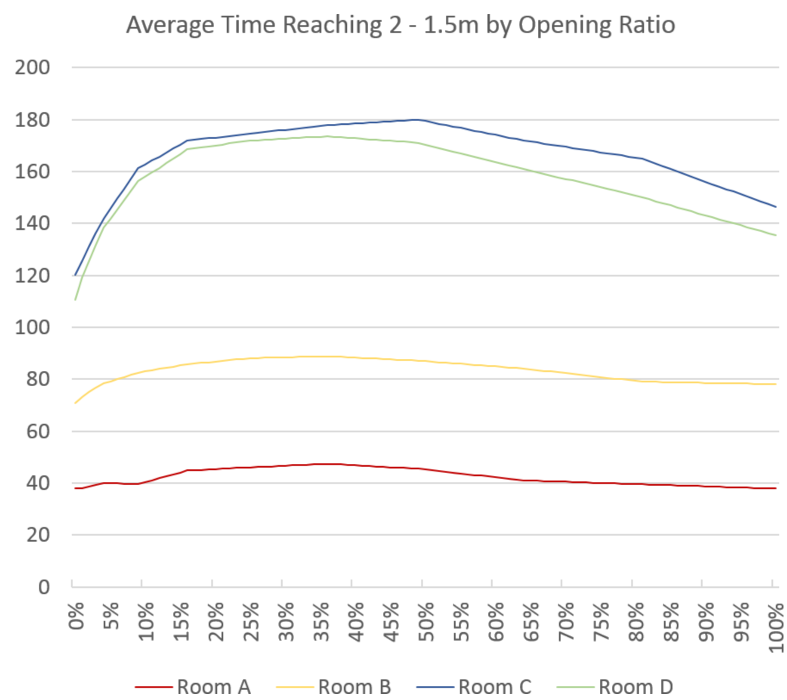


Figure 6.8: Simulation results by opening ratio. X axis denotes opening ratio, and Y axis denotes the average simulation time (in seconds) to reach the 2m-1.5m zone.

which is shown in table 6.1.

6.2.2 Opening Size

Opening size may also affect smoke propagation. To investigate the influence of various opening sizes on smoke propagation, a set of models with different opening sizes were modeled and simulated using FDS (figure 6.9). In each model, the openings are evenly distributed and the total area of the openings is constant. The model with the opening size of 40cm used smaller openings for the leftover rows to match the total opening area. The simulation results are shown in figure 6.10. The simulation results show that the size of the grille has limited influence on smoke propagation.

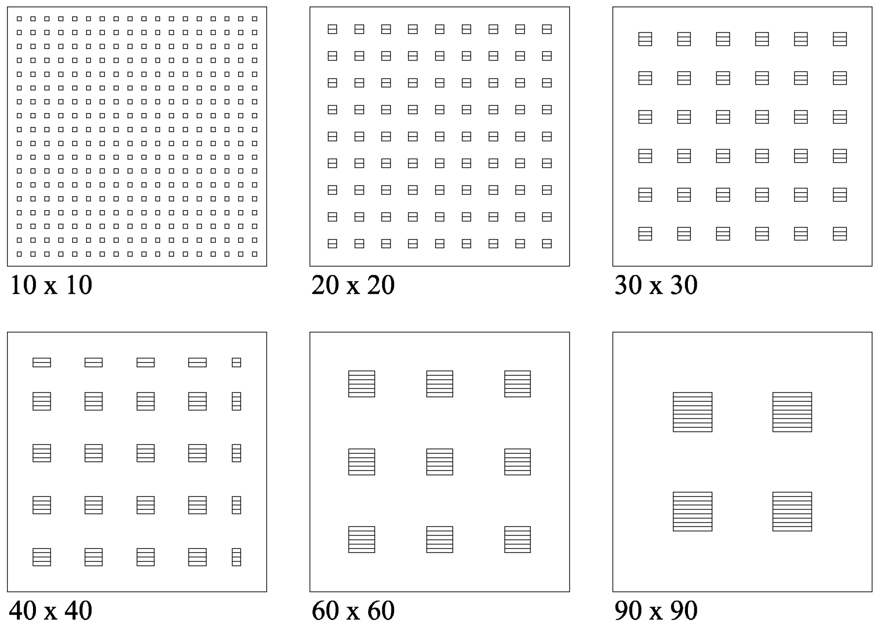


Figure 6.9: Ceiling plans of the models with different grille sizes.

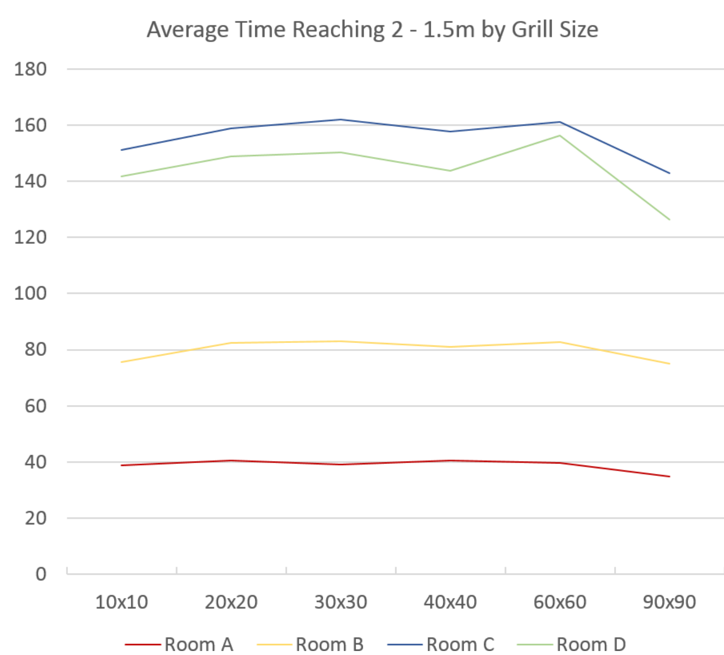


Figure 6.10: Simulation results by grille size. X axis denotes opening size, and Y axis denotes the average simulation time (in seconds) to reach the 2m-1.5m zone.

6.2.3 Opening Distribution

The distribution of openings may also affect smoke propagation. To investigate how opening distribution influences smoke propagation, a set of models with different types of distribution were simulated in FDS (figure 6.11). The total area of the openings in each model is constant. The simulation results show that A and C types are most effective in delaying smoke propagation, and D, E, and G types are least effective (figure 6.12). Combined with the observation of the distribution drawings, it is very likely that evenly distributed openings are more effective in delaying smoke propagation. To confirm and generalize this claim, more extensive simulations are needed.

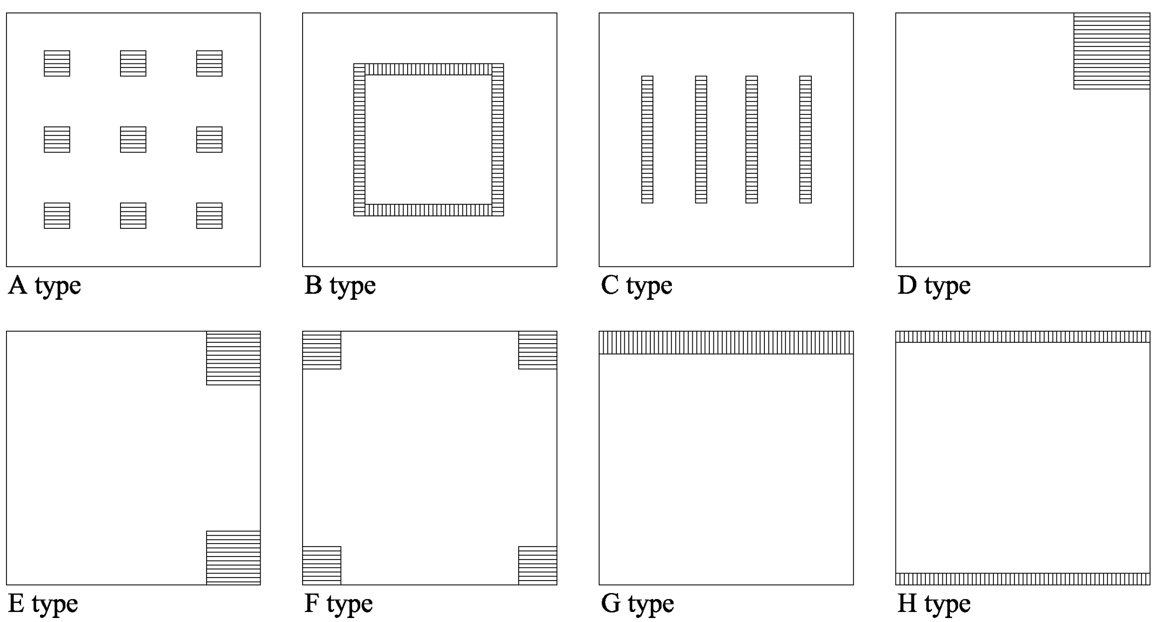


Figure 6.11: Different types of grille distribution.

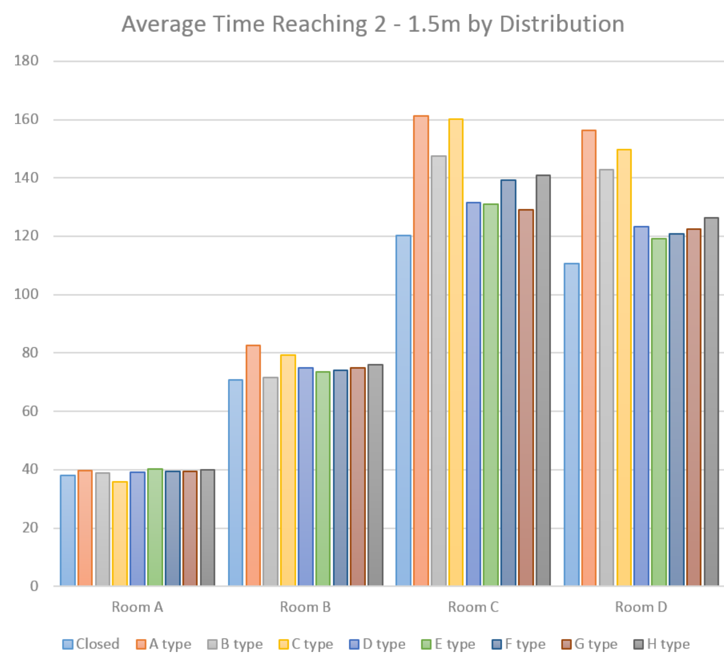


Figure 6.12: Simulation results by distribution type.

6.2.4 Plenum Height

Plenum height also affects smoke propagation. CFAST simulations showed that the higher the plenum space, the longer it takes for smoke to propagate to the next room. To cross-validate and to more precisely investigate the effect of different plenum height on smoke propagation, a set of models with different plenum height were simulated using FDS. Figure 6.13 shows the section of the simulation models. The ceiling height remains at 2.8m while the plenum height H varies in each model. There are total of nine models with the lowest plenum height at 0.2m, increment of 0.1m, and the highest plenum height of 1.0 m. In other words, the floor height of the models changes 0.1m incrementally. Floor height is usually decided by many other important design factors, such as construction costs, building codes, mechanical systems, the quality of the space, etc. However, theses simulations are for pure research purposes of investigating the relation between plenum height and smoke propagation.

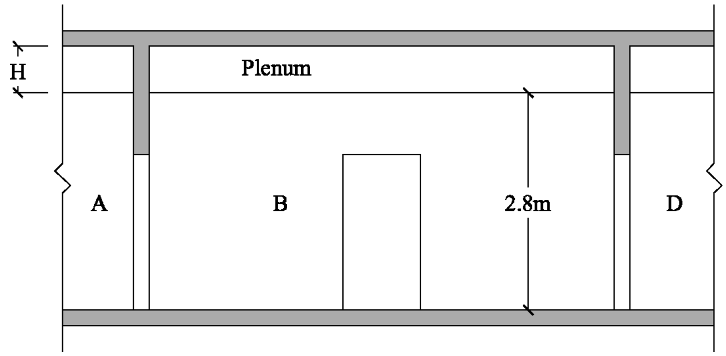


Figure 6.13: Plenum height.

Simulation results show that plenum height has little influence on room A and B (figure 6.14). On the other hand, in the rooms further away from the fire source, room C and D, the time for smoke to reach the 2-1.5m zone is almost linearly proportional to the plenum height.

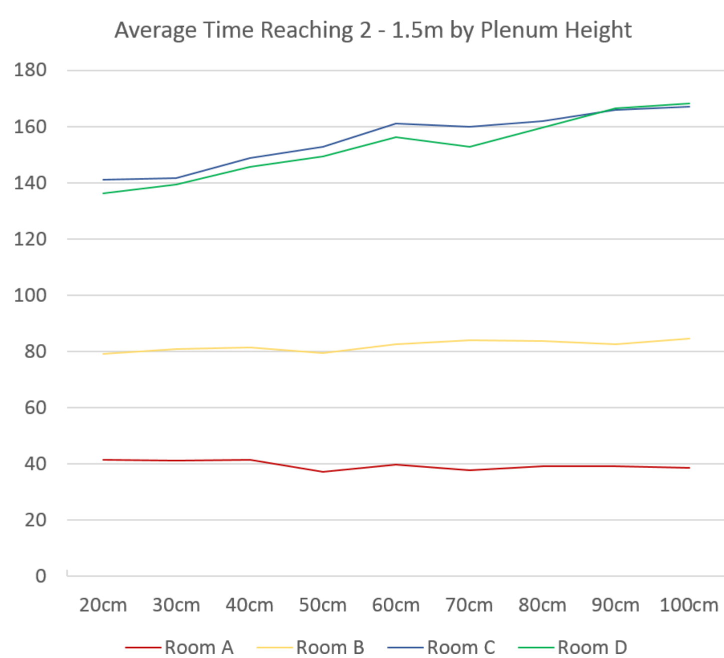


Figure 6.14: Simulation results by plenum height.

6.2.5 Door Height

Door height can affect smoke propagation. CFAST simulations showed that the higher the doors, the faster smoke propagates to the next room. To cross-validate and to more precisely investigate how door height influences smoke propagation, a set of models with various door height were simulated using FDS. There are total of 11 models with the lowest door height at 1.8m, increment of 0.1m, and the highest door height of 2.8m. The simulation results show that smoke propagation time is almost linearly proportional to door height except for the fire of origin (figure 6.15).

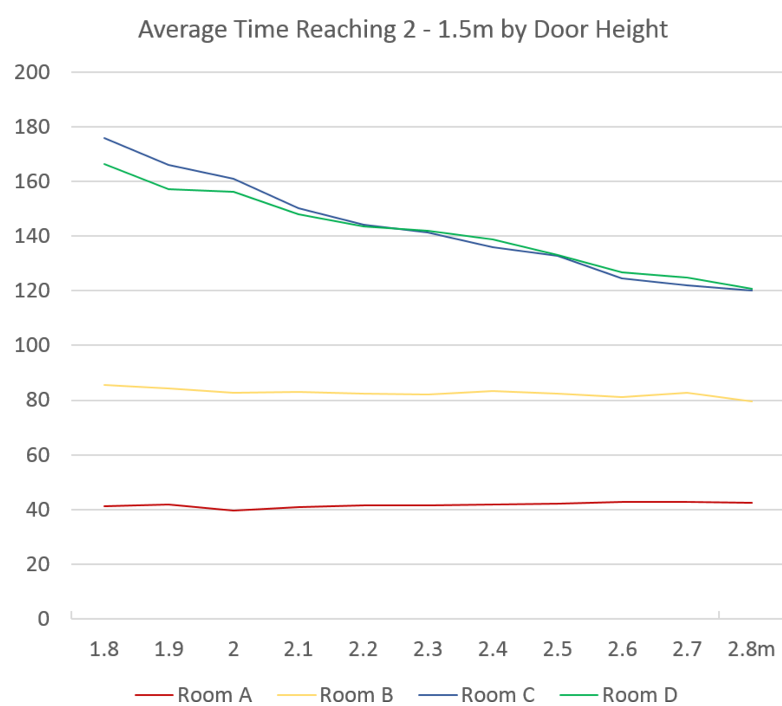


Figure 6.15: Simulation results by door height.

6.3 Summary of the Findings

As identified in CFAST simulations, FDS simulations also confirmed that ceiling design and door design affect smoke propagation. FDS simulations provided more precise insight on how opening ratio, opening size, opening distribution, plenum height, and door height affect smoke propagation.

- Opening 16-50% of the ceiling has the maximum smoke delaying effect which can delay smoke propagation time up to 60%.
- The size of the openings has little influence on smoke propagation when the openings are evenly distributed and the total area remains constant.
- Different opening distributions have different smoke propagation time. Evenly distributed openings are likely to have better smoke delaying effect. To confirm and generalize this claim, more extensive simulation data are needed.
- The higher the plenum space, the longer the smoke propagation time. The relation between plenum height and smoke propagation time is approximately linear.
- The higher the doors, the shorter the smoke propagation time. The relation between door height and smoke propagation time is approximately linear.

This section presents examples that simulations can discover new knowledge which building codes have not yet captured. If building smoke propagation simulation is integrated into design process in the future, I believe that designers will be able to apply creativity to the problems of smoke propagation and discover new solutions.

7. CONCLUSION

A new software system architecture has been designed to incorporate smoke propagation and evacuation simulation into BIM. The incompatibility between smoke propagation simulation models, which use simplified building representations, and BIM, which use complex and complete building representations, is arguably the primary challenge of the integration. This research developed a set of algorithms that overcome the incompatibility issue and thus enable designers to perform smoke propagation simulation directly on a BIM model. To demonstrate the integration of smoke propagation simulation and BIM, a software prototype was developed using C# and the Revit API. The prototype allows architects with little prior knowledge of smoke propagation simulation or CFAST user interface to perform smoke propagation simulation on a Revit model in a few minutes. The visualization module shows how smoke propagates from one room to another, which helps architects to better understand fire safety.

A simple multi-agent evacuation simulation model was developed using C# and Revit API to provide architects with more informative feedback. As the default setting, the agents evacuate through the shortest egress paths. At each simulation step, each agent collects the data of the surrounding environment, such as CO concentration, which is stored in the CFAST simulation results. At the end of the simulation, the software reports the collected data about the agents as graphs. Architects can quantitatively evaluate fire safety of their design based on the graphs. The evacuation results also can be visualized as an animation which aids in visual inspection of the bottlenecks and flawed circulation design. The evacuation simulation model provides more intuitive feedback to designers compared to smoke propagation simulation alone.

The validity of the algorithms was tested by FDS simulations and CFAST simulations.

The validation tests showed that the transformation algorithms introduced 5-10% of error in the majority of the test cases, and the room selection algorithm introduced 2-7% of error. A few extreme test cases (shed models) showed more than 10% of error.

Several pieces of new knowledge were found while performing smoke propagation simulation in CFAST related to how ceiling design and door design affect fire safety. To prove this finding and codify precise effects of ceiling design and door design on fire safety, a series of FDS simulations were performed as experiments. The test simulation showed that opening 16-25% of the ceiling can slow down smoke propagation speed up to 60%. The smoke deterring effect diminishes as the opening ratio increases to more than 50%. Besides opening ratio, the distribution of the opening and door height also affect smoke propagation speed.

7.1 Contributions of the Research

The system architecture developed in this research allows seamless data flow from BIM to smoke propagation simulation and evacuation simulation. The new system architecture not only automated majority of the simulation workloads that have been done manually until now, but also provides architects a user-friendly platform to perform smoke propagation simulation without understanding the details and specialized knowledge required by the simulation tools.

The simplified building definition used in zone models reduces practicality of simulating real-world buildings. CFD models reduce practicality due to extremely long running time. Both zone models and CFD models place a heavy burden on architects and other building designers to understand complex tools and interfaces, arguably dissuading the use of smoke propagation simulation in architectural design. The integration achieved in this research overcomes the issues of complexity of shapes and simulation time. In other words, the algorithms enabled the simulation of complex real-world buildings within a short amount of time. Through extensive validations tests, the algorithms are proven to be accurate within a small margin of error. Although the software prototype developed in this research used Revit and CFAST in specific, the algorithms can be generalized to other zone models and BIM authoring applications. CFD models may also be incorporated into a system using similar techniques, and could become practical if processing power becomes more available.

This research provided insights on how ceiling and door design affect building fire safety. 1). Opening 16-25% of the ceiling can deter smoke propagation up to 60%. 2). Smoke deterring effect is better when the openings are evenly distributed. 3). Shorter doors decrease smoke propagation speed. These findings need further validation tests with different approaches so that they can be reliable to provide architects rules of thumb in designing ceilings and doors. The advantage of these rules of thumb is that architects can improve the fire safety of their design by applying the rules without the need of running any smoke propagation simulation. The integration of smoke propagation simulation and BIM provides a platform for designers and researchers to discover more new knowledge through fire simulation. The ability to find new knowledge through simulation is not limited to ceiling and door design.

In practical aspect, integrating smoke propagation simulation into architectural design process helps designers to easily perform smoke propagation simulation with little prior knowledge about smoke propagation simulation and the user interface of the simulation tools. By enabling architects to visually examine their design, it also helps architects to better understand smoke propagation and increase their tacit judgment about safety in buildings. Ultimately, the integrated system provides architects with a new tool to help them make data-driven design decisions and tacit understating, and thus improve the fire safety of their design.

In educational aspect, the integrated system helps architecture students to better understand building fire safety. By incorporating a simulation tool into a design tool, it provides students with a visual and straightforward way of learning building fire safety, complementing knowledge obtained by reading books and articles.

Lastly, a minor contribution of this study is the results of the FDS resolution tests. Setting the simulation resolution in FDS is a trade-off between accuracy and simulation time. The results of the resolution tests conducted in this study serve as a guideline for setting appropriate resolution when running FDS simulations.

7.2 Limitations

The primary limitation of this research is the degree of accuracy of the algorithms. The algorithms used in this research introduce some amount of error. Validation tests of the algorithms were conducted using FDS simulation and CFAST simulation which are also not perfectly accurate compared to physical experiments. The amount of error is likely to accumulate at each step of selecting 30 rooms, transforming the shape of the rooms, and validating the algorithms. If each step has small enough error, the combined error will have an acceptable upper limit.

7.3 Future work

The integrated system developed in this dissertation provides architects with rapid design feedback. The interpretation of the simulation results and the optimization of the design are left to the architects. Further studies are needed to improve the integrated system such that it provides optimization suggestions to architects based on the simulation results. This can help architects to focus on more important design decisions.

The integrated system is designed to perform an individual run for each room of fire origin. To better understand the fire safety of a design, multiple simulation runs should be performed with the fire origin set to a different room each time. Currently, it is up to designers to gather the simulation results of each individual runs and analyze the simulation results. Running multiple simulations automatically by setting different room of fire origin each time for all rooms would be a good feature to implement in the future. This can provide designers with more useful feedback while reducing manual workload.

In the validation tests, the shed models generated disconcertingly large differences between the models before and after the transformation. Conducting more extensive tests with more target parameters to pinpoint the reason that caused errors in the shed models would be another valuable work to do in the future. This may help to identify other factors that affect the error rate of the transformation algorithms.

In CFAST, fire spread from one object to another is prescribed by the user, not by a computer model. Prescribing fire is difficult and has a great impact on the accuracy of smoke propagation simulation depending on how well the virtual fire matches the actual fire. Creating a fire spread model in the future can increase simulation accuracy and reduce manual work.

Rooms can be separated physically by walls or virtually by their functions. For example, a lobby and a corridor are often separated by a virtual surface, not necessarily by a wall. In this case, the virtual surface should be considered as a type of connection that allows smoke propagation between the two rooms. Currently, ToFAST recognizes doors as the only type of connection between two rooms. Virtual surfaces, defined as room separator in Revit, need to be recognized as a type of connection between the rooms in ToFAST. In addition, wall openings also need to be added as a type of connection between two rooms.

The integrated system assumes that all walls extend to the slab of the upper floor. In reality, walls may stop at a ceiling or even below a ceiling. How these walls impact smoke propagation needs to be investigated in the future. Furthermore, new algorithms are needed to account for the rooms with walls that do not extend to the slab of the upper floor.

The current version of ToFAST by default assumes that all doors are open in a building fire. CFAST provides the functionalities of setting the state of each door to closed, open, partially open, or open after certain period of time. A user interface to set door state needs to be added to ToFAST in the future.

This dissertation focused on the smoke propagation of building fires with respect to the spatial configuration of building design. To improve simulation accuracy, HVAC systems, pressurized stairwell, fire doors, and many other fire safety related features need to be studied carefully.

The room selection algorithm used in the integrated system selects rooms based on smoke travel distance. Other selection algorithms, such as eliminating the least influential rooms, should be studied and compared to the current selection algorithm.

Integration of smoke propagation coupled with building evacuation into a Building Information Model can potentially change design processes and practices in a significant way. Future designers may well model these aspects of building performance as a routine of their services and deliberations.

REFERENCES

[1] "World fire statistics centre bulletin vol. 28." `https://www.genevaassociation.org/media/186703/ga2012-fire28.pdf`. Accessed: 2014-05-10.

[2] M. Clayton, P. Fudge, and J. Thompson, "Automated plan review for building code compliance using bim," in *Proceedings of 20th International Workshop: Intelligent Computing in Engineering (EG-ICE 2013)*, pp. 1–10, 2013.

[3] "eplan soutions: plan review software for goverment." `https://eplansoft.com/products/eplan/`. Accessed: 2017-08-10.

[4] F. D. Ching and S. R. Winkel, *Building codes illustrated: a guide to understanding the 2012 International Building Code*, vol. 6. John Wiley & Sons, 2012.

[5] "Civilian fire fatalities in residential buildings (20092011)." `https://nfa.usfa.fema.gov/downloads/pdf/statistics/v14i2.pdf`. Accessed: 2017-08-10.

[6] J. B. Terrill, R. R. Montgomery, and C. F. Reinhardt, "Toxic gases from fires," *Science*, vol. 200, no. 4348, pp. 1343–1347, 1978.

[7] G. Tunstall, *Managing the building design process*. Routledge, 2006.

[8] M. M. Birky, B. Halpin, Y. Caplan, R. S. Fisher, J. McAllister, and A. Dixon, "Fire fatality study," *Fire and Materials*, vol. 3, no. 4, pp. 211–217, 1979.

[9] W. K. Smith and J. B. King, "Surface temperatures of materials during radiant heating to ignition," *Journal of Fire and Flammability*, vol. 1, no. 4, pp. 272–288, 1970.

[10] T. Ohlemiller and M. Summerfield, “Radiative ignition of polymeric materials in oxygen/nitrogen mixtures,” in *Symposium on Combustion*, vol. 13, pp. 1087–1094, Elsevier, 1971.

[11] K. Kishore and K. M. Das, “Flammability index of polymeric materials,” *Colloid and Polymer Science*, vol. 258, no. 1, pp. 95–98, 1980.

[12] B. Moghtaderi, V. Novozhilov, D. Fletcher, and J. Kent, “A new correlation for bench-scale piloted ignition data of wood,” *Fire Safety Journal*, vol. 29, no. 1, pp. 41–59, 1997.

[13] J. R. Lawson, W. D. Walton, and W. Twilley, “Fire performance of furnishings as measured in the nbs furniture calorimeter,” *NIST Interagency/Internal Report (NISTIR)*, 1984.

[14] V. Babrauskas and S. Grayson, *Heat release in fires.* Taylor & Francis, 1990.

[15] R. Buch, “Rates of heat release and related fire parameters for silicones,” *Fire Safety Journal*, vol. 17, no. 1, pp. 1–12, 1991.

[16] H. C. Tran and R. H. White, “Burning rate of solid wood measured in a heat release rate calorimeter,” *Fire and Materials*, vol. 16, no. 4, pp. 197–206, 1992.

[17] T. Harada, “Time to ignition, heat release rate and fire endurance time of wood in cone calorimeter test,” *Fire and Materials*, vol. 25, no. 4, pp. 161–167, 2001.

[18] W. Chow and C. Leung, “Survey on partition walls commonly used in hong kong and estimation of the heat release rates during fire,” *Architectural Science Review*, vol. 44, no. 4, pp. 379–390, 2001.

[19] J. Zhu, A. B. Morgan, F. J. Lamelas, and C. A. Wilkie, “Fire properties of polystyrene-clay nanocomposites,” *Chemistry of Materials*, vol. 13, no. 10, pp. 3774–3780, 2001.

[20] A. Mouritz, Z. Mathys, and A. Gibson, "Heat release of polymer composites in fire," *Composites Part A: Applied Science and Manufacturing*, vol. 37, no. 7, pp. 1040–1054, 2006.

[21] W. Thornton, "The relation of oxygen to the heat of combustion of organic compounds," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 33, no. 194, pp. 196–203, 1917.

[22] C. Huggett, "Estimation of rate of heat release by means of oxygen consumption measurements," *Fire and Materials*, vol. 4, no. 2, pp. 61–65, 1980.

[23] M. L. Janssens, "Measuring rate of heat release by oxygen consumption," *Fire Technology*, vol. 27, no. 3, pp. 234–249, 1991.

[24] D. Larson and R. Viskanta, "Transient combined laminar free convection and radiation in a rectangular enclosure," *Journal of Fluid Mechanics*, vol. 78, no. 1, pp. 65–85, 1976.

[25] J. Quintiere, "Growth of fire in building compartments," in *Fire Standards and Safety*, ASTM International, 1976.

[26] J. G. Quintiere and M. T. Harkleroad, "New concepts for measuring flame spread properties," in *Fire Safety: Science and Engineering*, ASTM International, 1985.

[27] Y. Hasemi, "Thermal modeling of upward wall flame spread," *Fire Safety Science*, vol. 1, pp. 87–96, 1986.

[28] N. Cheney and J. Gould, "Fire growth and acceleration," *International Journal of Wildland Fire*, vol. 7, no. 1, pp. 1–5, 1997.

[29] F. M. Esposito and Y. Alarie, "Inhalation toxicity of carbon monoxide and hydrogen cyanide gases released during the thermal decomposition of polymers," *Journal of Fire Sciences*, vol. 6, no. 3, pp. 195–242, 1988.

[30] T. E. Bernard and J. Duker, “Modeling carbon monoxide uptake during work,” *The American Industrial Hygiene Association Journal*, vol. 42, no. 5, pp. 361–364, 1981.

[31] Y. Alarie, “Toxicity of fire smoke,” *Critical Reviews in Toxicology*, vol. 32, no. 4, pp. 259–289, 2002.

[32] E. E. Zukoski and T. Kubota, “Two-layer modeling of smoke movement in building fires,” *Fire and Materials*, vol. 4, no. 1, pp. 17–27, 1980.

[33] A. Hokugo, D. Yung, and G. V. Hadjisophocleous, “Experiments to validate the nrcc smoke movement model for fire risk-cost assessment,” *Fire Safety Science*, vol. 4, pp. 805–816, 1994.

[34] Y. He and V. Beck, “Smoke spread experiment in a multi-storey building and computer modelling,” *Fire Safety Journal*, vol. 28, no. 2, pp. 139–164, 1997.

[35] “Kobra3d: a cfd model.” `http://www.ist-net.de/kobra-3d/`. Accessed: 2017-08-10.

[36] “Smartfire introduction.” `https://fseg.gre.ac.uk/smartfire/`. Accessed: 2017-08-10.

[37] R. D. Peacock, P. A. Reneke, and G. P. Forney, *CFAST-consolidated model of fire growth and smoke transport (version 6) user’s guide*. NIST, 2012.

[38] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt, “Fire dynamics simulator user’s guide,” *NIST Special Publication*, vol. 1019, p. 6thEdition, 2013.

[39] “Third party software for fds simulation.” `https://github.com/firemodels/fds-smv`. Accessed: 2017-08-10.

[40] M. Salley and R. Kassawara, “Verification and validation of selected fire models for nuclear power plant applications,” tech. rep., U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, 2007.

[41] J. Bailey and P. Tatem, “Validation of fire/ smoke spread model (cfast) using ex-uss shadwell internal ship conflagration control (iscc) fire tests,” tech. rep., Naval Research Lab, 1995.

[42] R. D. Peacock, W. W. Jones, and R. W. Bukowski, “Verification of a model of fire and smoke transport,” *Fire Safety Journal*, vol. 21, no. 2, pp. 89–129, 1993.

[43] J. Bailey, G. P. Forney, P. Tatem, and W. W. Jones, “Development and validation of corridor flow submodel for cfast,” *Journal of Fire Protection Engineering*, vol. 12, no. 3, pp. 139–161, 2002.

[44] W. W. Jones and G. P. Forney, “Improvement in predicting smoke movement in compartmented structures,” *Fire Safety Journal*, vol. 21, no. 4, pp. 269–297, 1993.

[45] “Fds validation reports.” `https://drive.google.com/folderview?id=0B-EZ4HlrI6VDT2R5SjNFOGtIdTg&usp=sharing#list`. Accessed: 2017-08-10.

[46] NBIMS, “Frequently asked questions about the national bim standard.”

[47] C. Wu, S. Zarrinmehr, M. R. Asl, and M. J. Clayton, “Facilitating fire and smoke simulation using building information modeling,” in *International Conference on Computer-Aided Architectural Design Futures*, pp. 366–382, Springer, 2015.

[48] M. R. Asl, S. Zarrinmehr, M. Bergin, and W. Yan, “Bpopt: a framework for bim-based performance optimization,” *Energy and Buildings*, vol. 108, pp. 401–412, 2015.

[49] C. Wu and M. Clayton, "Bim-based acoustic simulation framework," in *30th CIB W78 International Conference*, 2013.

[50] A. Monteiro and J. P. Martins, "A survey on modeling guidelines for quantity takeoff-oriented bim-based design," *Automation in Construction*, vol. 35, pp. 238–253, 2013.

[51] B. Becerik-Gerber and S. Rice, "The perceived value of building information modeling in the us building industry," *Journal of Information Technology in Construction (ITcon)*, vol. 15, no. 15, pp. 185–201, 2010.

[52] S. A. Jones and H. M. Benstein, "The business value of bim in north america: multi-year trend analysis and user ratings (20072012)," tech. rep., McGraw-Hill Construction, 2012.

[53] J. L. Hennessy and D. A. Patterson, *Computer architecture: a quantitative approach*. Elsevier, 2011.

[54] E. Dijkstra, "A note on two problems in connection with graphs," 1959.

[55] O. B. Bayazit, J.-M. Lien, and N. M. Amato, "Better group behaviors in complex environments using global roadmaps," *Artificial Life 8*, vol. 8, p. 362, 2003.

[56] A. Johnson, "Clipper: an open source freeware library for clipping and offsetting lines and polygons." `http://www.angusj.com/delphi/clipper.php`. Accessed: 2017-08-10.

[57] "Optimal reciprocal collision avoidance." `http://gamma.cs.unc.edu/ORCA/`. Accessed: 2017-08-10.

[58] "Fds user manual." `https://github.com/firemodels/fds/releases/download/FDS6.5.3/FDS_User_Guide.pdf`. Accessed: 2017-09-29.

[59] C. Wu, K. Xing, and M. Clayton, "Fire propagation simulation for large buildings in cfast: using bim to facilitate simulation process," in *13th International Conference on Design and Decision Support Systems in Architecture and Urban Planning*, 2016.

[60] R. Newbold, "Some social and economic consequences of the ad 64 fire at rome," *Latomus*, vol. 33, no. Fasc. 4, pp. 858–869, 1974.

[61] R. Porter, "Cleaning up the great wen: public health in eighteenth-century london," *Medical History*, no. 11, p. 61, 1991.

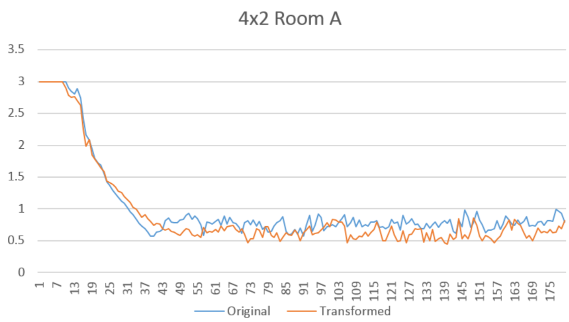
[62] J. Arnold, *Large building fires and subsequent code changes*. Clark County Department of Development Services, Building Division, 2005.

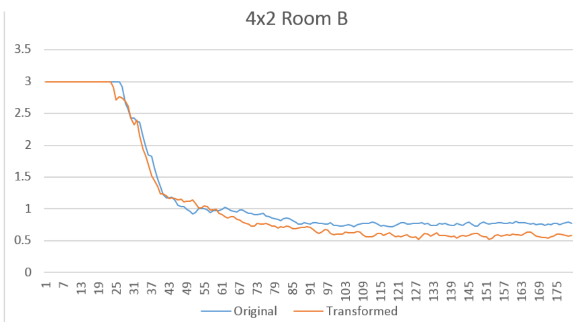
APPENDIX A

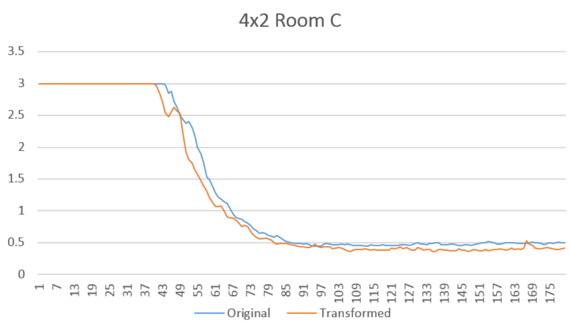
VALIDATION TEST RESULTS FOR THE TRANSFORMATION ALGORITHMS

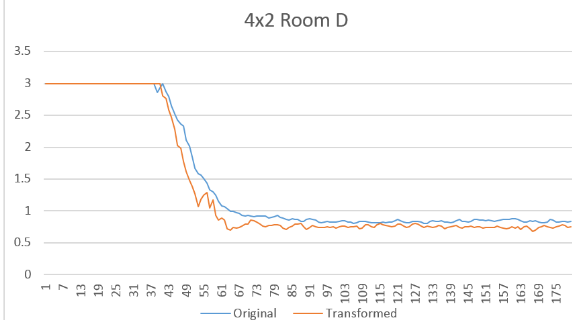
To investigate the validity of the transformation algorithms, a set of validation tests have been performed. The models used in the validation tests include variety of non-cuboid shape general rooms and corridors. These non-cuboid models were simulated using FDS. Then, the models are transformed using the transformation algorithms, and simulated using FDS. The results of the validation tests, before and after the transformation, were compared and visualized with graphs. In each of the following graphs, X axis shows the simulation time in seconds and Y axis shows the smoke height in meters. The smoke height is calculated by averaging the sensor data in the room. Cyan lines denote the simulation results of the original models, and the orange lines denote the simulation results of the transformed models. The gap between the lines can be interpreted as the error introduced by transforming the shape using the transformation algorithms. The details of the simulation results are shown in the following figures.

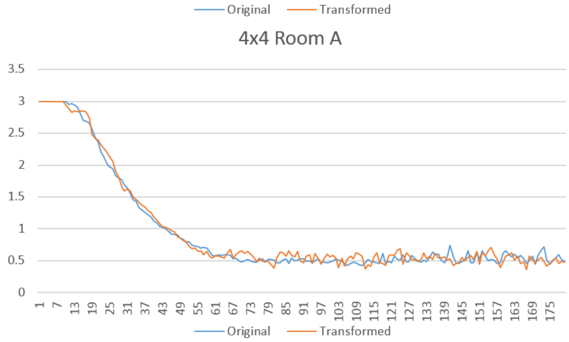
A.1 Shoe Shape Models

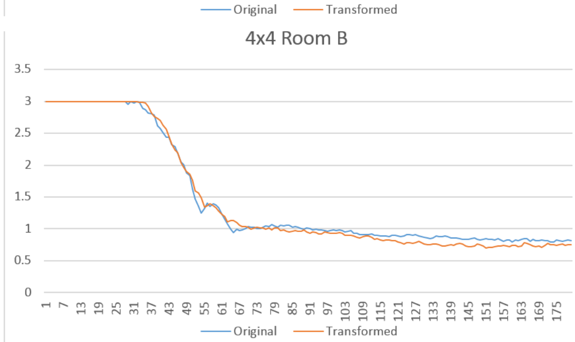


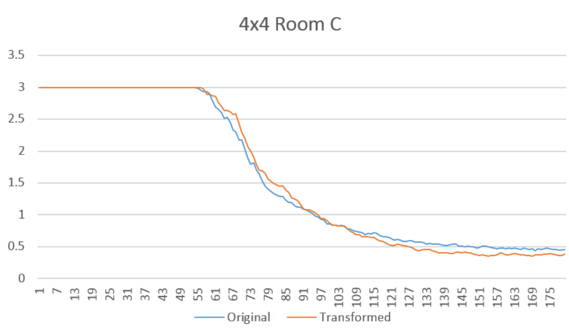


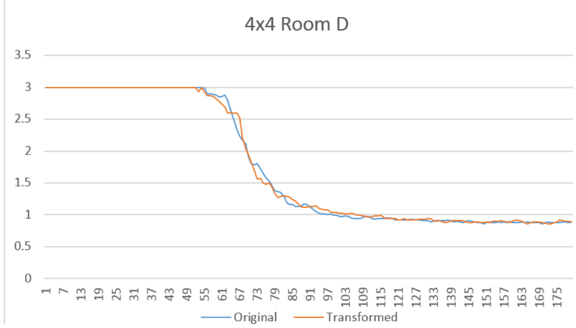




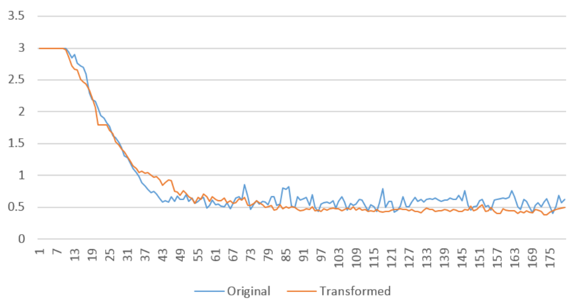




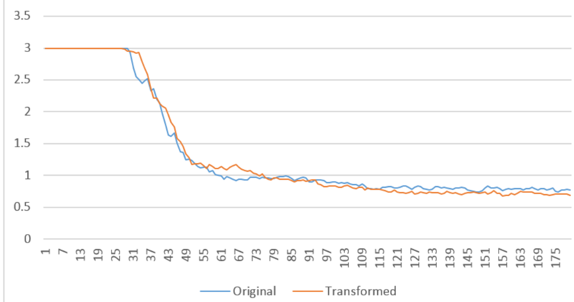




6x2 Room A

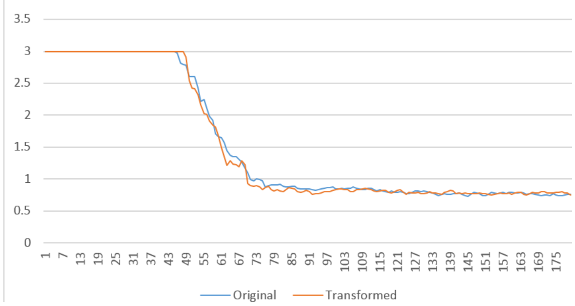


6x2 Room B

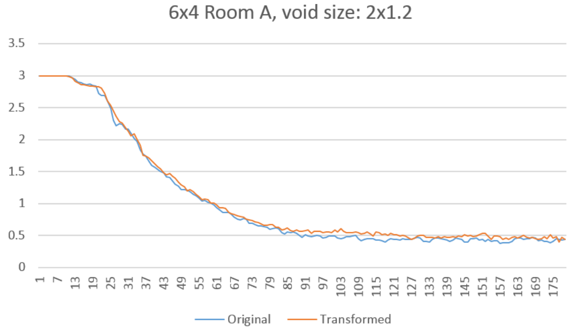


6x2 Room C

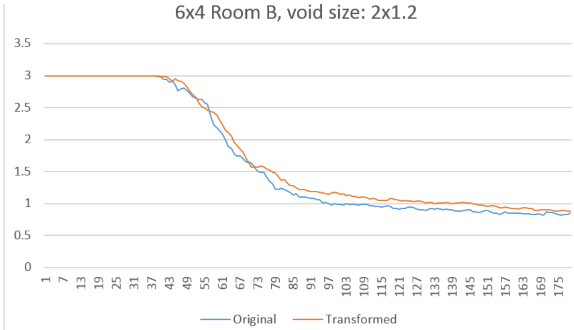
6x2 Room D



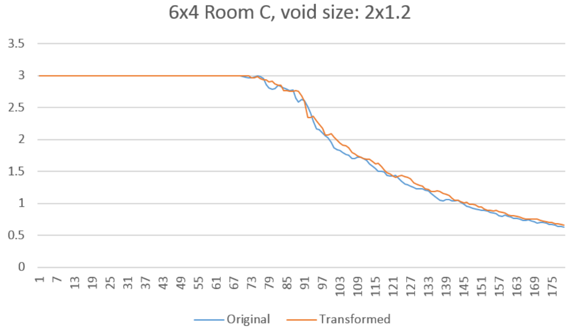
6x4 Room A, void size: 2x1.2



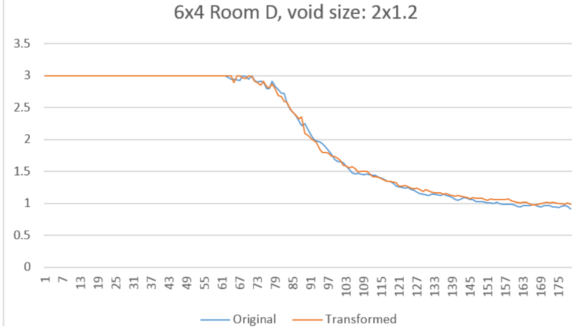
6x4 Room B, void size: 2x1.2

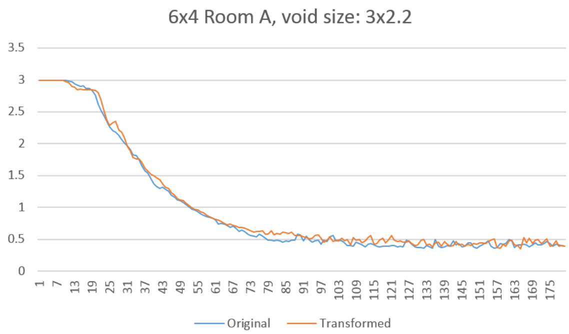


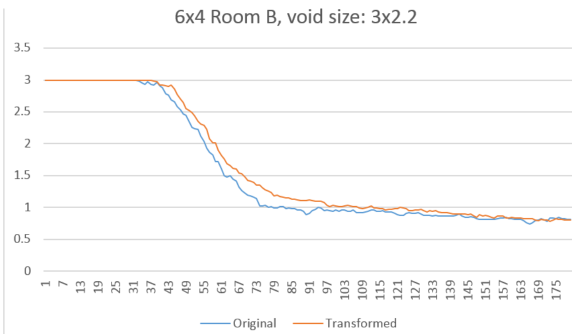
6x4 Room C, void size: 2x1.2

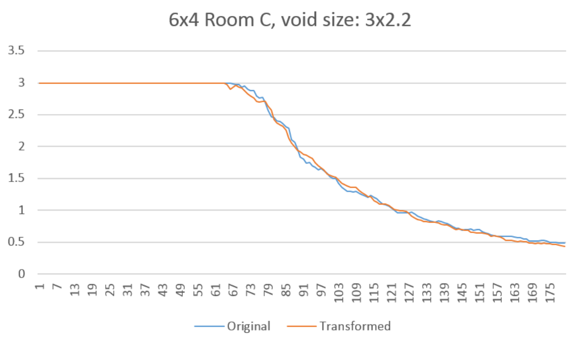


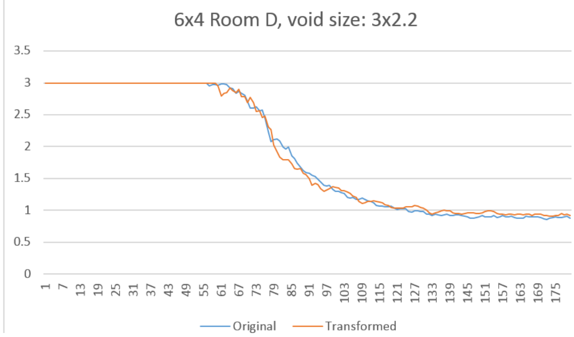
6x4 Room D, void size: 2x1.2

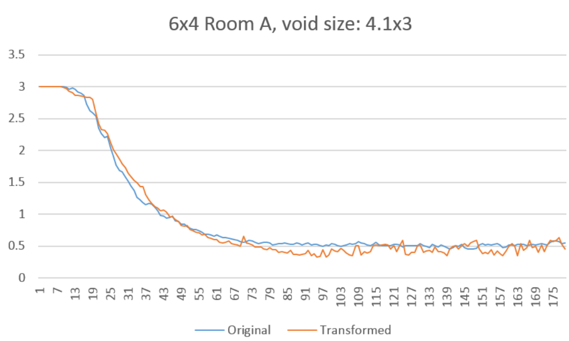


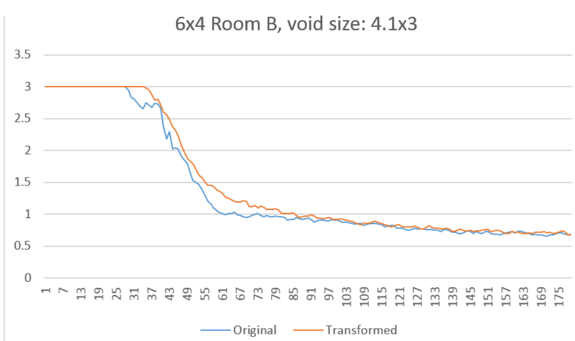

6x4 Room A, void size: 3x2.2
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

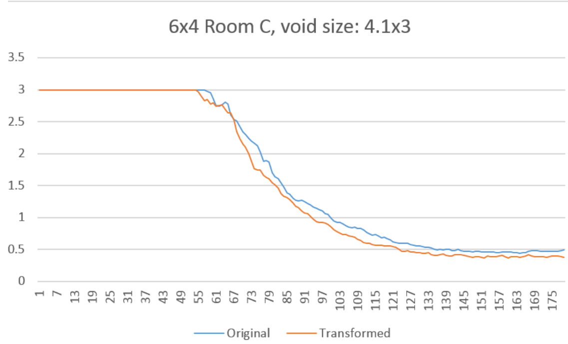

6x4 Room B, void size: 3x2.2
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

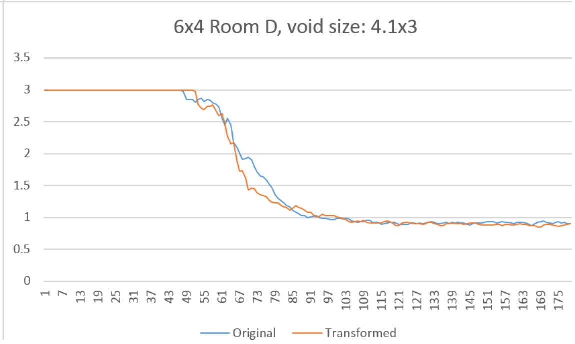

6x4 Room C, void size: 3x2.2
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

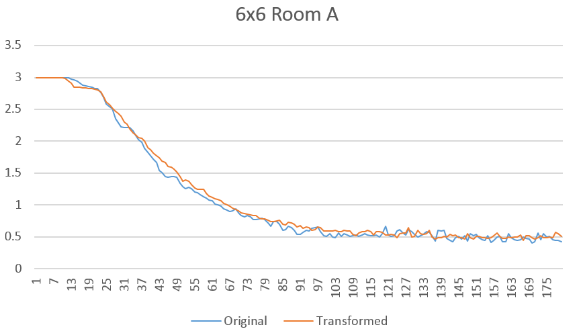

6x4 Room D, void size: 3x2.2
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

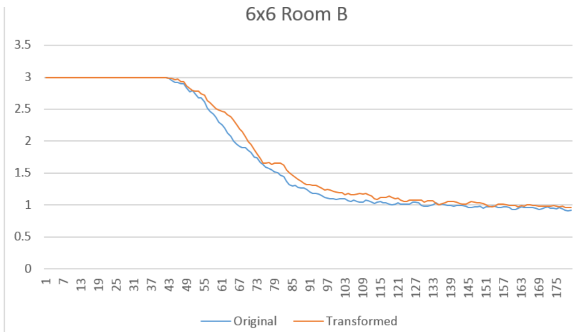

6x4 Room A, void size: 4.1x3
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

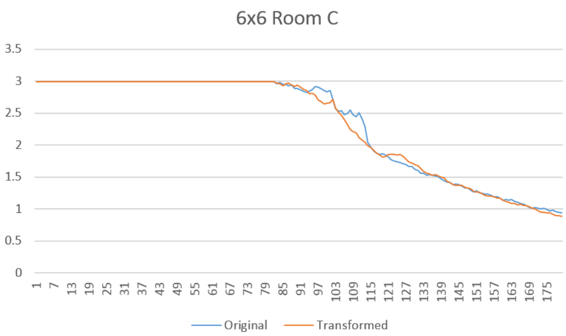

6x4 Room B, void size: 4.1x3
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

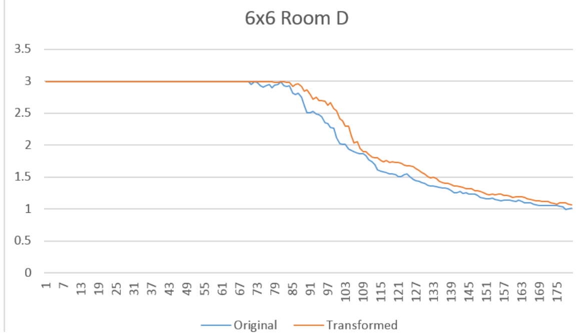

6x4 Room C, void size: 4.1x3
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

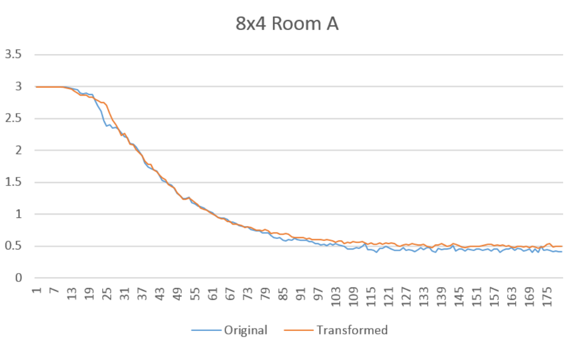

6x4 Room D, void size: 4.1x3
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

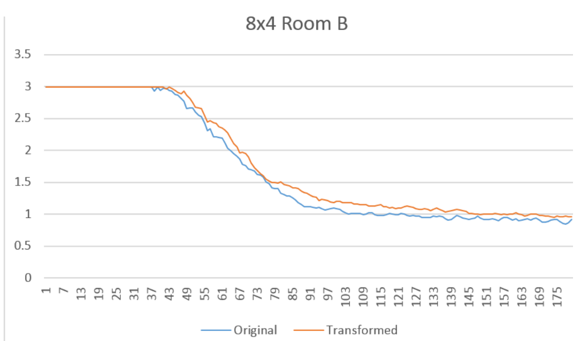

6x6 Room A
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

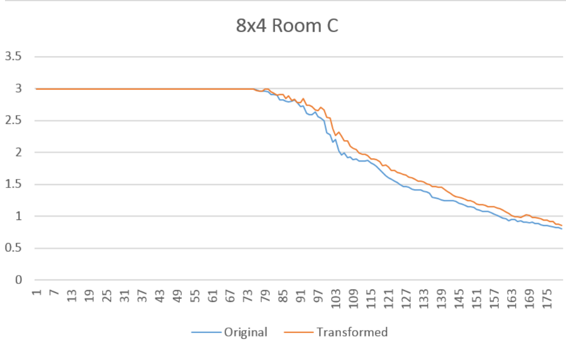

6x6 Room B
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

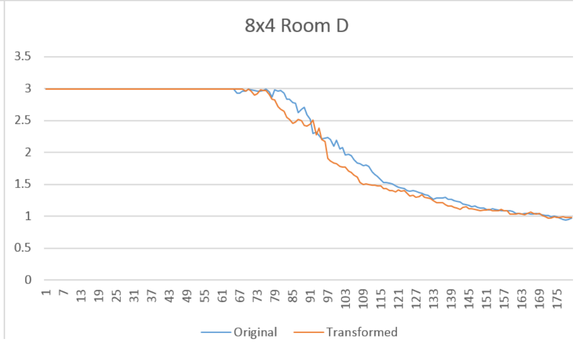

6x6 Room C
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

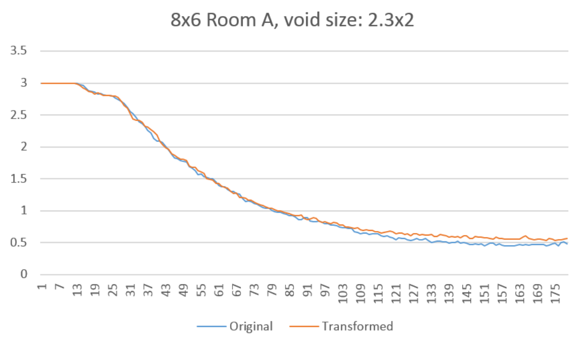

6x6 Room D
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

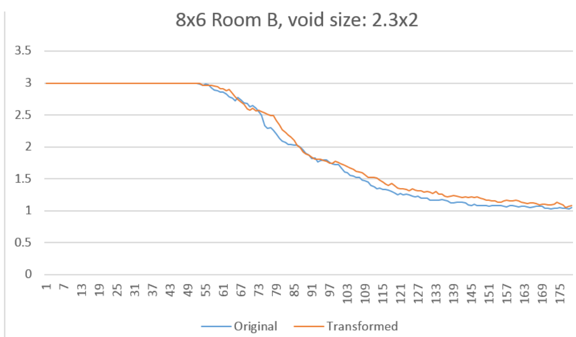

8x4 Room A
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

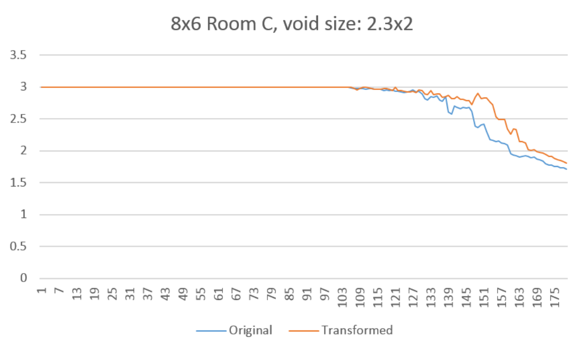

8x4 Room B
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

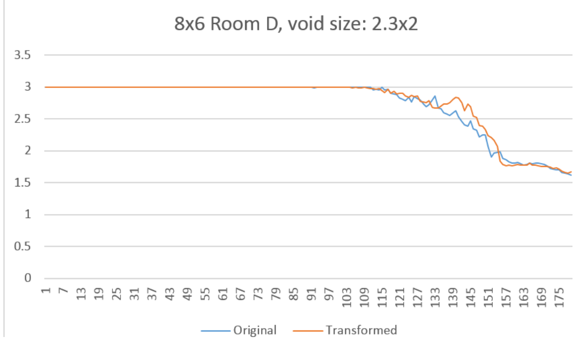

8x4 Room C
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

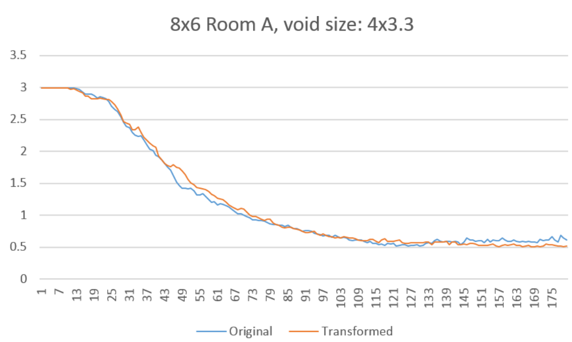

8x4 Room D
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

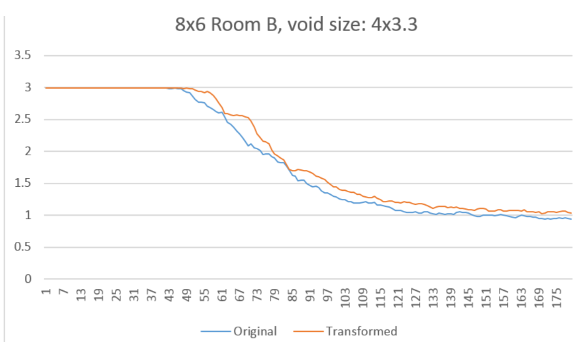

8x6 Room A, void size: 2.3x2
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

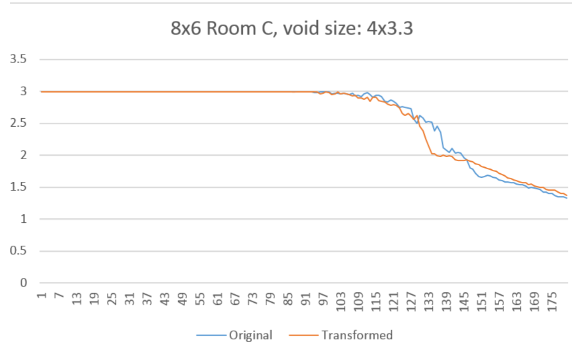

8x6 Room B, void size: 2.3x2
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

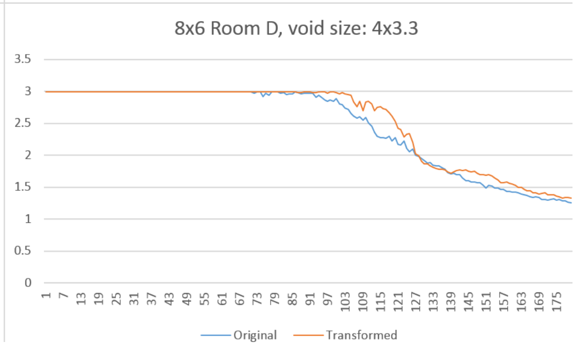

8x6 Room C, void size: 2.3x2
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

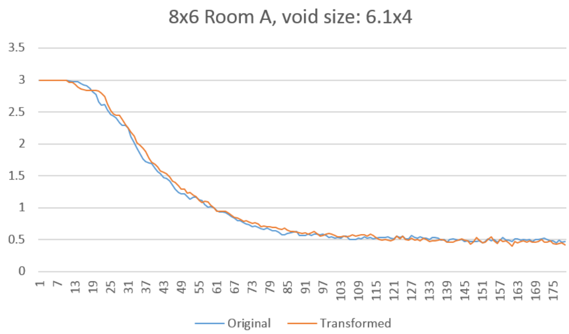

8x6 Room D, void size: 2.3x2
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

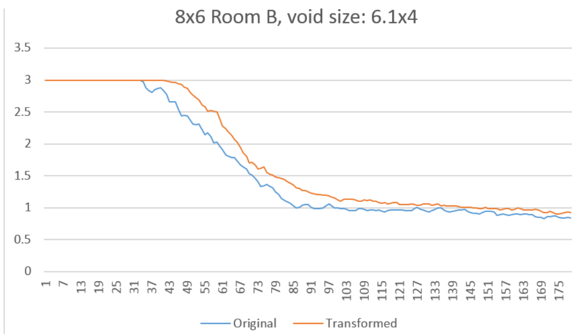

8x6 Room A, void size: 4x3.3
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

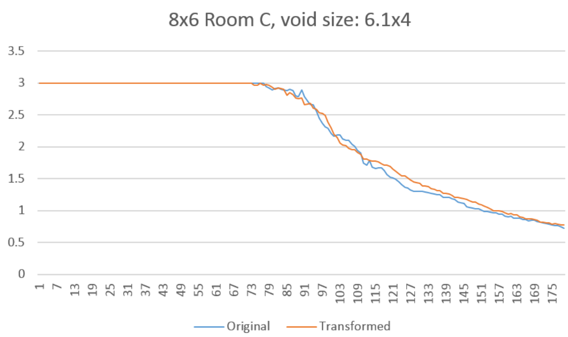

8x6 Room B, void size: 4x3.3
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

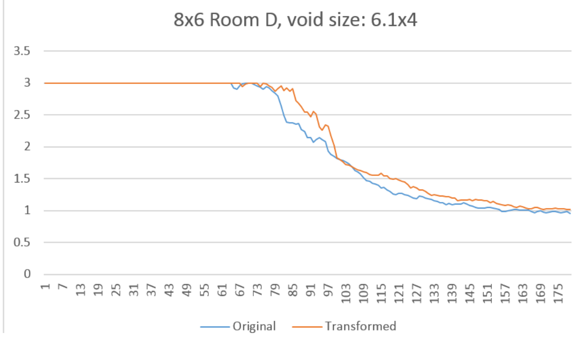

8x6 Room C, void size: 4x3.3
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

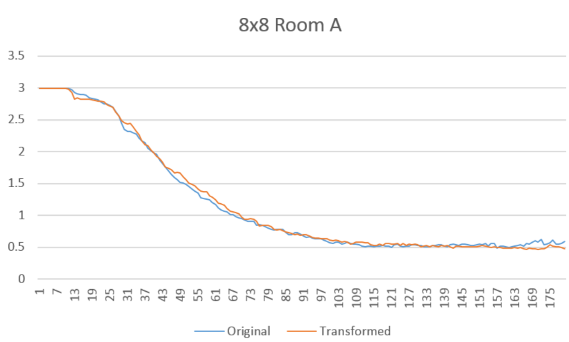

8x6 Room D, void size: 4x3.3
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

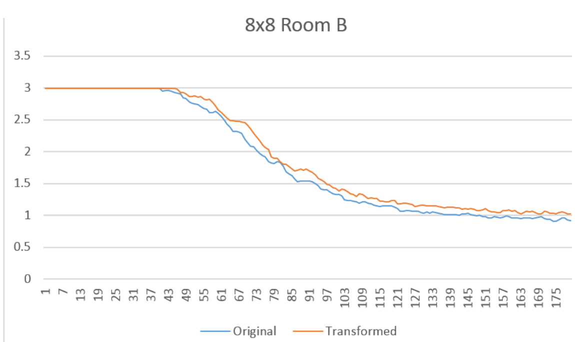

8x6 Room A, void size: 6.1x4
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

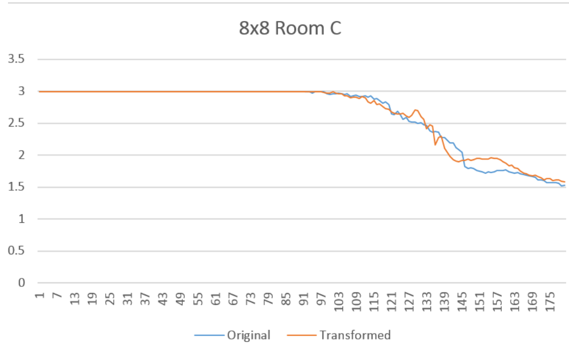

8x6 Room B, void size: 6.1x4
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

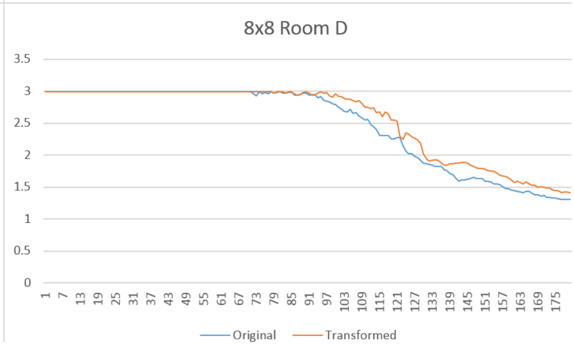

8x6 Room C, void size: 6.1x4
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

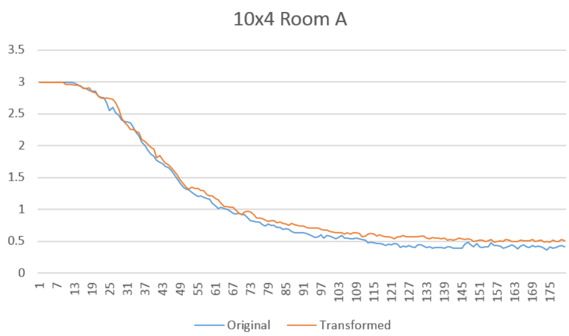

8x6 Room D, void size: 6.1x4
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

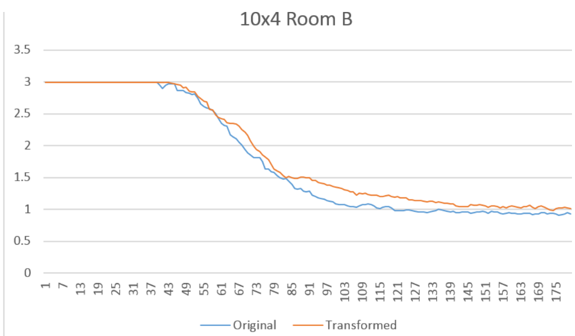

8x8 Room A
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

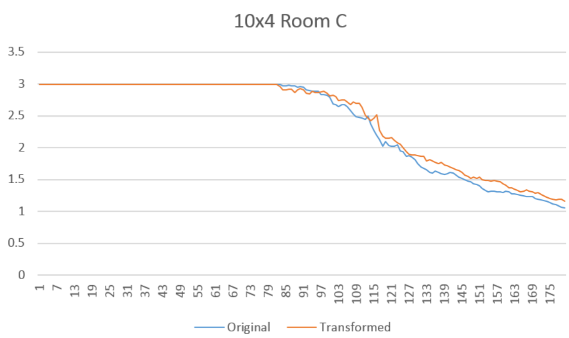

8x8 Room B
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

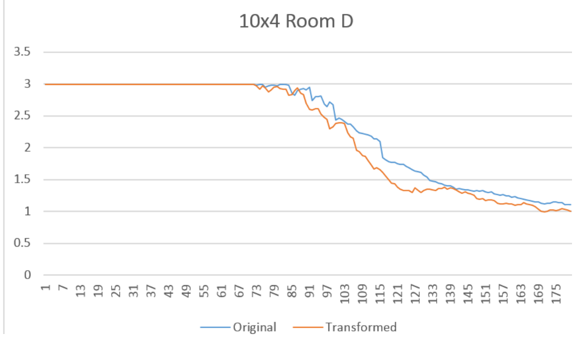

8x8 Room C
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

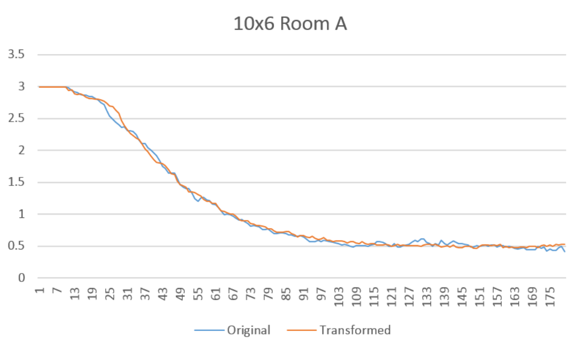

8x8 Room D
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

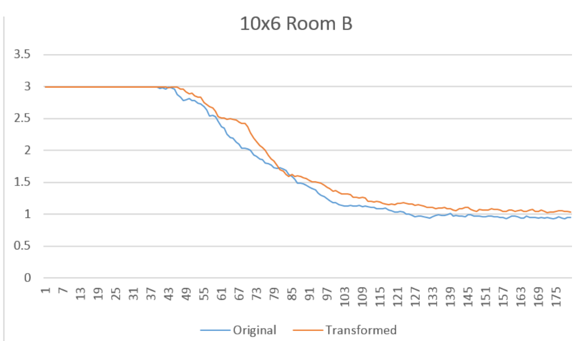

10x4 Room A
Original
Transformed

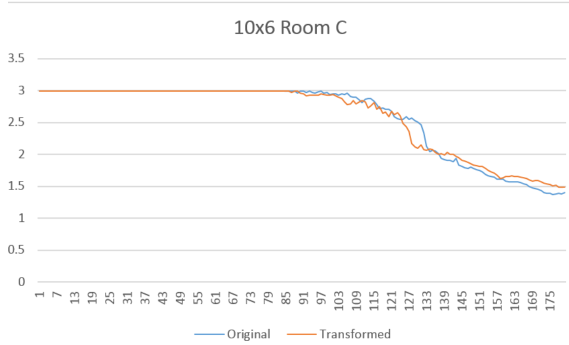

10x4 Room B
Original
Transformed

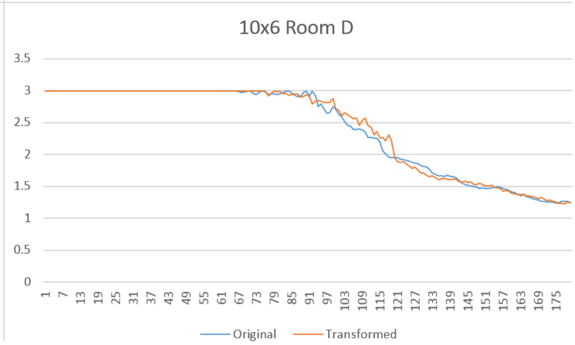

10x4 Room C
Original
Transformed

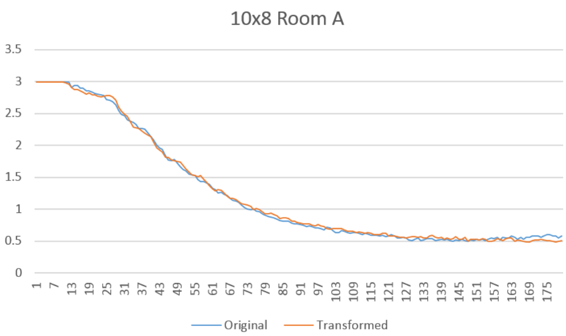

10x4 Room D
Original
Transformed

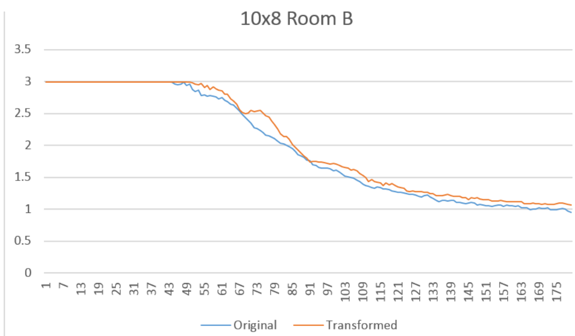

10x6 Room A
Original
Transformed

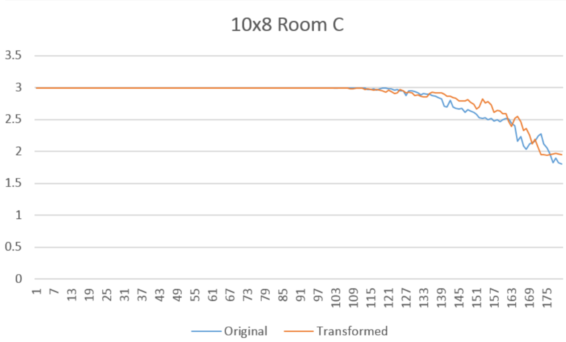

10x6 Room B
Original
Transformed

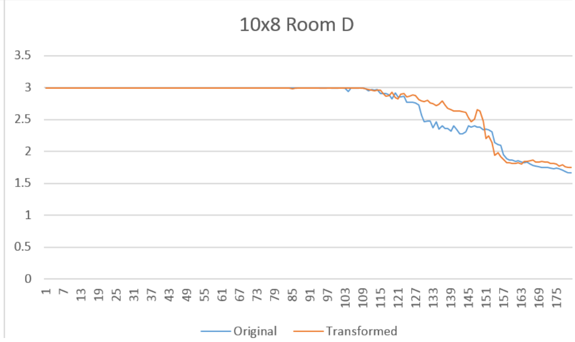

10x6 Room C
Original
Transformed

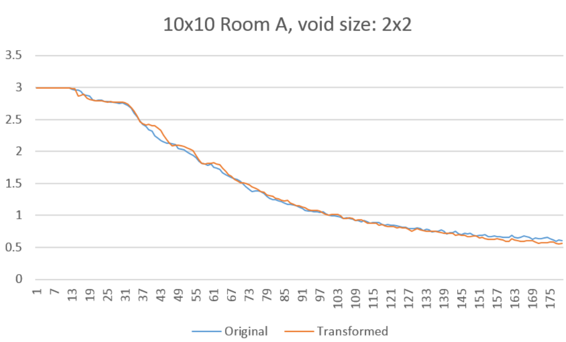

10x6 Room D
Original
Transformed

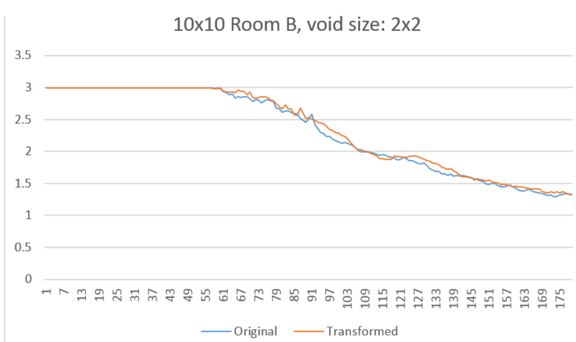

10x8 Room A
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

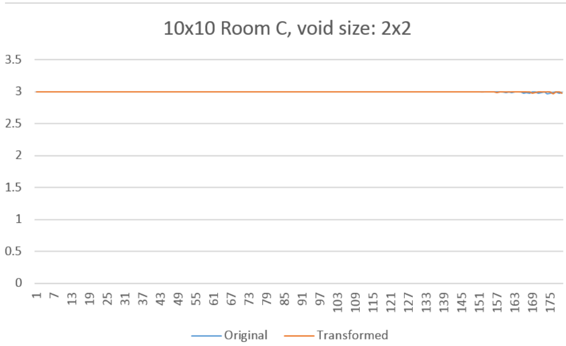

10x8 Room B
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

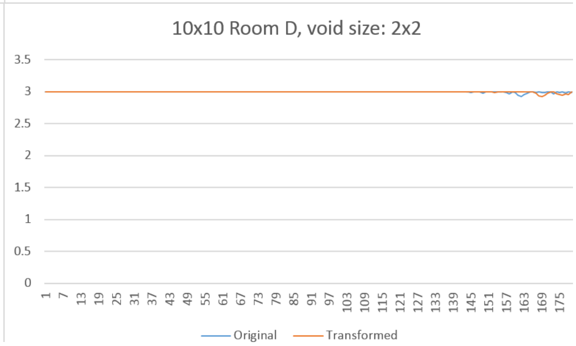

10x8 Room C
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

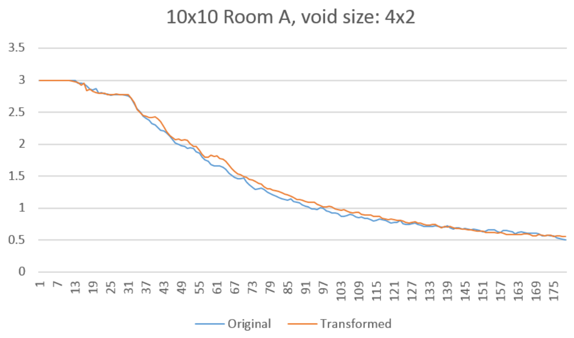

10x8 Room D
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

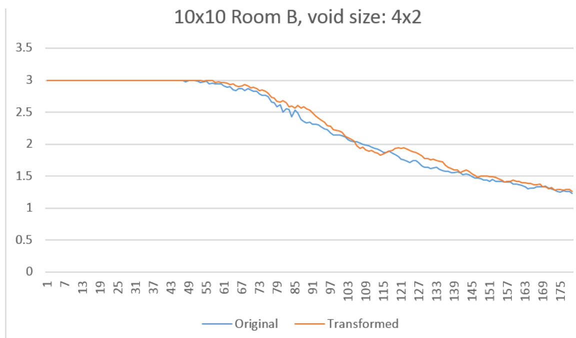

10x10 Room A, void size: 2x2
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

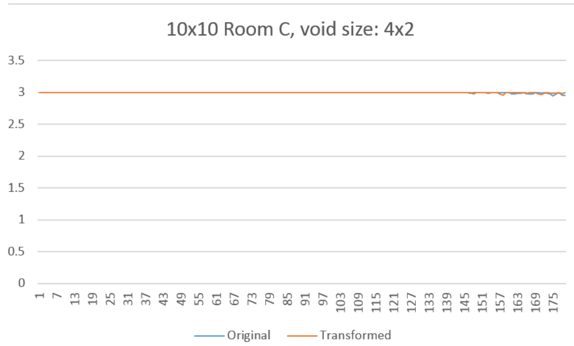

10x10 Room B, void size: 2x2
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

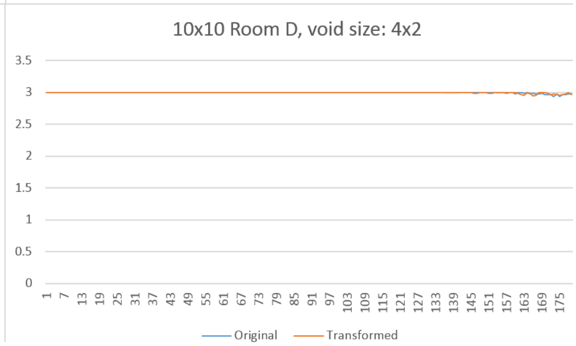

10x10 Room C, void size: 2x2
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

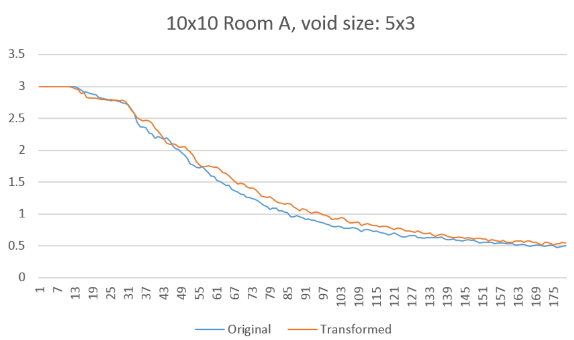

10x10 Room D, void size: 2x2
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

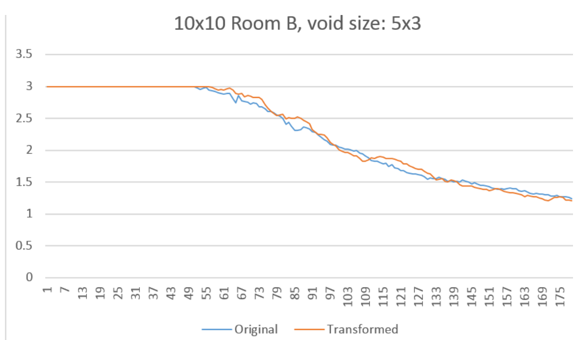

10x10 Room A, void size: 4x2
Original
Transformed

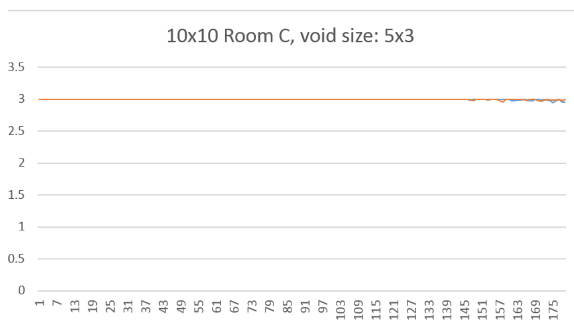

10x10 Room B, void size: 4x2
Original
Transformed

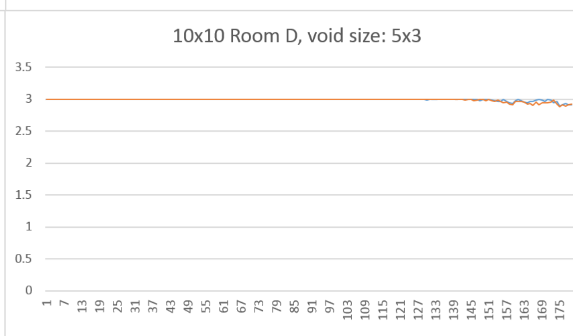

10x10 Room C, void size: 4x2
Original
Transformed

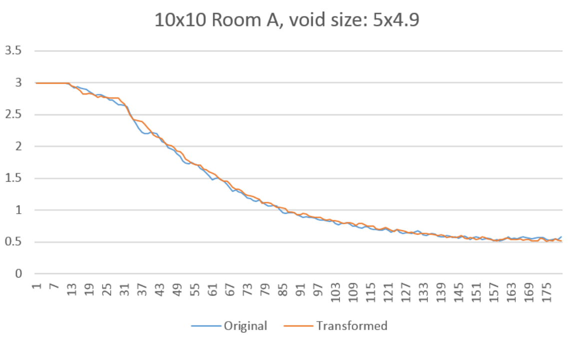

10x10 Room D, void size: 4x2
Original
Transformed

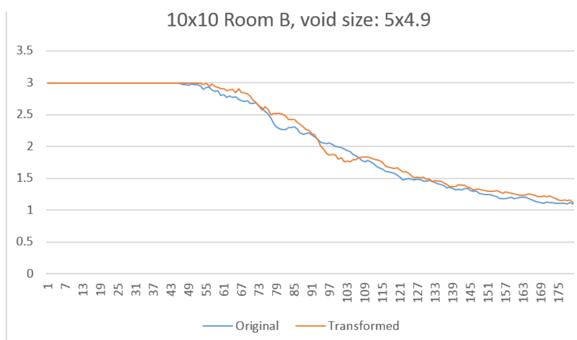

10x10 Room A, void size: 5x3
Original
Transformed

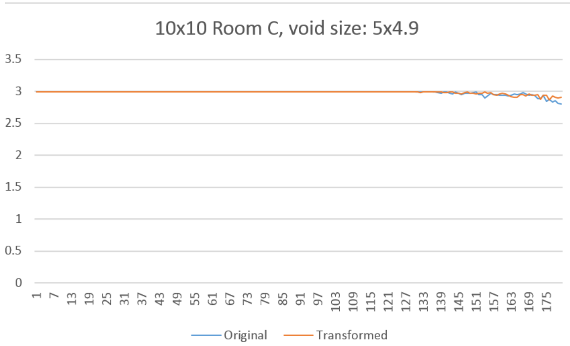

10x10 Room B, void size: 5x3
Original
Transformed

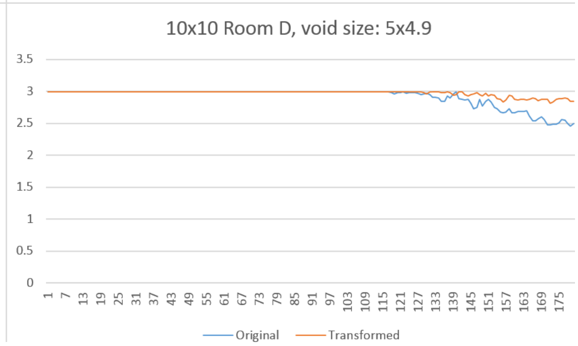

10x10 Room C, void size: 5x3
Original
Transformed

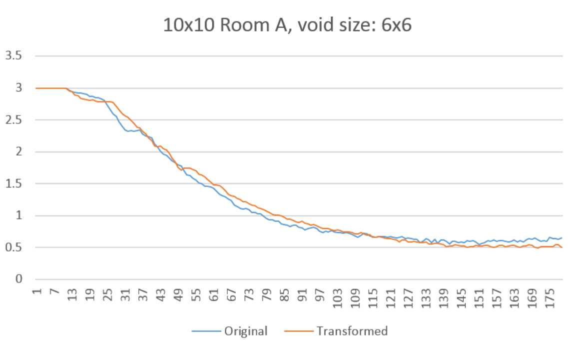

10x10 Room D, void size: 5x3
Original
Transformed

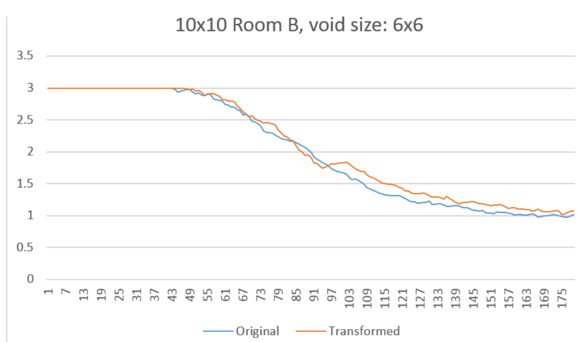

10x10 Room A, void size: 5x4.9
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

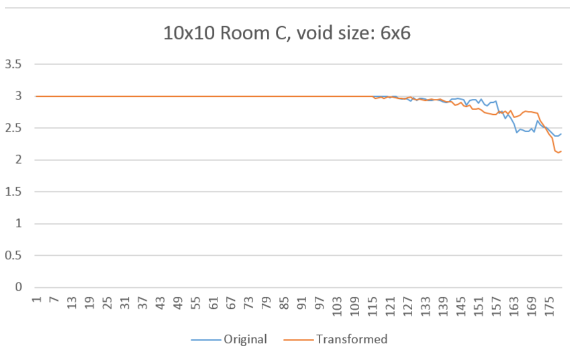

10x10 Room B, void size: 5x4.9
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

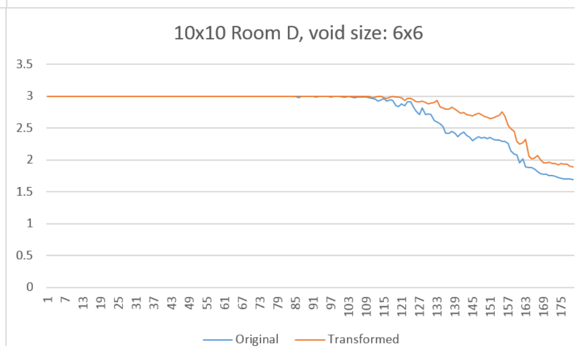

10x10 Room C, void size: 5x4.9
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed


10x10 Room D, void size: 5x4.9
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

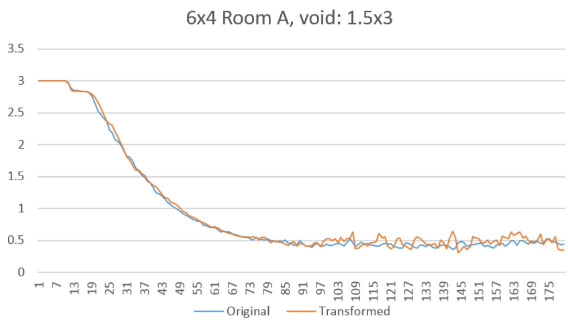

10x10 Room A, void size: 6x6
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

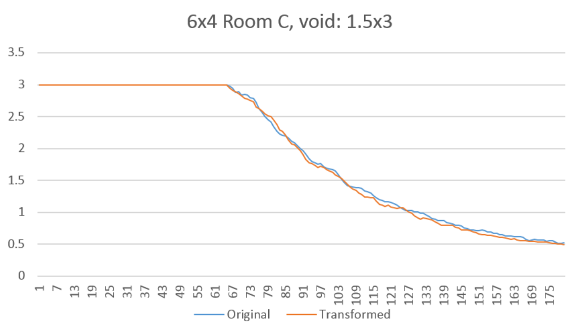

10x10 Room B, void size: 6x6
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

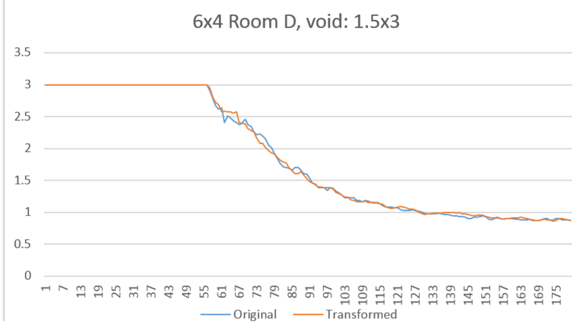

10x10 Room C, void size: 6x6
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

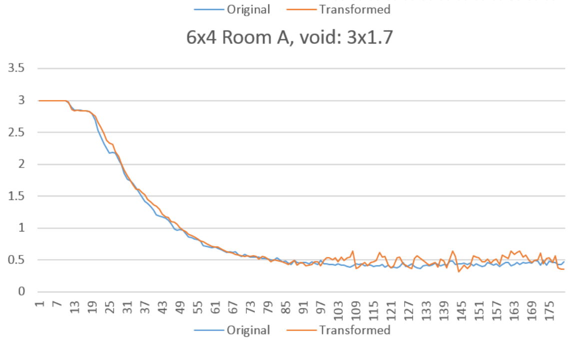

10x10 Room D, void size: 6x6
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

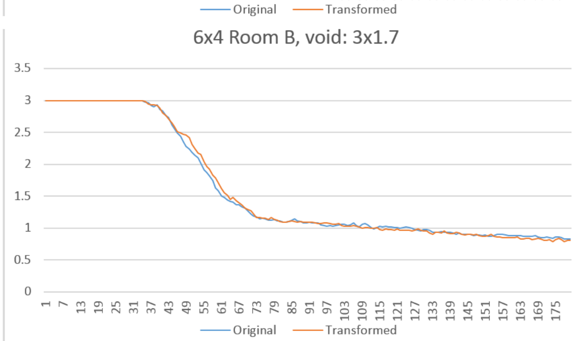
A.2 SIM Card Shape Models

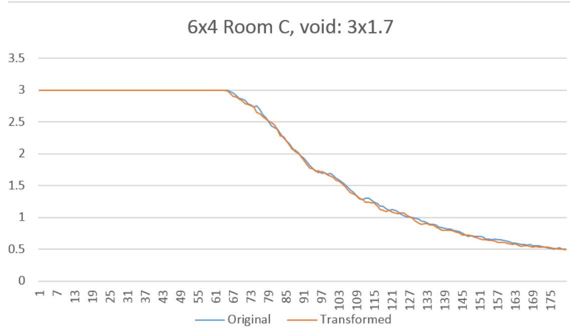


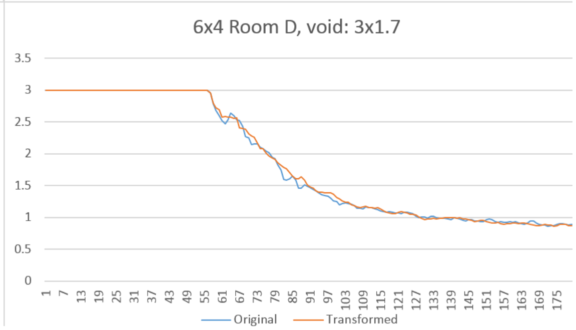


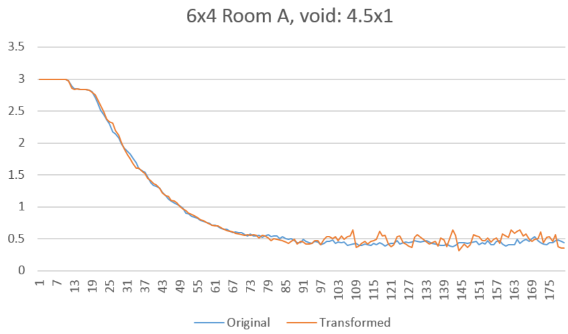


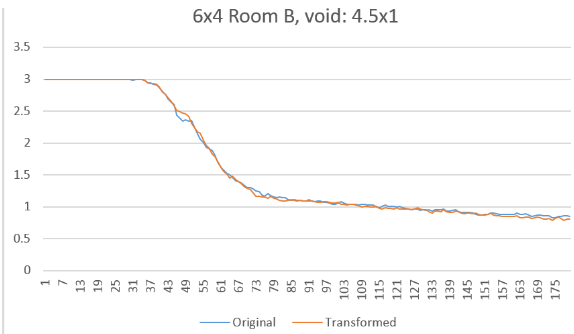


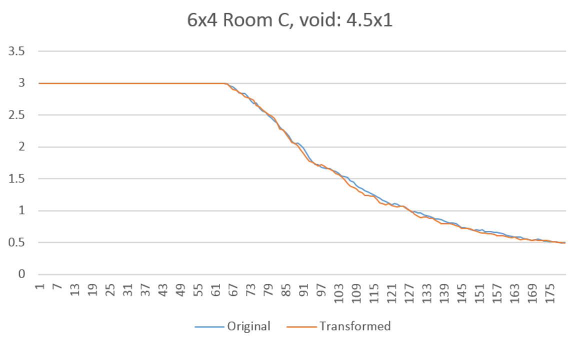


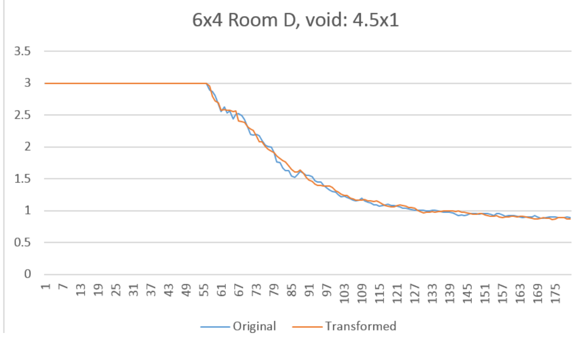


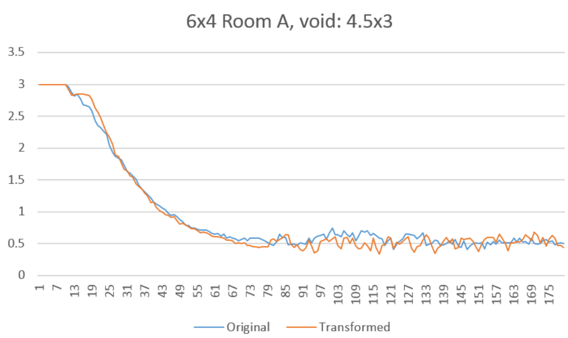


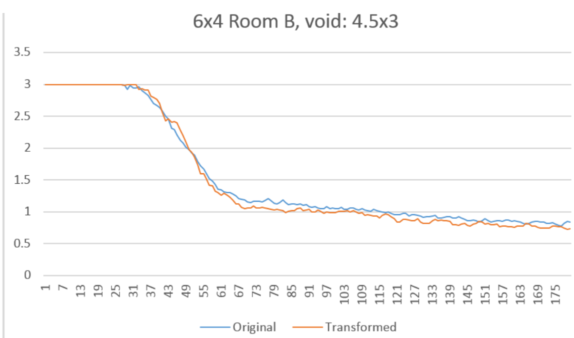

6x4 Room A, void: 4.5x1
Original
Transformed

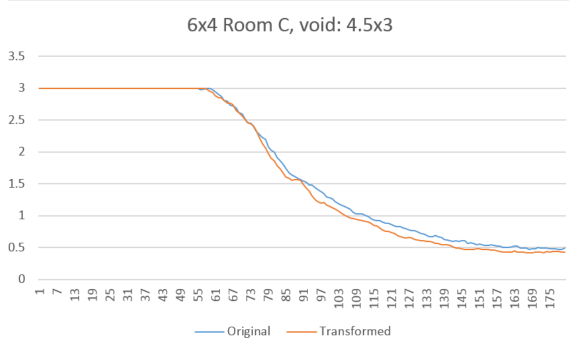

6x4 Room B, void: 4.5x1
Original
Transformed

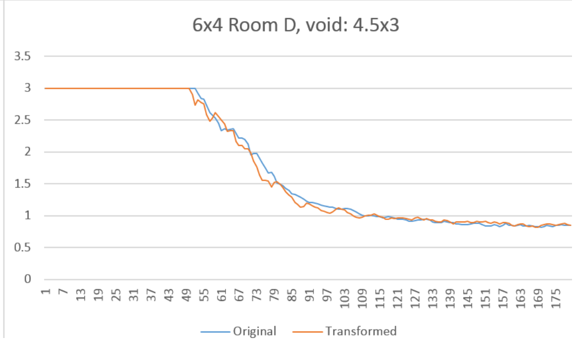

6x4 Room C, void: 4.5x1
Original
Transformed

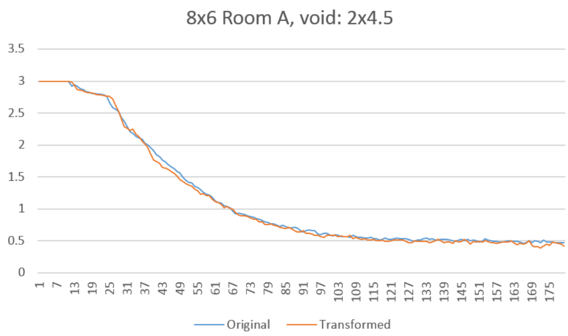

6x4 Room D, void: 4.5x1
Original
Transformed

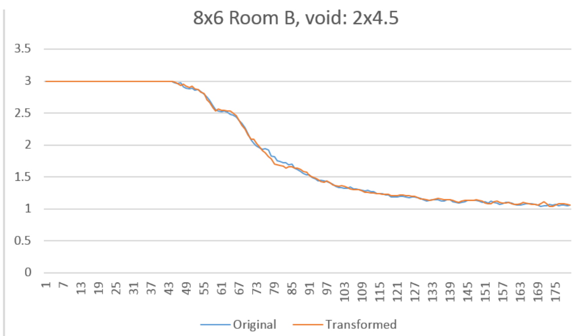

6x4 Room A, void: 4.5x3
Original
Transformed

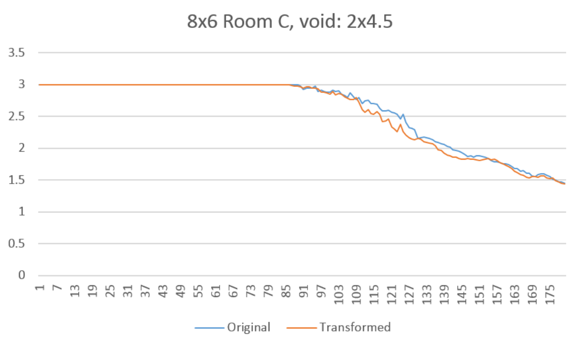

6x4 Room B, void: 4.5x3
Original
Transformed

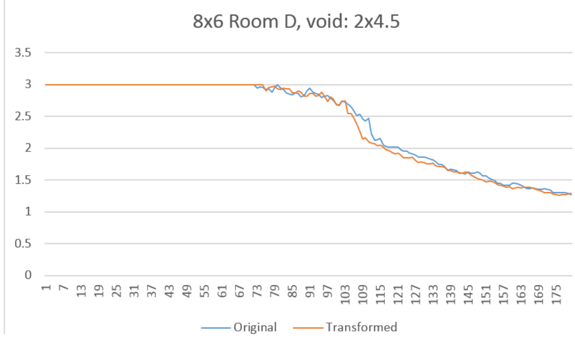

6x4 Room C, void: 4.5x3
Original
Transformed

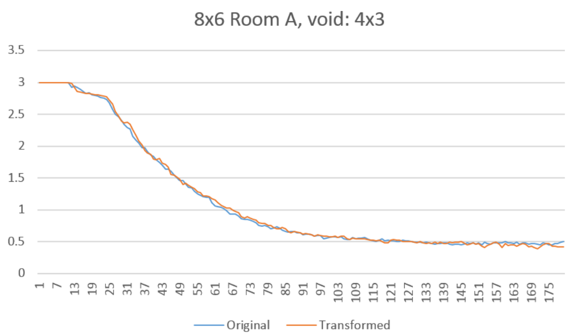

6x4 Room D, void: 4.5x3
Original
Transformed

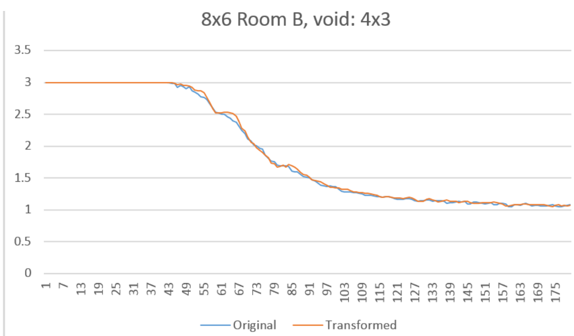

8x6 Room A, void: 2x4.5
Original
Transformed

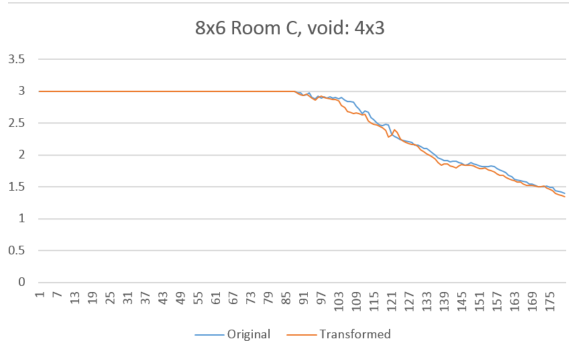

8x6 Room B, void: 2x4.5
Original
Transformed

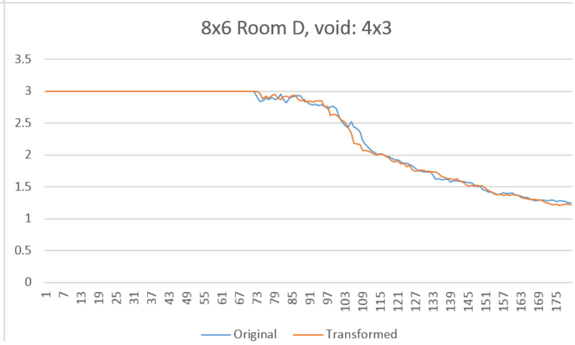

8x6 Room C, void: 2x4.5
Original
Transformed

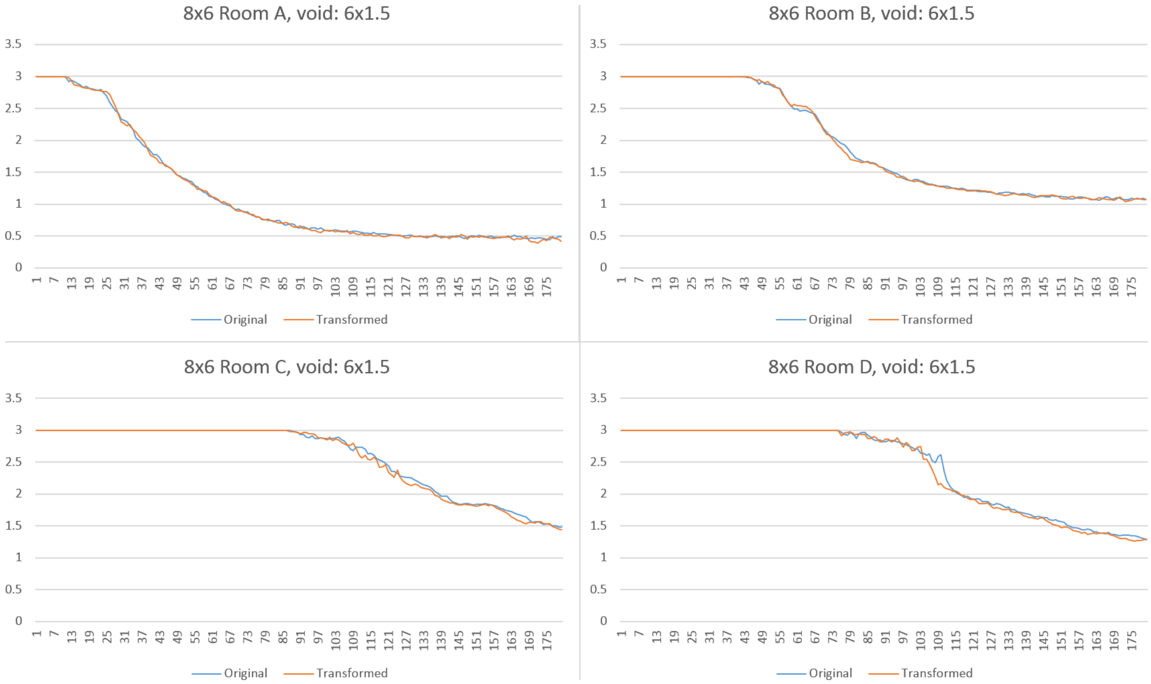

8x6 Room D, void: 2x4.5
Original
Transformed

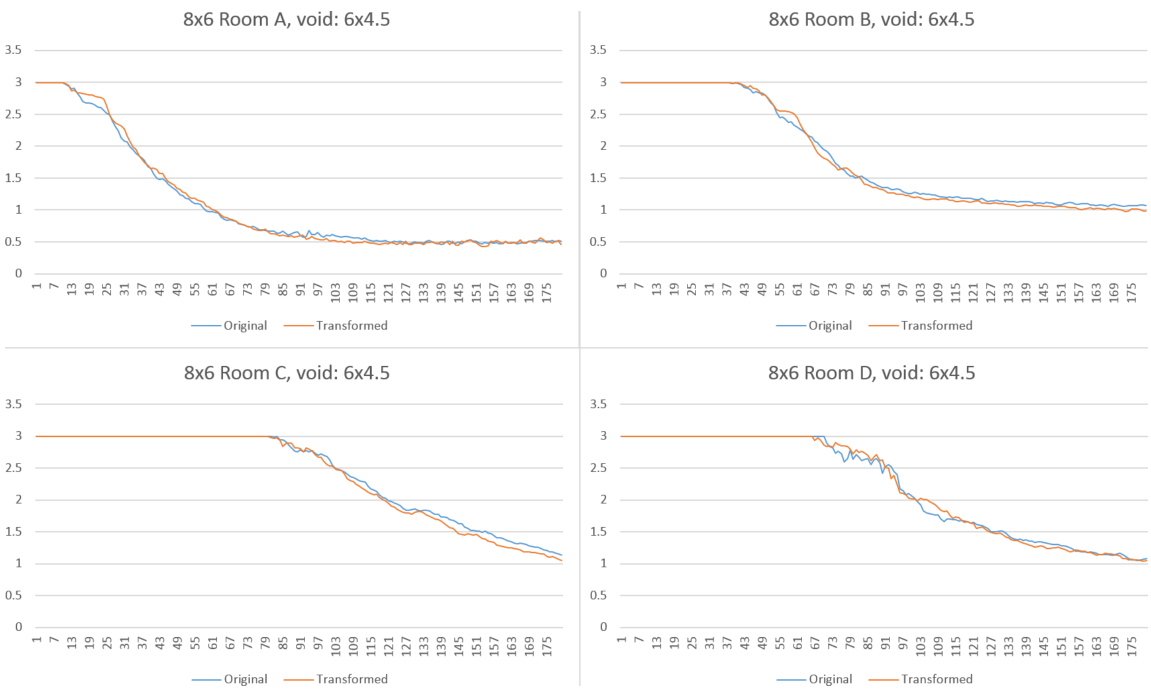

8x6 Room A, void: 4x3
Original
Transformed

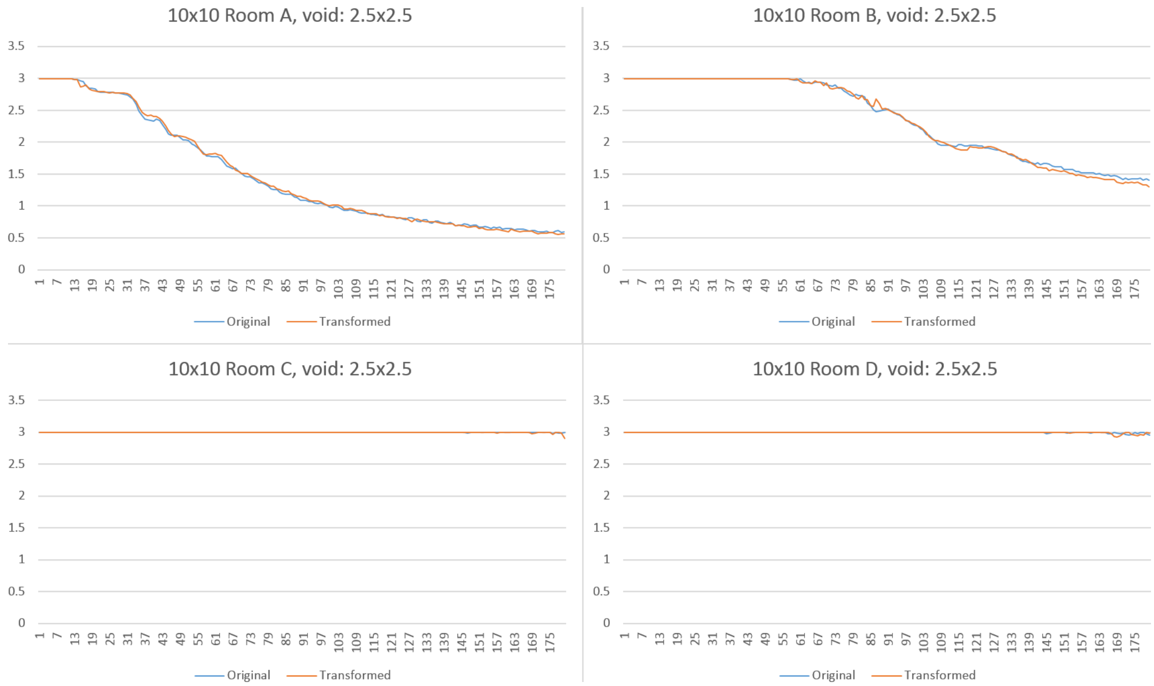

8x6 Room B, void: 4x3
Original
Transformed

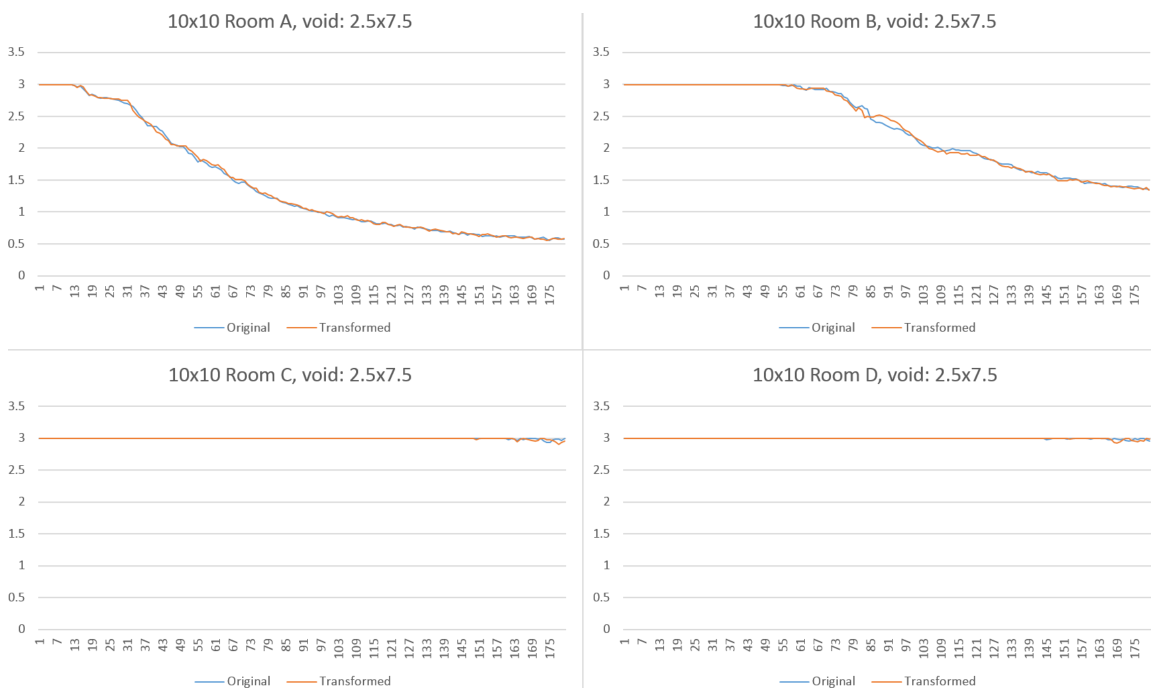

8x6 Room C, void: 4x3
Original
Transformed

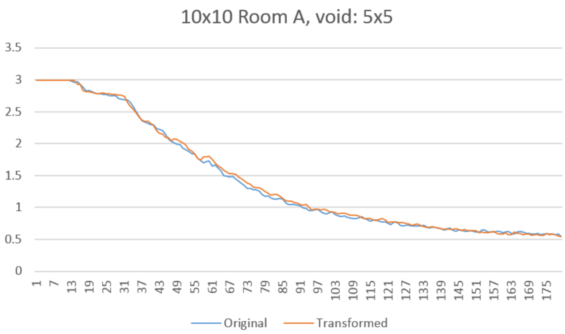

8x6 Room D, void: 4x3
Original
Transformed

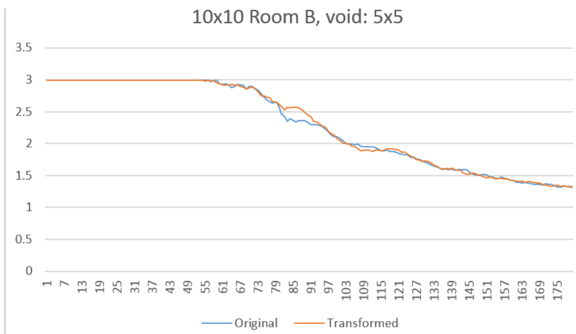

8x6 Room A, void: 6x1.5
8x6 Room B, void: 6x1.5
8x6 Room C, void: 6x1.5
8x6 Room D, void: 6x1.5
Original
Transformed

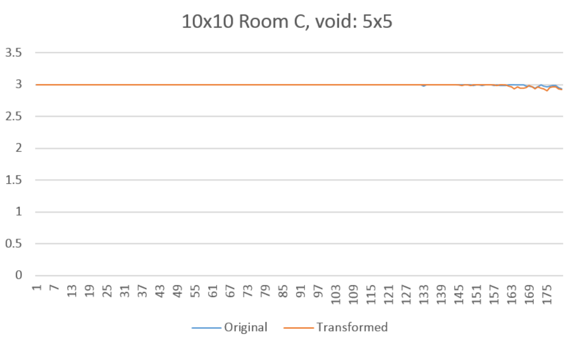

8x6 Room A, void: 6x4.5
8x6 Room B, void: 6x4.5
8x6 Room C, void: 6x4.5
8x6 Room D, void: 6x4.5
Original
Transformed

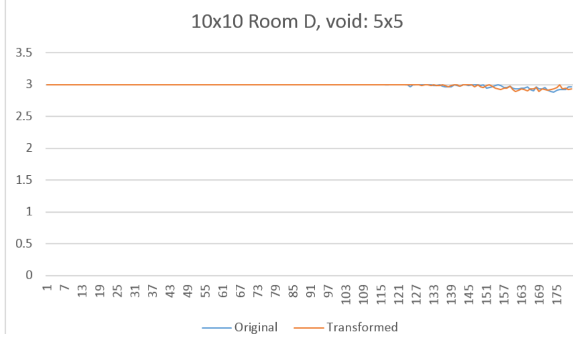

10x10 Room A, void: 2.5x2.5
10x10 Room B, void: 2.5x2.5
10x10 Room C, void: 2.5x2.5
10x10 Room D, void: 2.5x2.5
Original
Transformed

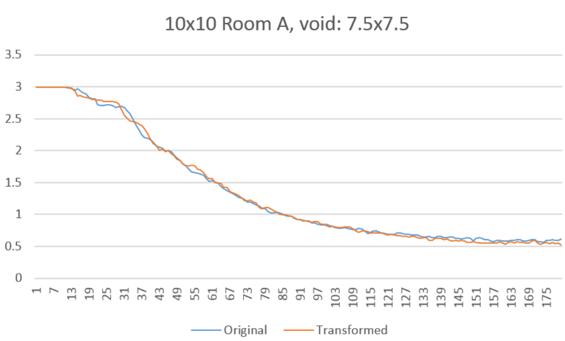

10x10 Room A, void: 2.5x7.5
10x10 Room B, void: 2.5x7.5
10x10 Room C, void: 2.5x7.5
10x10 Room D, void: 2.5x7.5
Original
Transformed

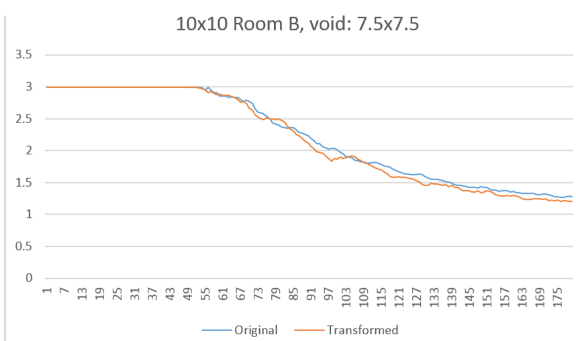

10x10 Room A, void: 5x5
Original
Transformed

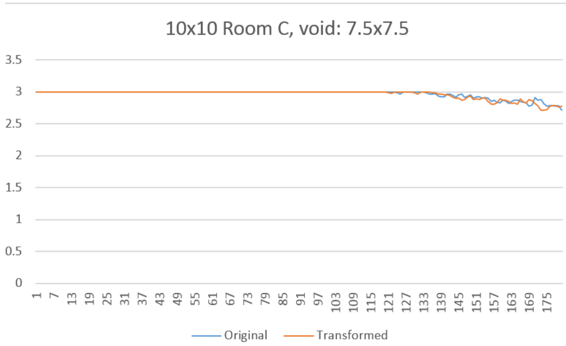

10x10 Room B, void: 5x5
Original
Transformed

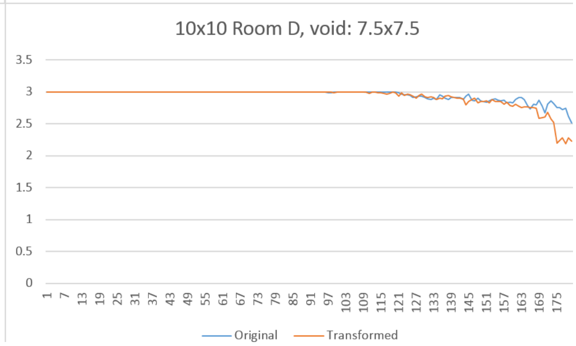

10x10 Room C, void: 5x5
Original
Transformed


10x10 Room D, void: 5x5
Original
Transformed

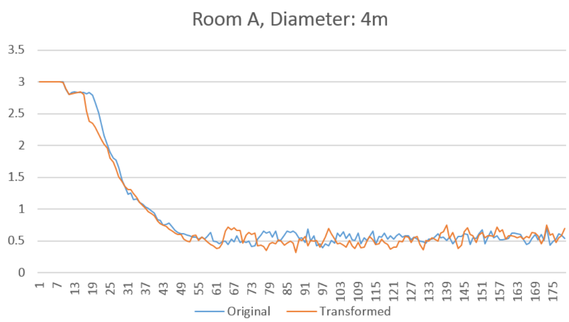

10x10 Room A, void: 7.5x7.5
Original
Transformed

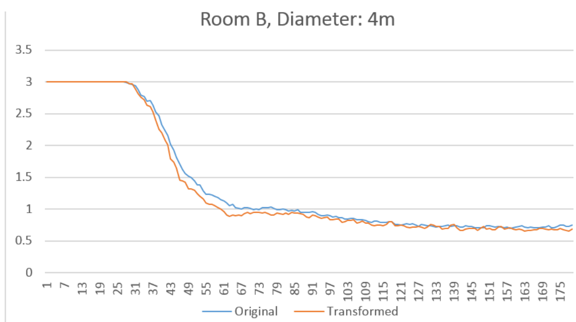

10x10 Room B, void: 7.5x7.5
Original
Transformed

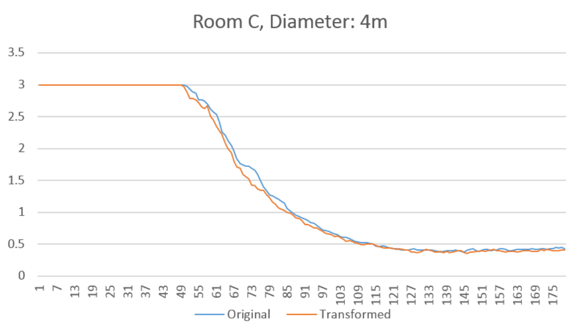

10x10 Room C, void: 7.5x7.5
Original
Transformed

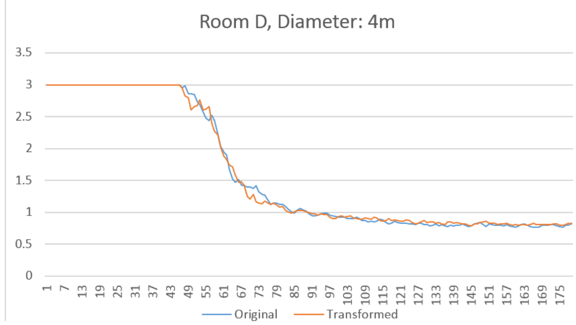

10x10 Room D, void: 7.5x7.5
Original
Transformed

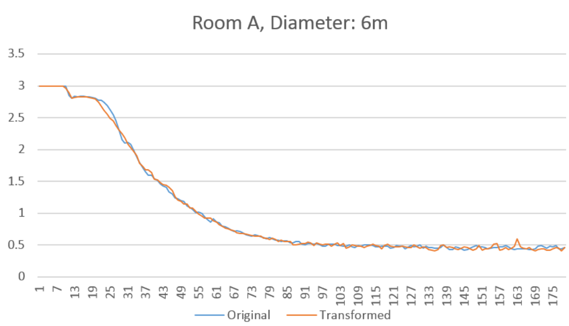
A.3 Circular Shape Models

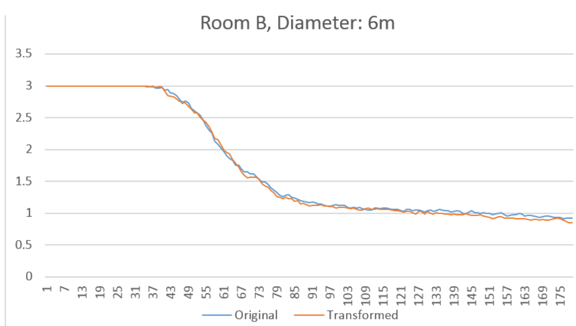


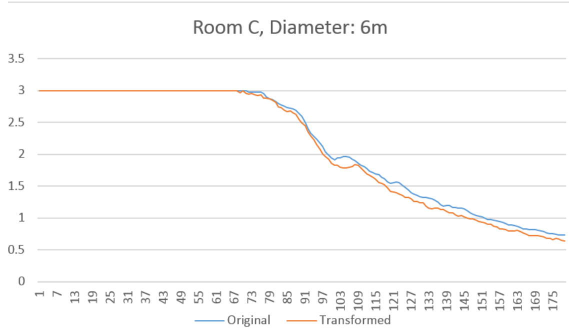


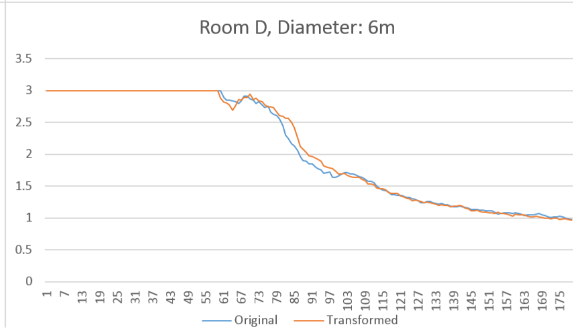


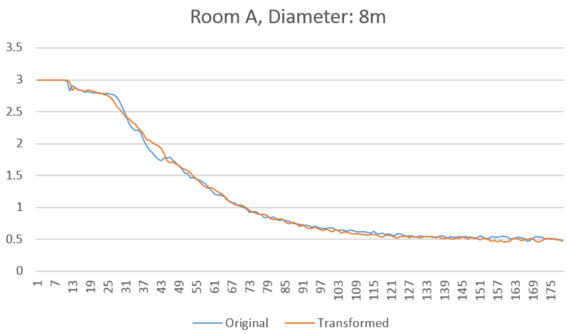


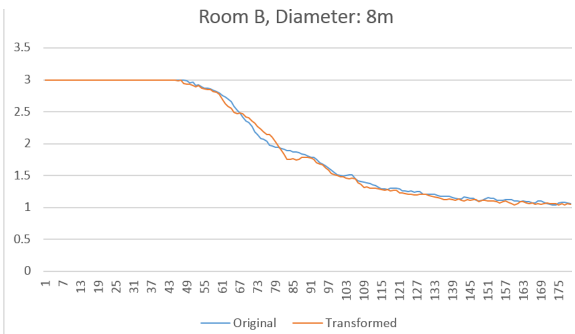


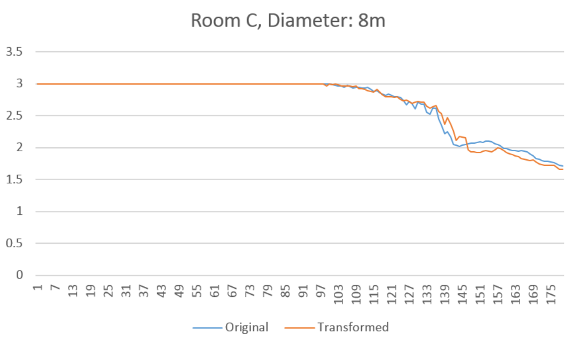


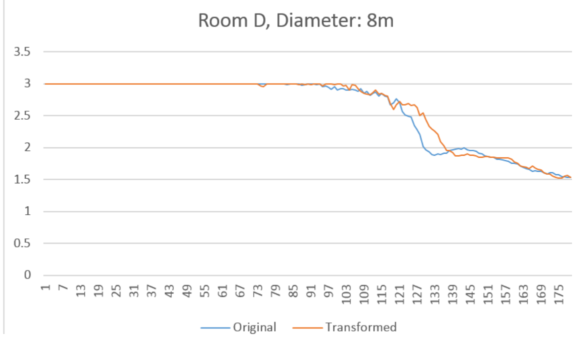


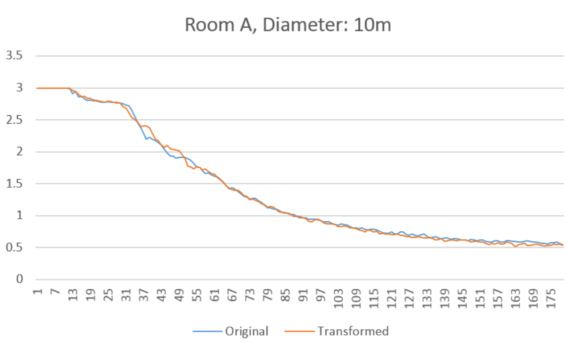


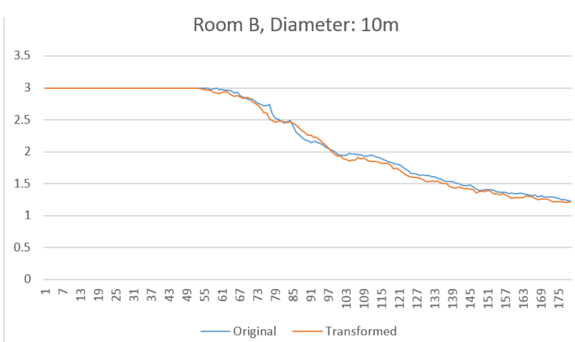

Room A, Diameter: 8m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

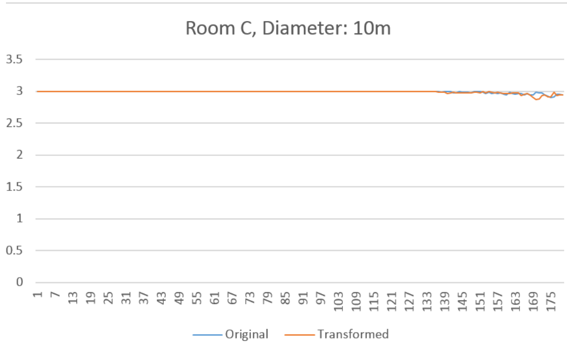

Room B, Diameter: 8m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

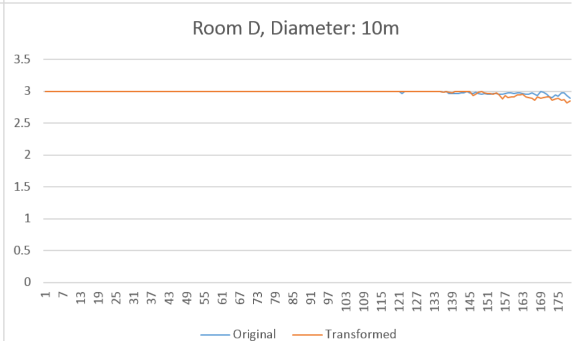

Room C, Diameter: 8m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed


Room D, Diameter: 8m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

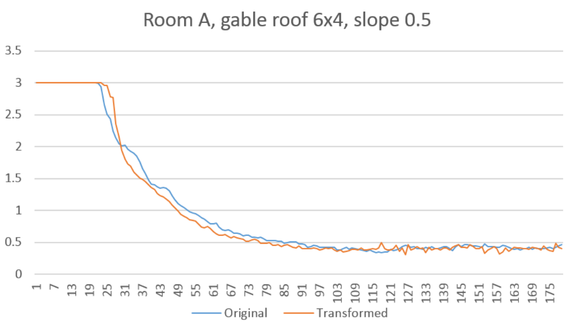

Room A, Diameter: 10m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

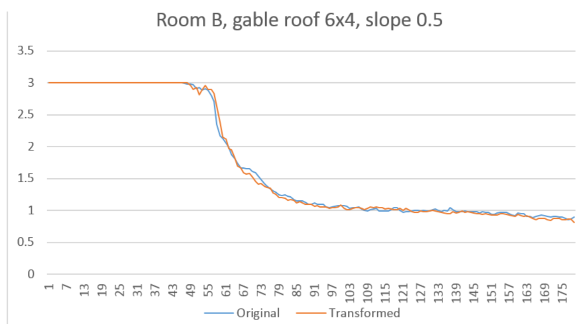

Room B, Diameter: 10m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

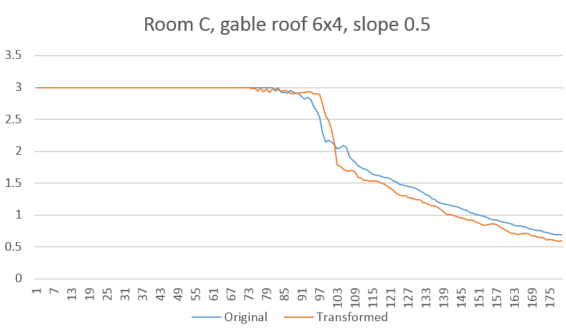

Room C, Diameter: 10m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

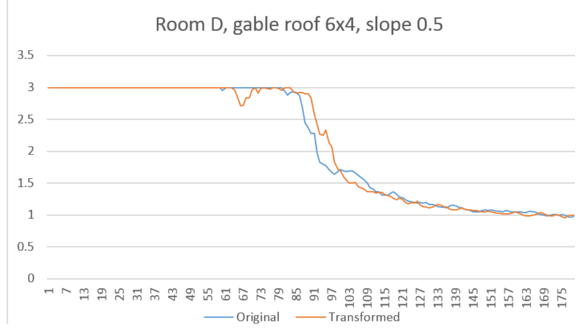

Room D, Diameter: 10m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

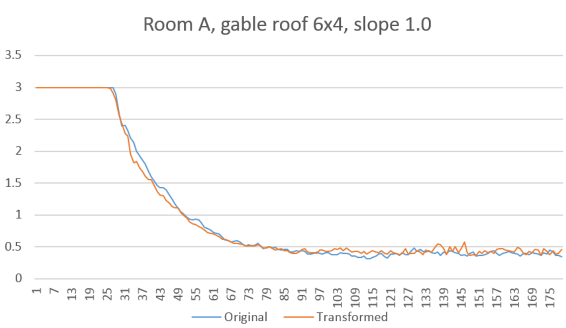
A.4 Gable Models

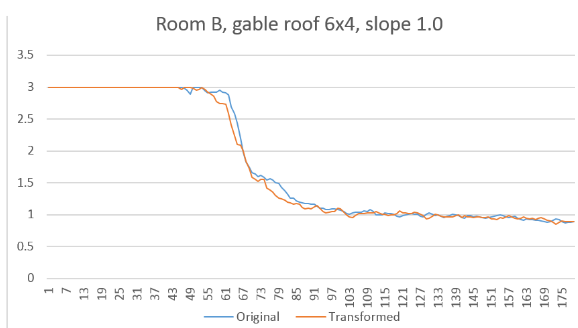


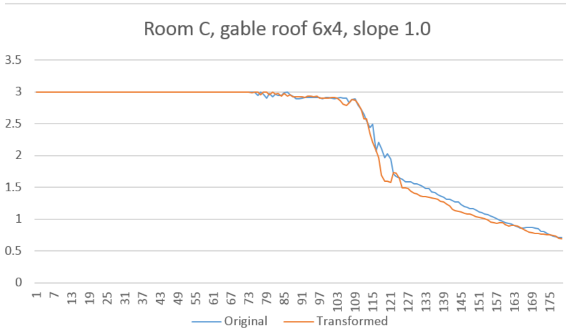


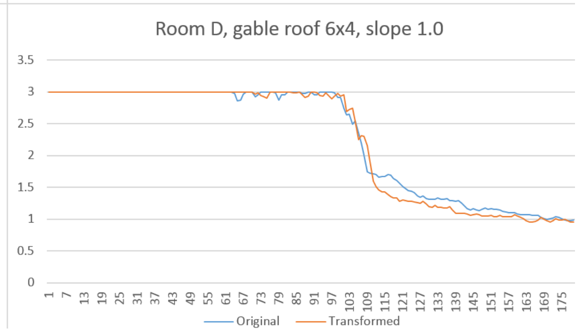


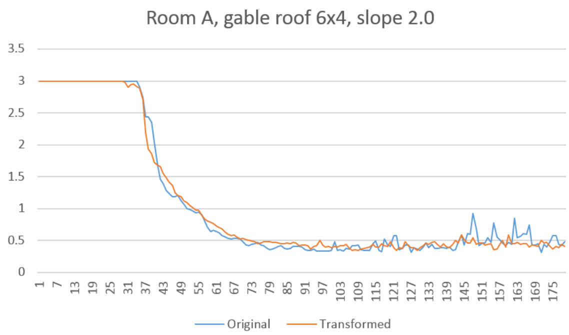


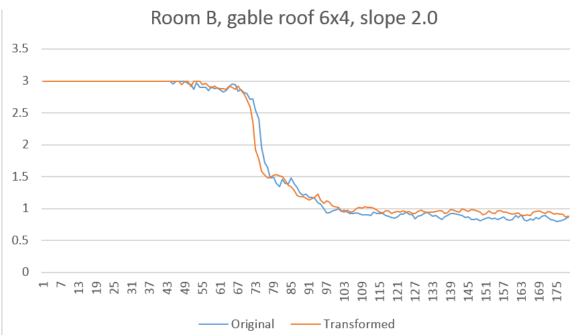


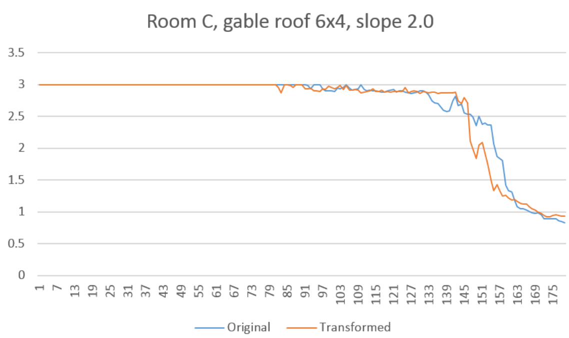


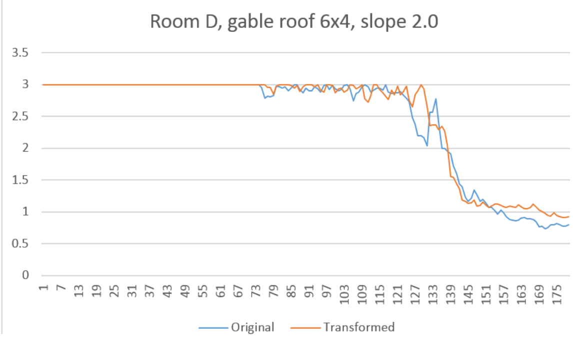


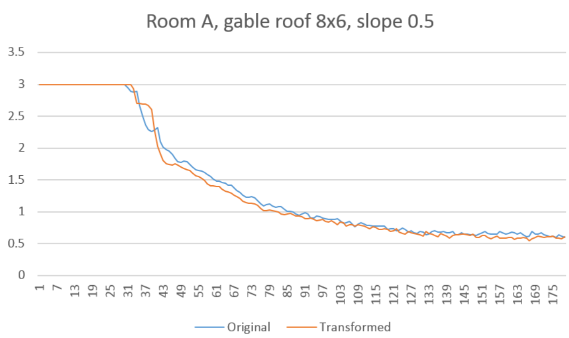


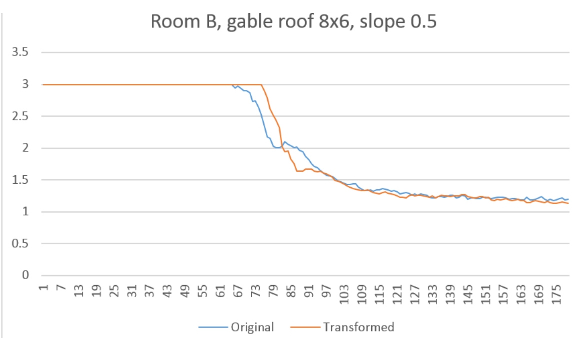

Room A, gable roof 6x4, slope 2.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

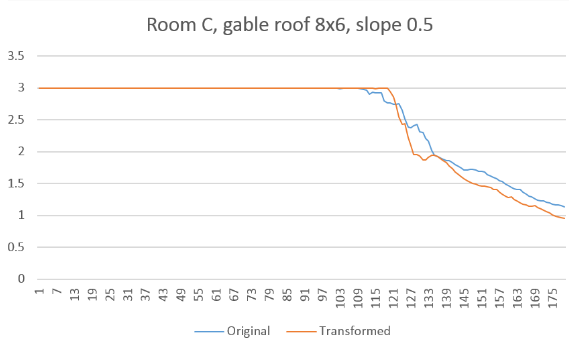

Room B, gable roof 6x4, slope 2.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

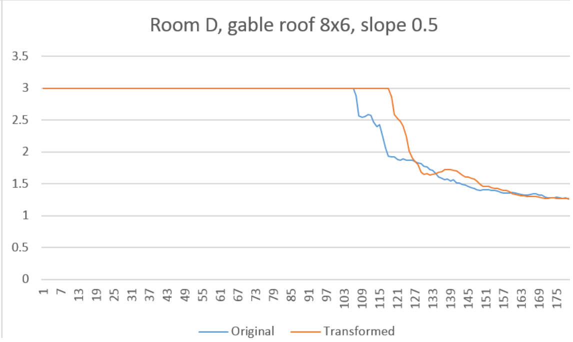

Room C, gable roof 6x4, slope 2.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

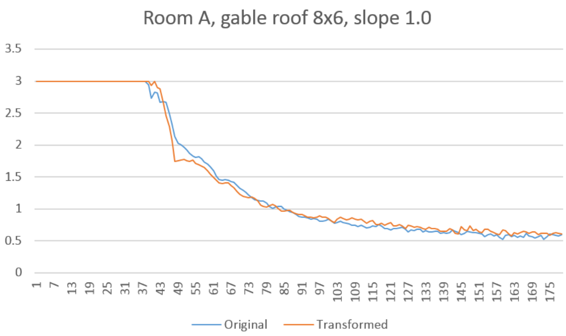

Room D, gable roof 6x4, slope 2.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

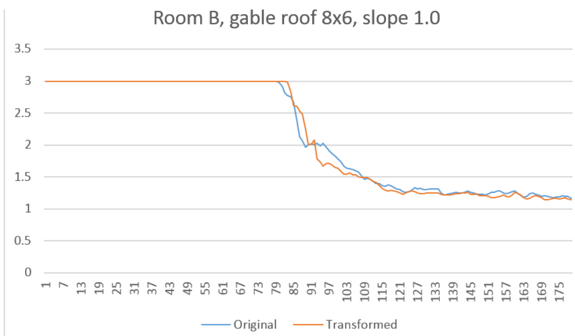

Room A, gable roof 8x6, slope 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

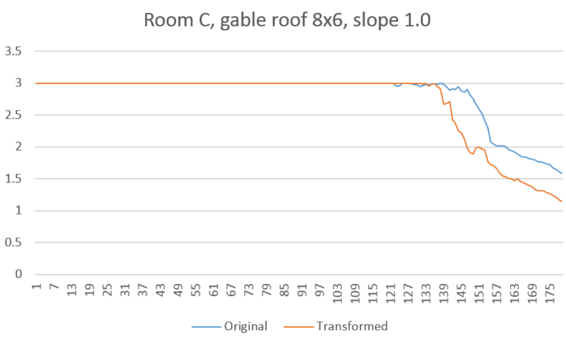

Room B, gable roof 8x6, slope 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

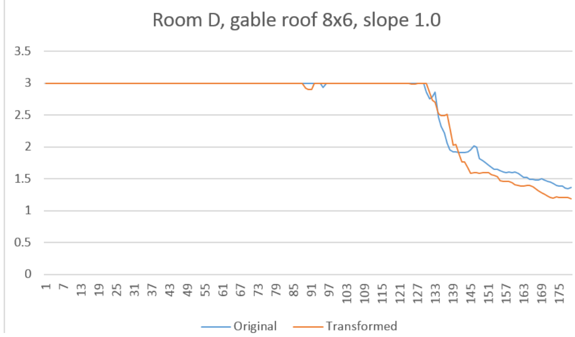

Room C, gable roof 8x6, slope 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

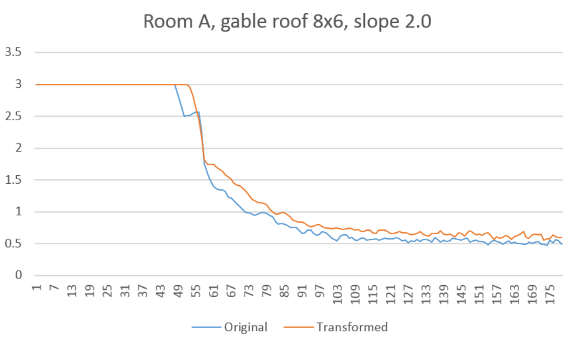

Room D, gable roof 8x6, slope 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

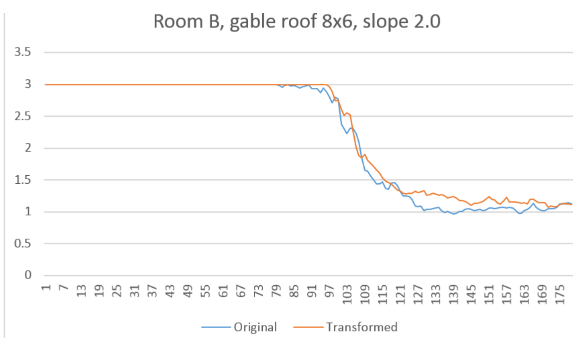

Room A, gable roof 8x6, slope 1.0
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

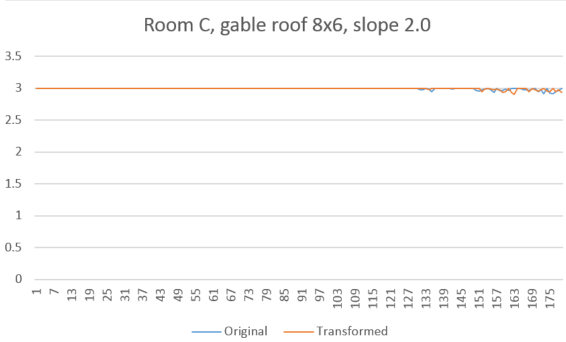

Room B, gable roof 8x6, slope 1.0
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

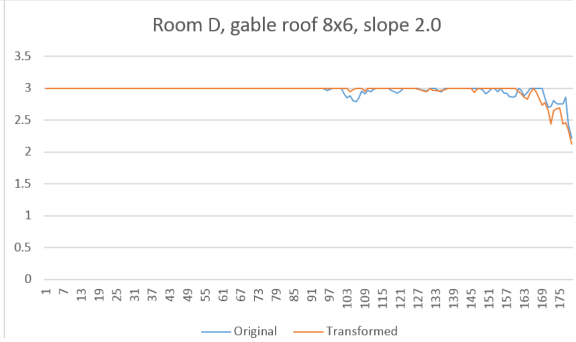

Room C, gable roof 8x6, slope 1.0
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

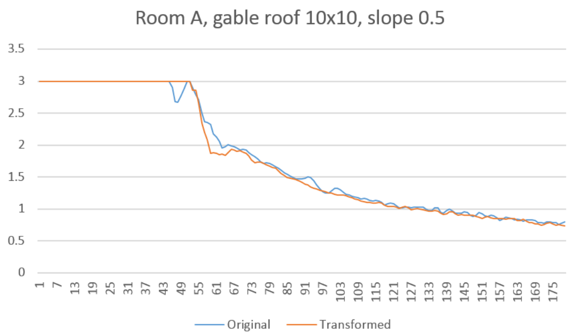

Room D, gable roof 8x6, slope 1.0
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

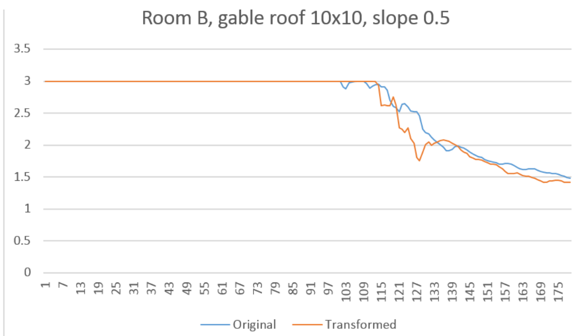

Room A, gable roof 8x6, slope 2.0
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

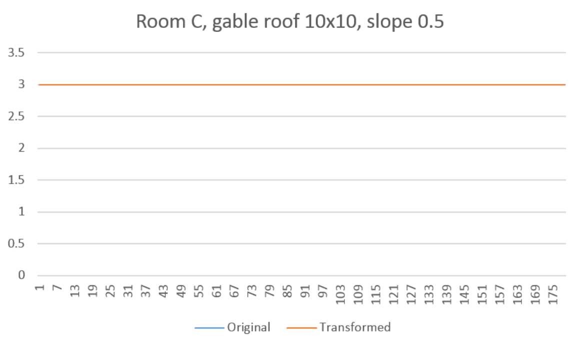

Room B, gable roof 8x6, slope 2.0
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

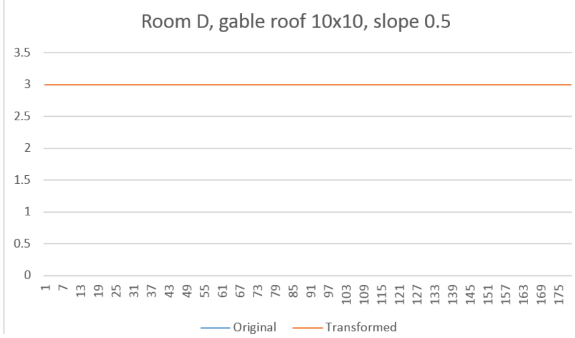

Room C, gable roof 8x6, slope 2.0
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

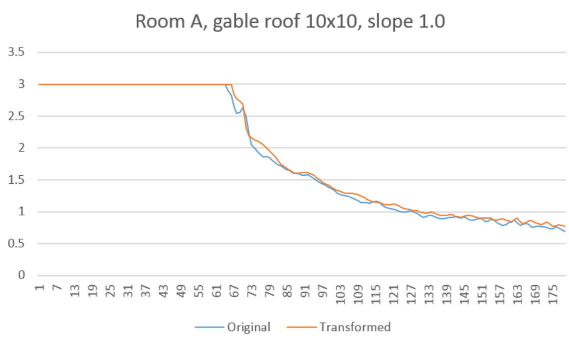

Room D, gable roof 8x6, slope 2.0
3.5 3 2.5 2 1.5 1 0.5 0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

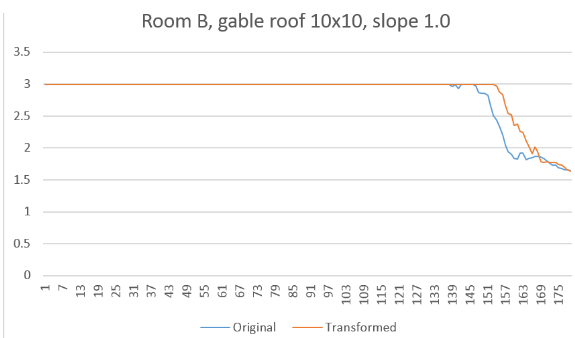

Room A, gable roof 10x10, slope 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

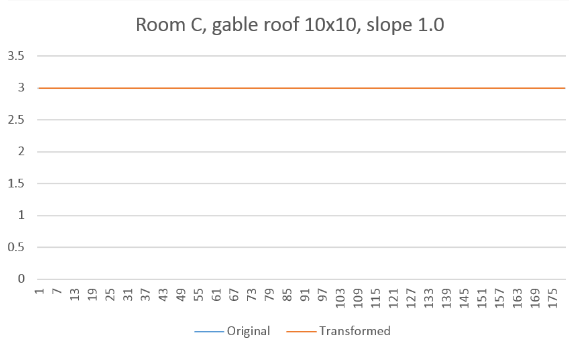

Room B, gable roof 10x10, slope 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

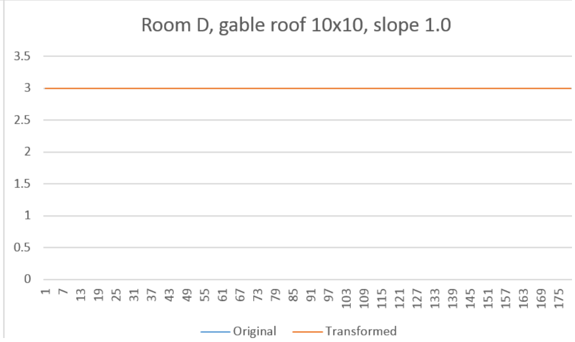

Room C, gable roof 10x10, slope 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed


Room D, gable roof 10x10, slope 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

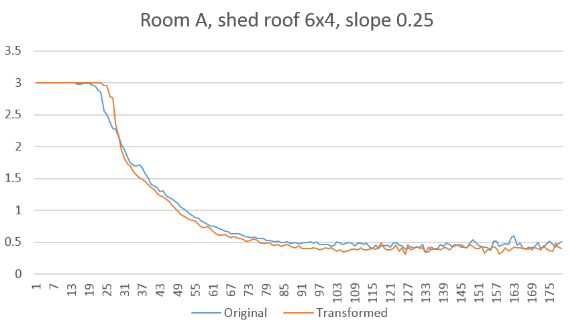

Room A, gable roof 10x10, slope 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

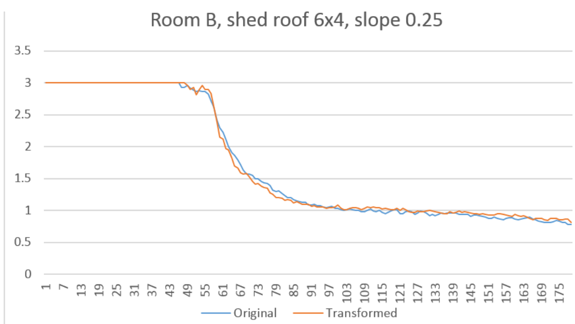

Room B, gable roof 10x10, slope 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

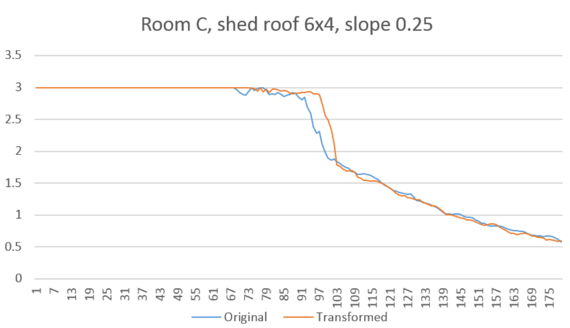

Room C, gable roof 10x10, slope 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

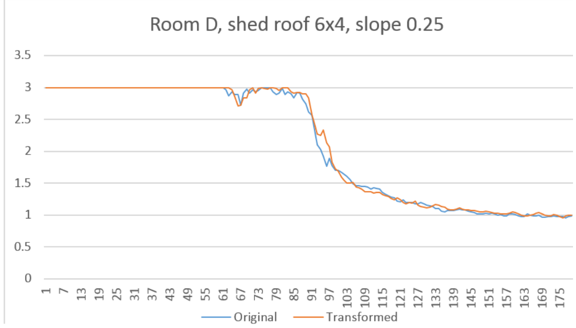

Room D, gable roof 10x10, slope 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

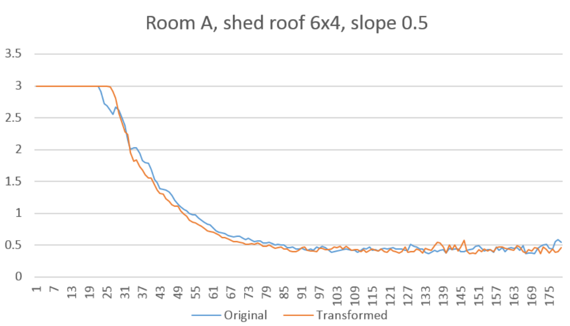
A.5 Shed Models

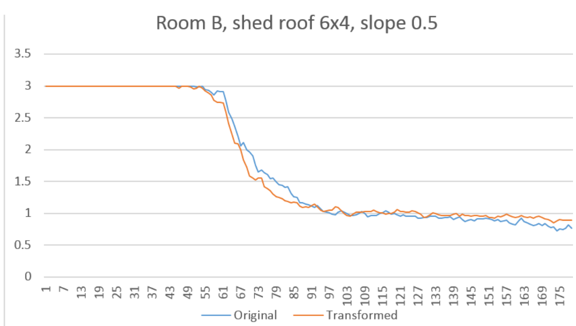


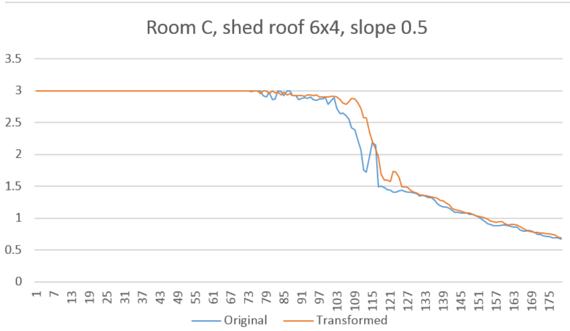


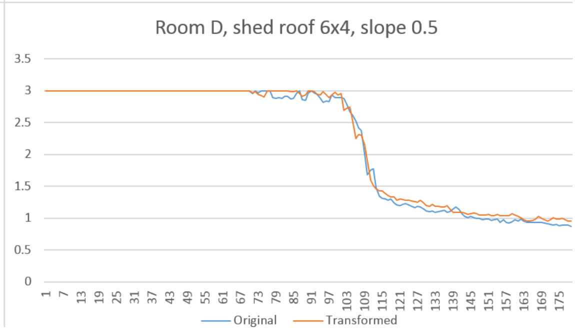


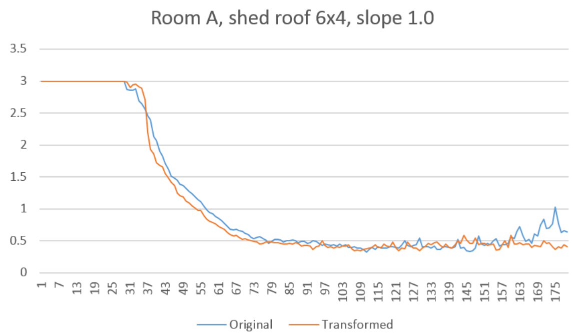


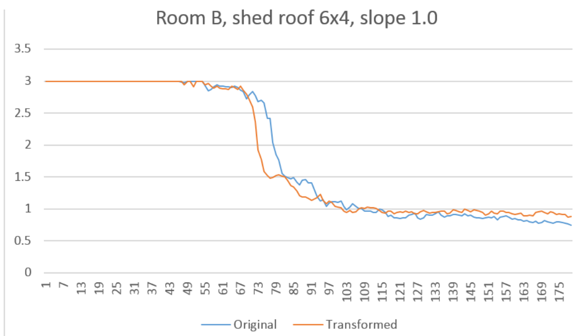


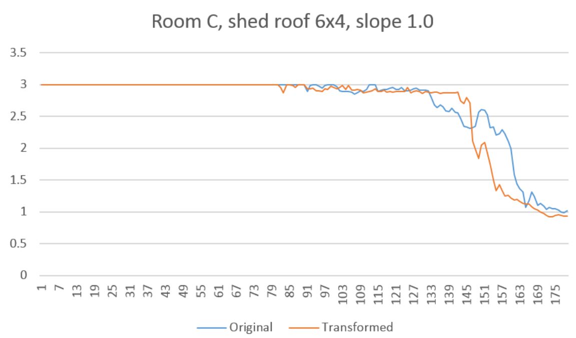


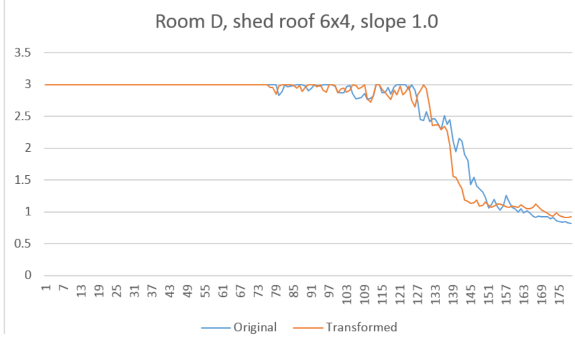


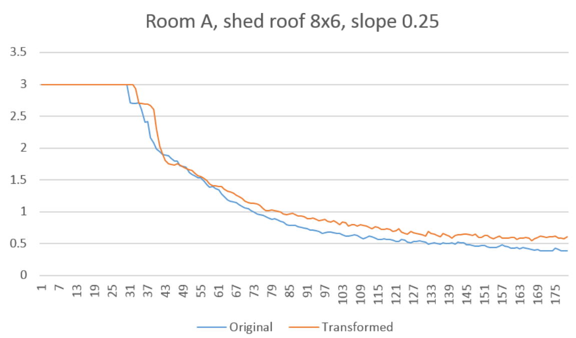


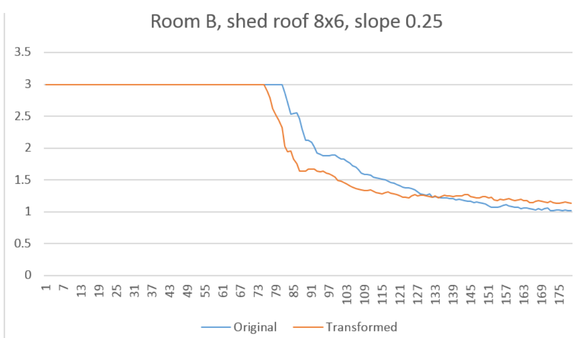

Room A, shed roof 6x4, slope 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

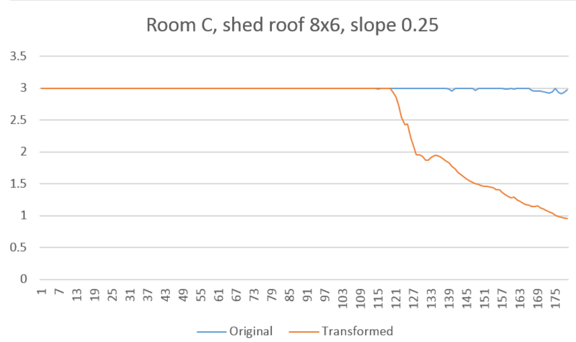

Room B, shed roof 6x4, slope 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

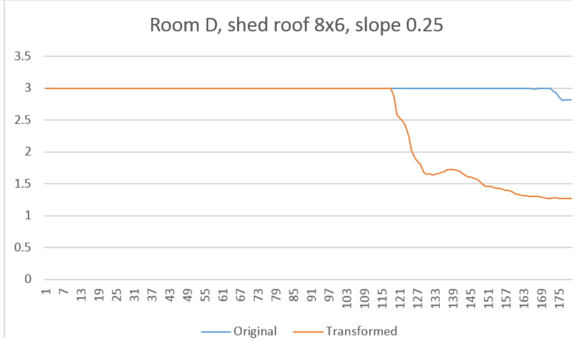

Room C, shed roof 6x4, slope 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

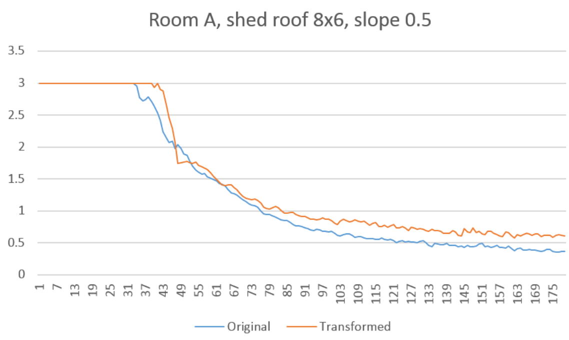

Room D, shed roof 6x4, slope 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

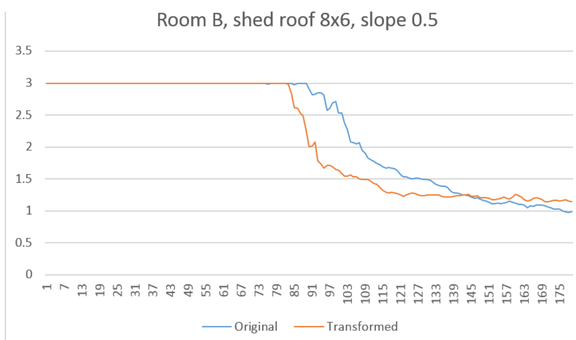

Room A, shed roof 8x6, slope 0.25
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

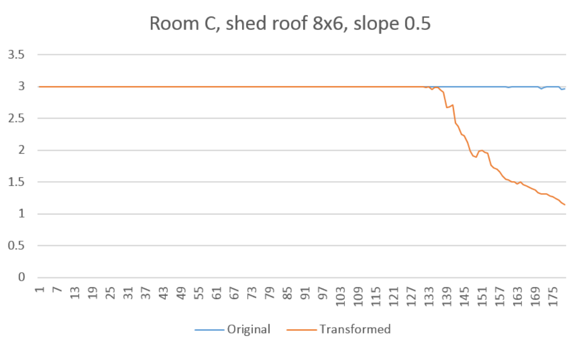

Room B, shed roof 8x6, slope 0.25
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

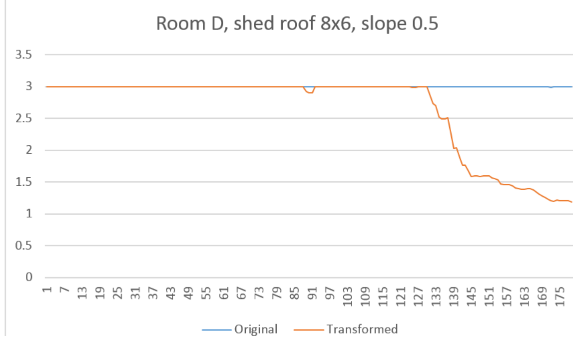

Room C, shed roof 8x6, slope 0.25
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

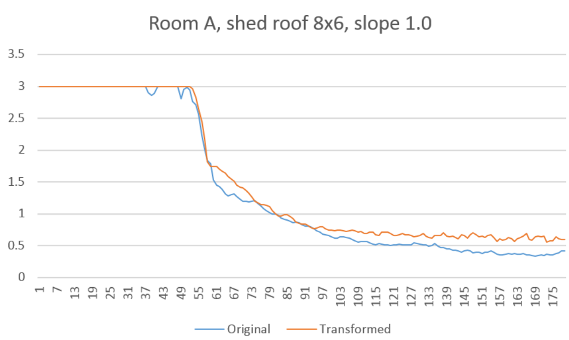

Room D, shed roof 8x6, slope 0.25
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

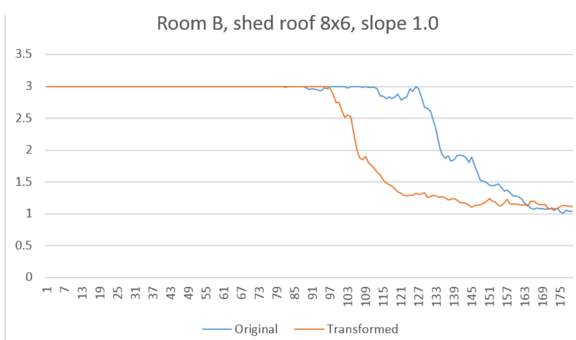

Room A, shed roof 8x6, slope 0.5
Original
Transformed

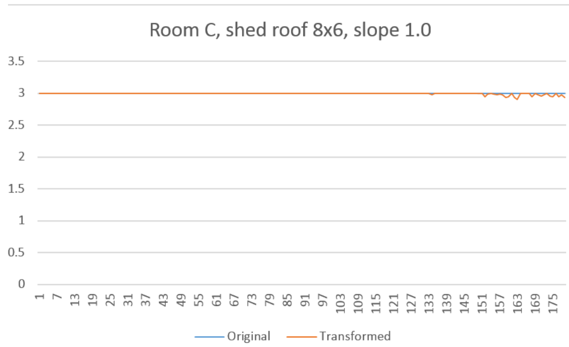

Room B, shed roof 8x6, slope 0.5
Original
Transformed

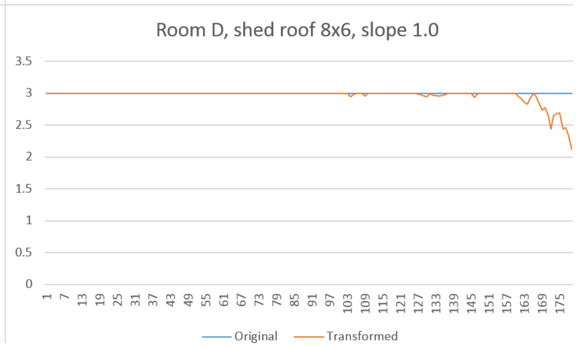

Room C, shed roof 8x6, slope 0.5
Original
Transformed

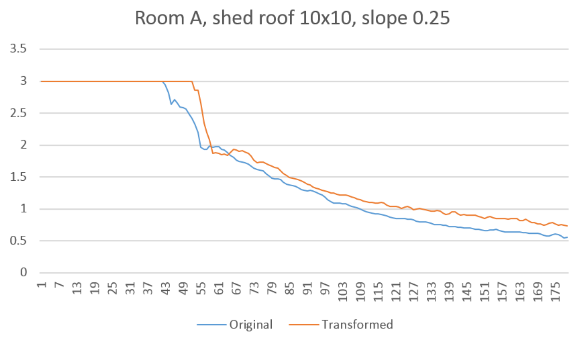

Room D, shed roof 8x6, slope 0.5
Original
Transformed

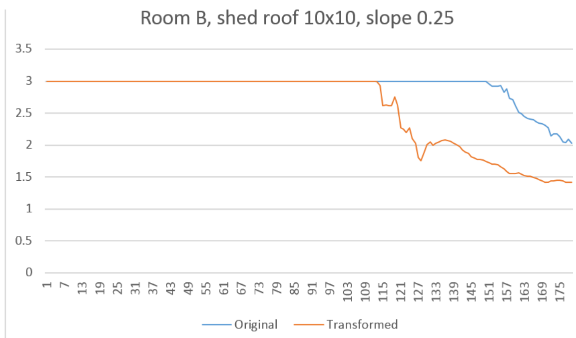

Room A, shed roof 8x6, slope 1.0
Original
Transformed

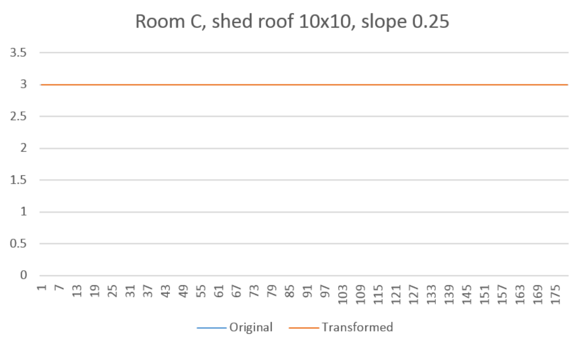

Room B, shed roof 8x6, slope 1.0
Original
Transformed

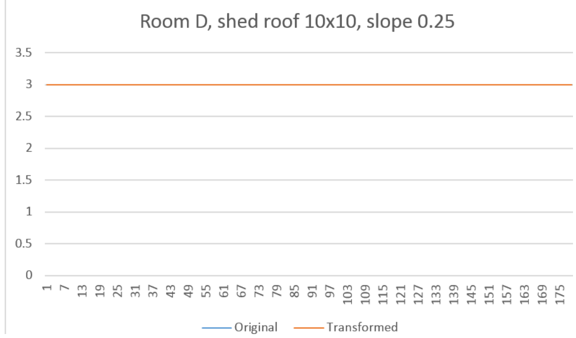

Room C, shed roof 8x6, slope 1.0
Original
Transformed

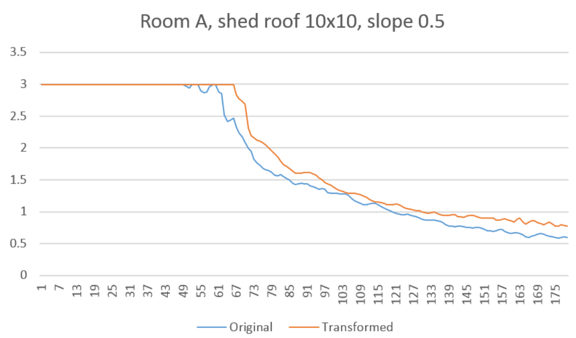

Room D, shed roof 8x6, slope 1.0
Original
Transformed

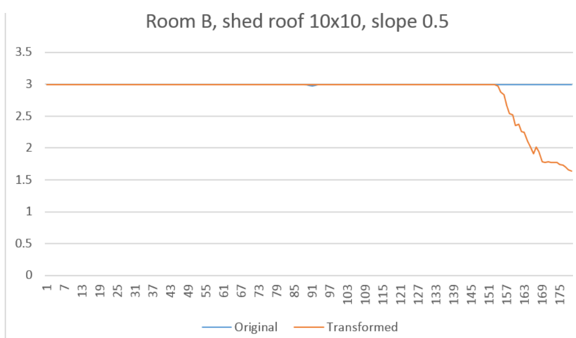

Room A, shed roof 10x10, slope 0.25
Original
Transformed

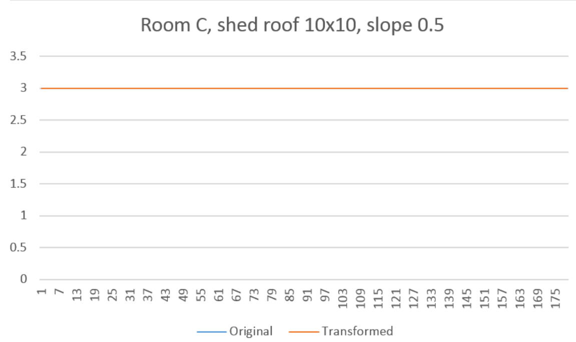

Room B, shed roof 10x10, slope 0.25
Original
Transformed

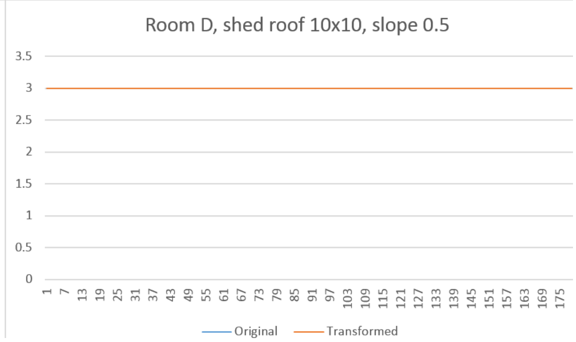

Room C, shed roof 10x10, slope 0.25
Original
Transformed


Room D, shed roof 10x10, slope 0.25
Original
Transformed

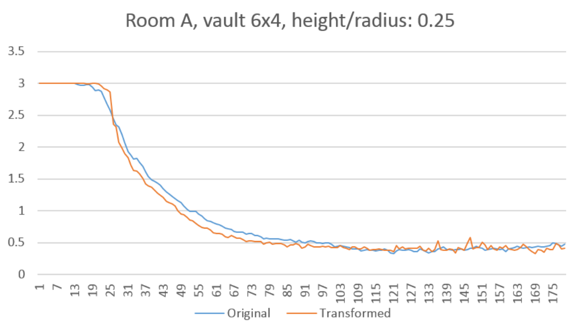

Room A, shed roof 10x10, slope 0.5
Original
Transformed

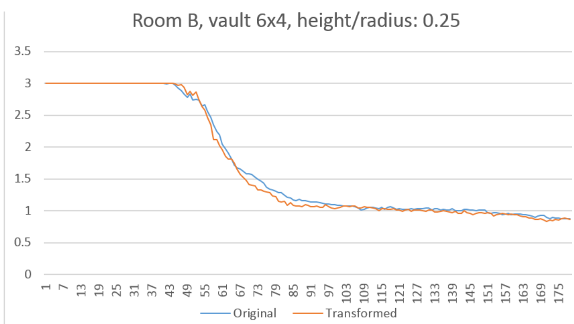

Room B, shed roof 10x10, slope 0.5
Original
Transformed

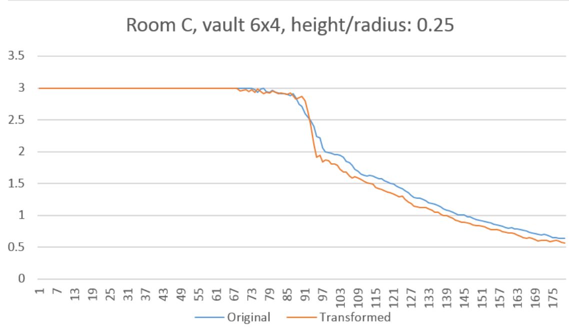

Room C, shed roof 10x10, slope 0.5
Original
Transformed

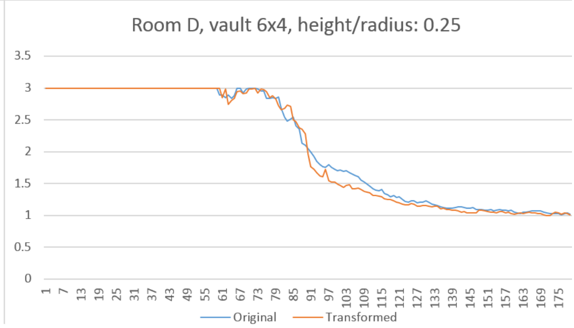

Room D, shed roof 10x10, slope 0.5
Original
Transformed

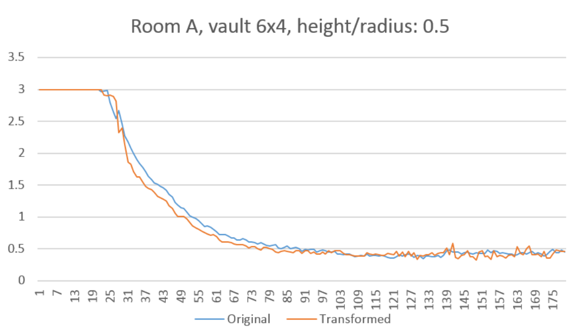
A.6 Vault Models

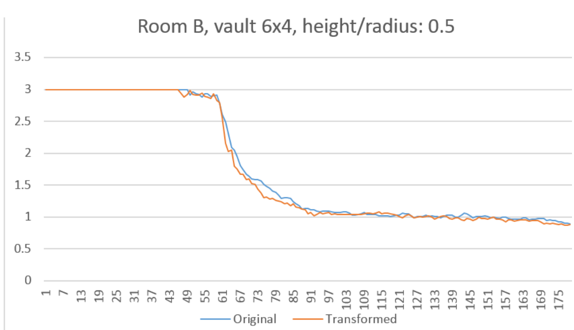


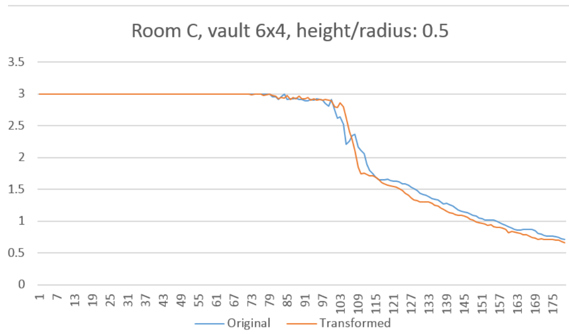


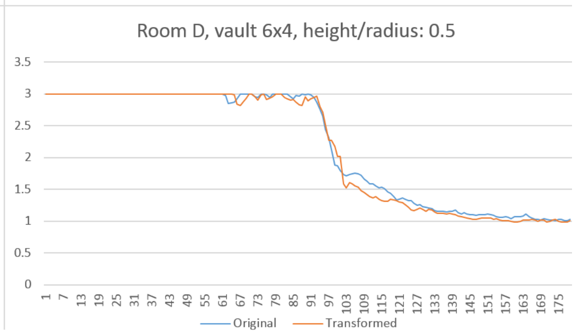


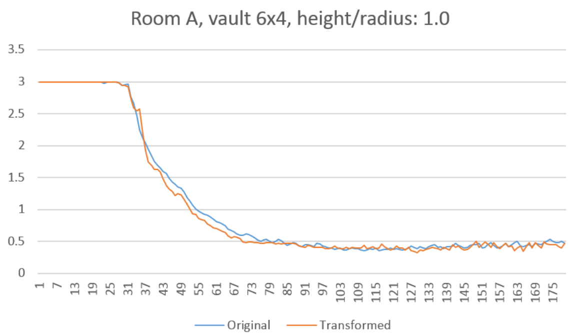


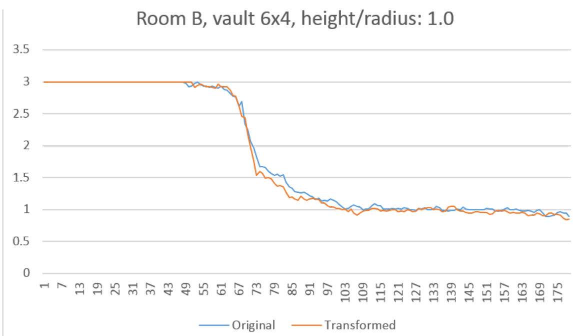


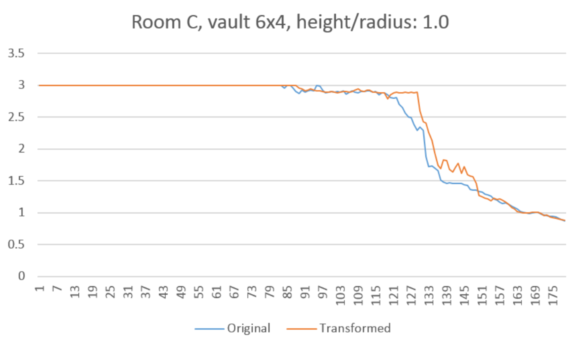


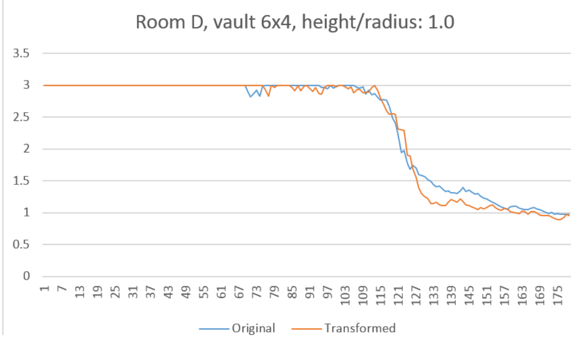


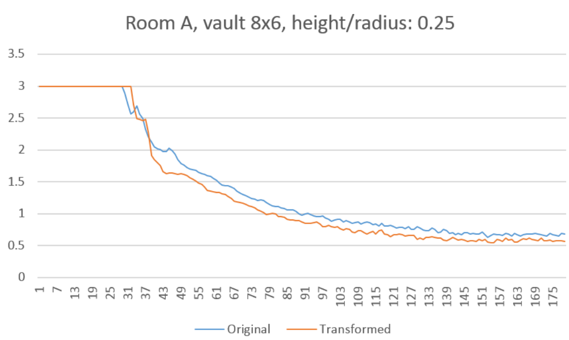


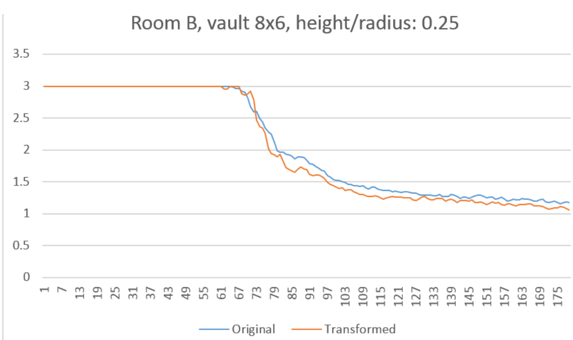

Room A, vault 6x4, height/radius: 1.0
Original
Transformed

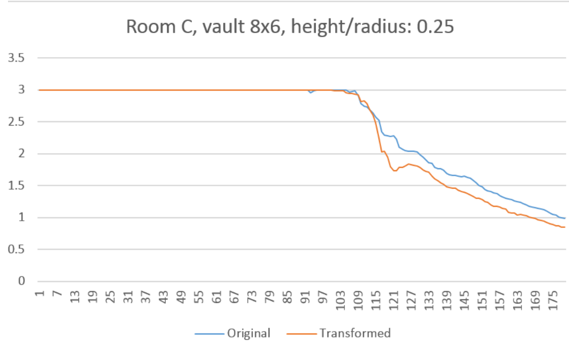

Room B, vault 6x4, height/radius: 1.0
Original
Transformed

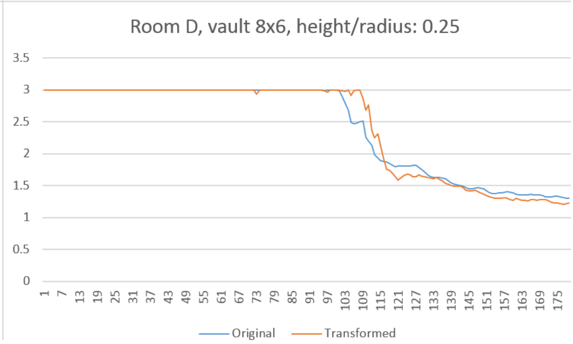

Room C, vault 6x4, height/radius: 1.0
Original
Transformed

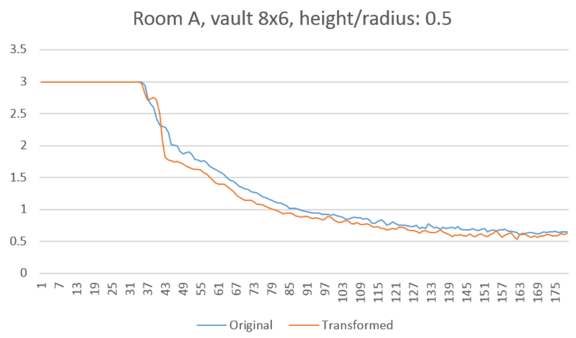

Room D, vault 6x4, height/radius: 1.0
Original
Transformed

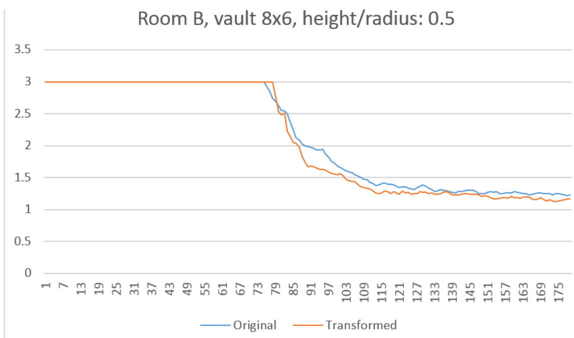

Room A, vault 8x6, height/radius: 0.25
Original
Transformed

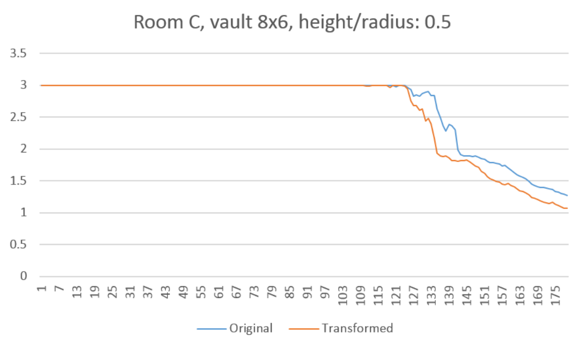

Room B, vault 8x6, height/radius: 0.25
Original
Transformed

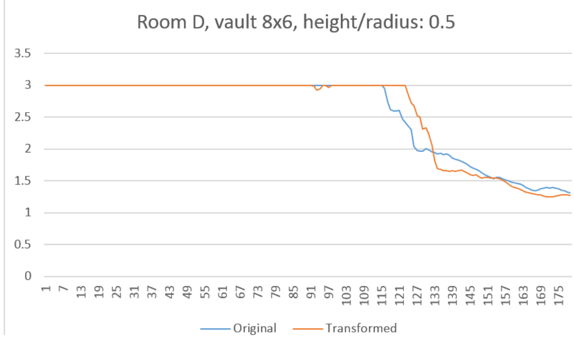

Room C, vault 8x6, height/radius: 0.25
Original
Transformed

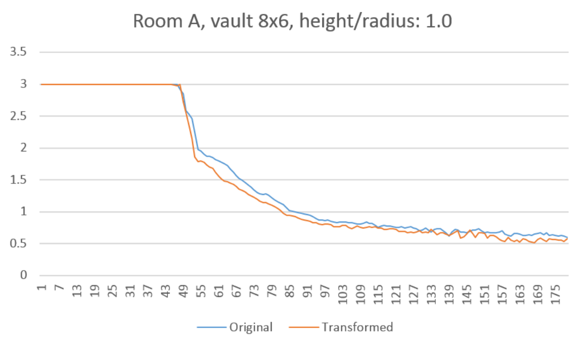

Room D, vault 8x6, height/radius: 0.25
Original
Transformed

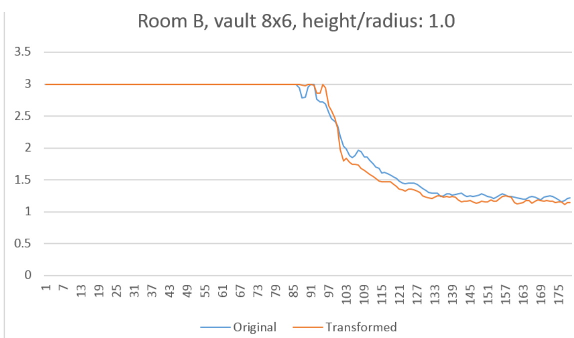

Room A, vault 8x6, height/radius: 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

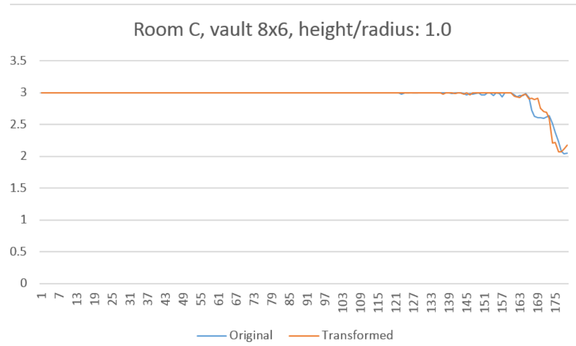

Room B, vault 8x6, height/radius: 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

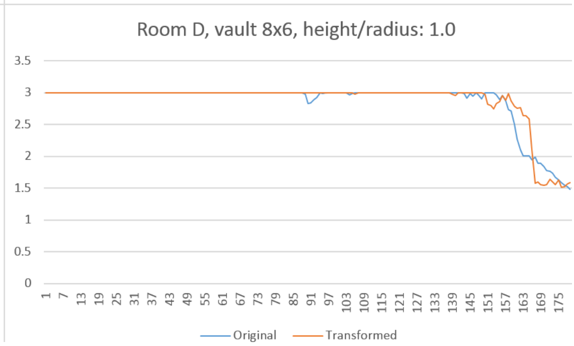

Room C, vault 8x6, height/radius: 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

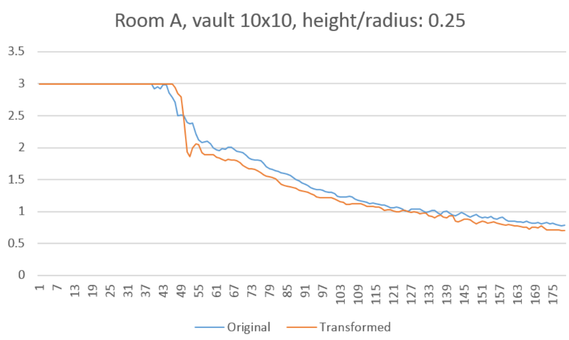

Room D, vault 8x6, height/radius: 0.5
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

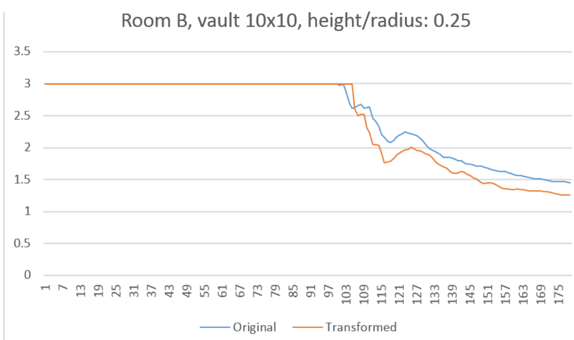

Room A, vault 8x6, height/radius: 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

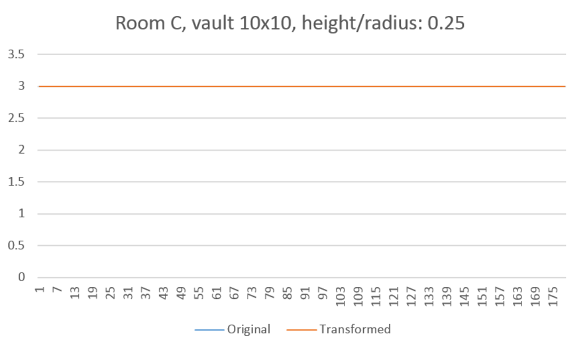

Room B, vault 8x6, height/radius: 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

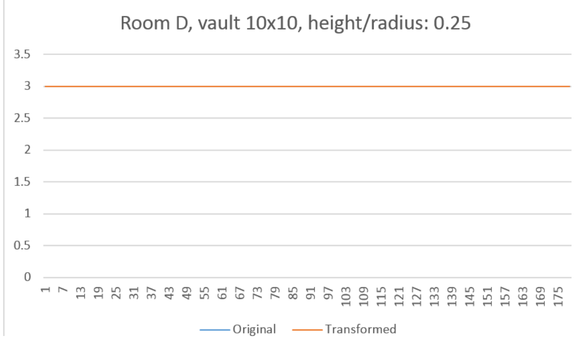

Room C, vault 8x6, height/radius: 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

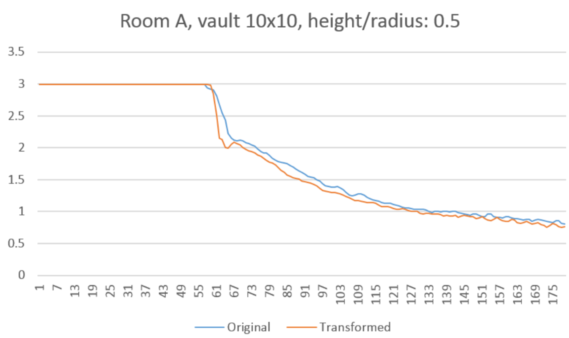

Room D, vault 8x6, height/radius: 1.0
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

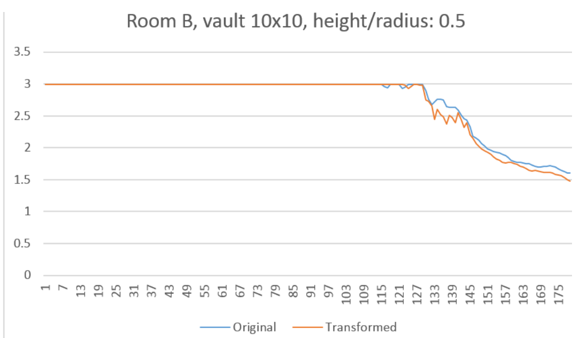

Room A, vault 10x10, height/radius: 0.25
Original
Transformed

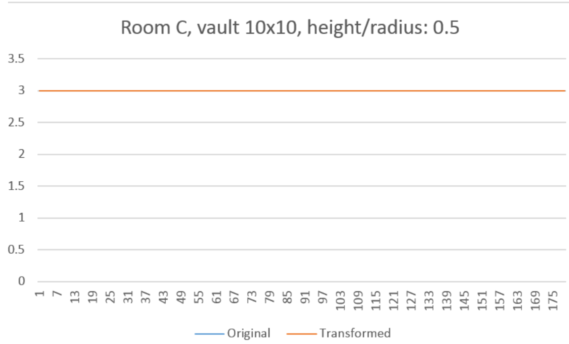

Room B, vault 10x10, height/radius: 0.25
Original
Transformed

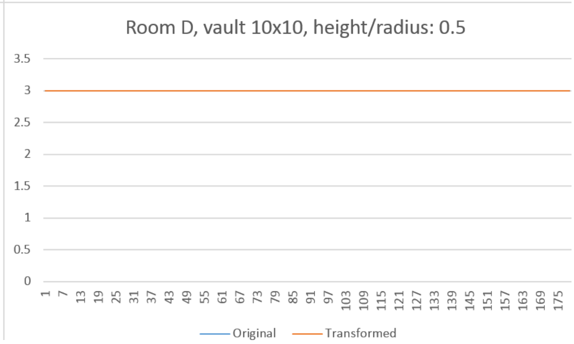

Room C, vault 10x10, height/radius: 0.25
Original
Transformed

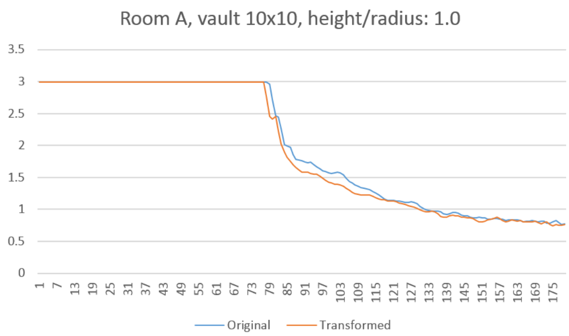

Room D, vault 10x10, height/radius: 0.25
Original
Transformed

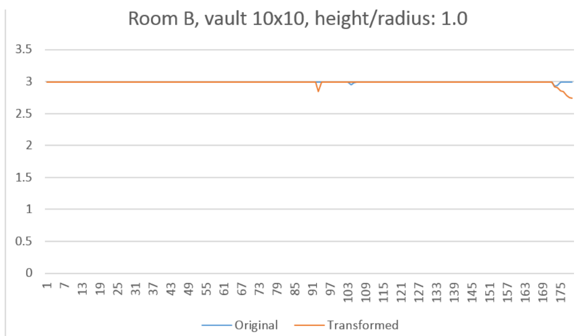

Room A, vault 10x10, height/radius: 0.5
Original
Transformed

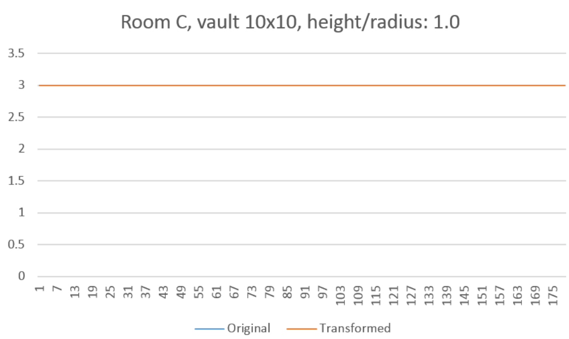

Room B, vault 10x10, height/radius: 0.5
Original
Transformed

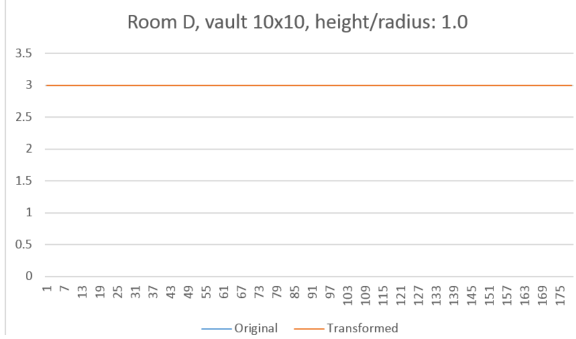

Room C, vault 10x10, height/radius: 0.5
Original
Transformed


Room D, vault 10x10, height/radius: 0.5
Original
Transformed

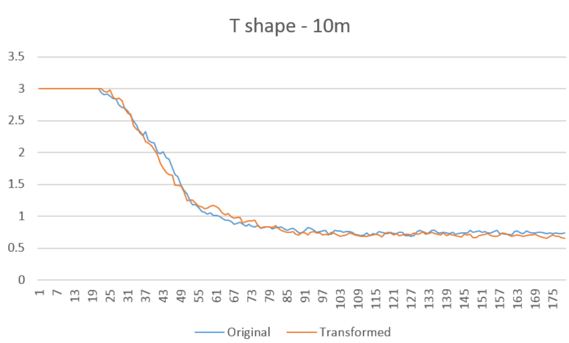


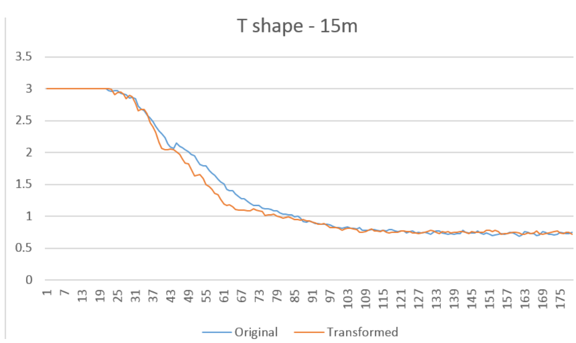


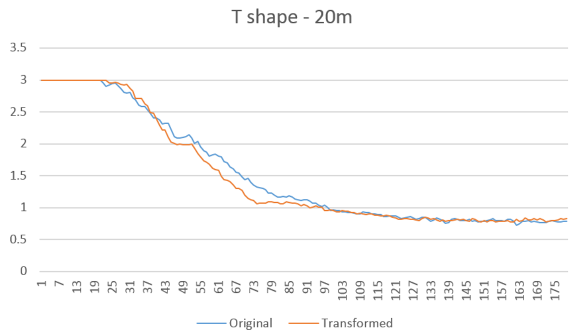


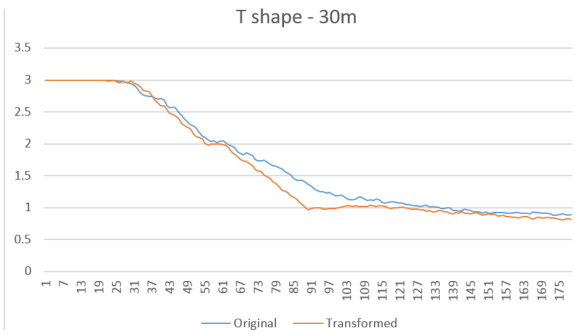


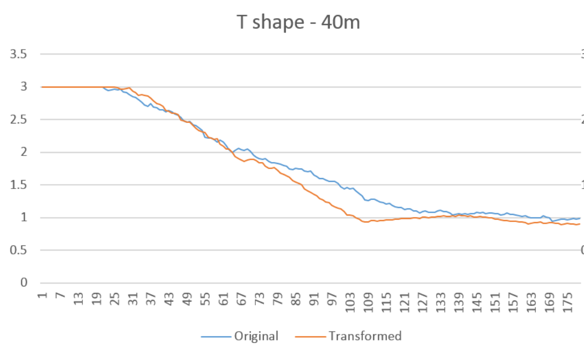
A.7 Corridors

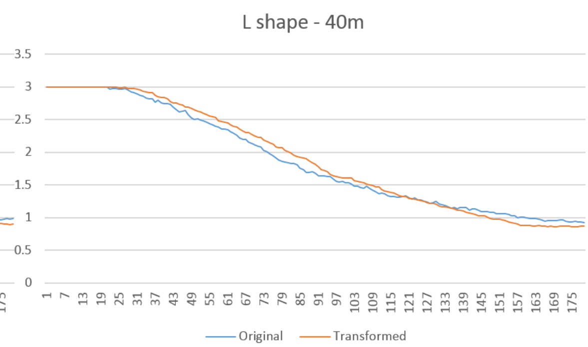


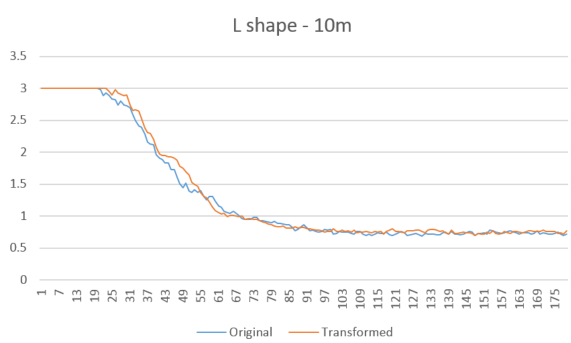


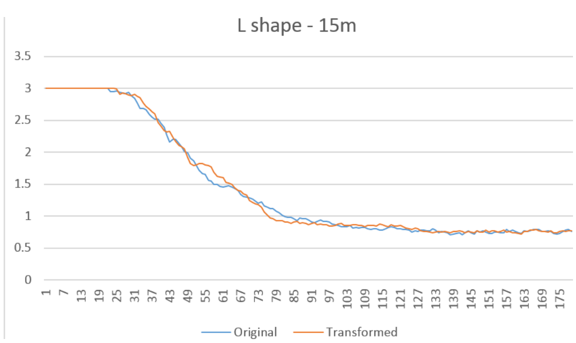

T shape - 20m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

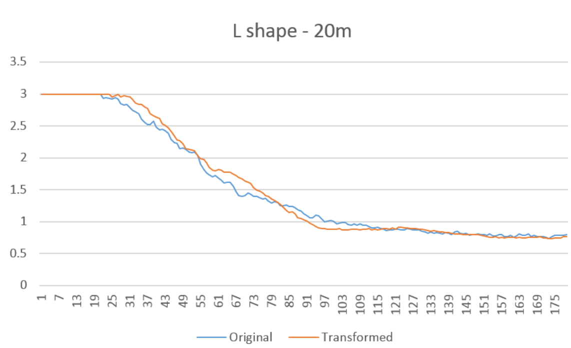

T shape - 30m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

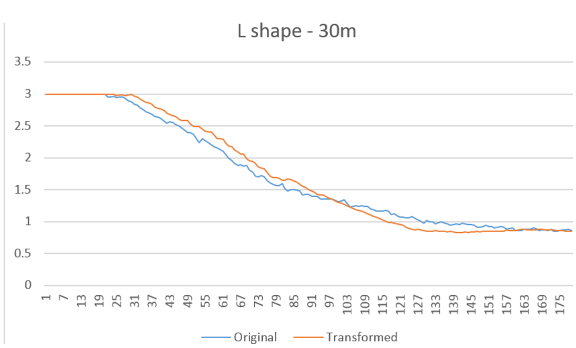

T shape - 40m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

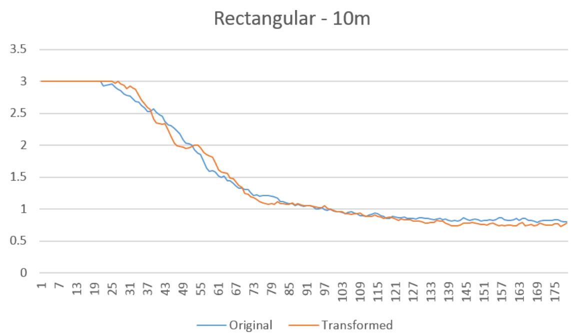

L shape - 40m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

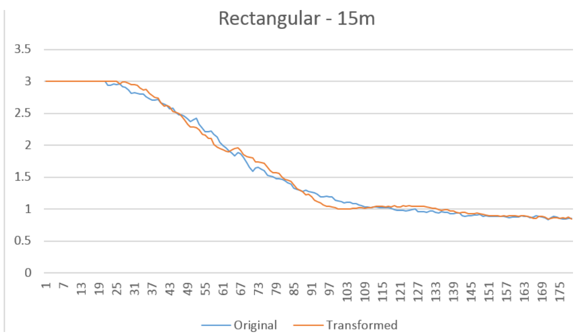

L shape - 10m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

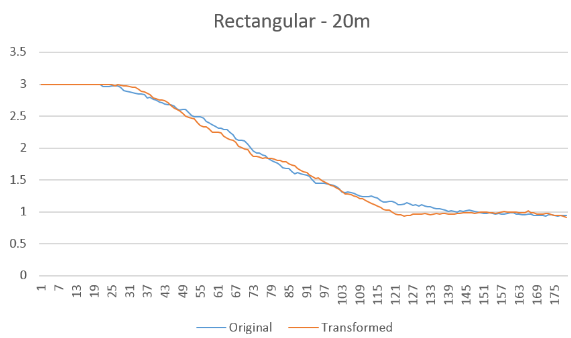

L shape - 15m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

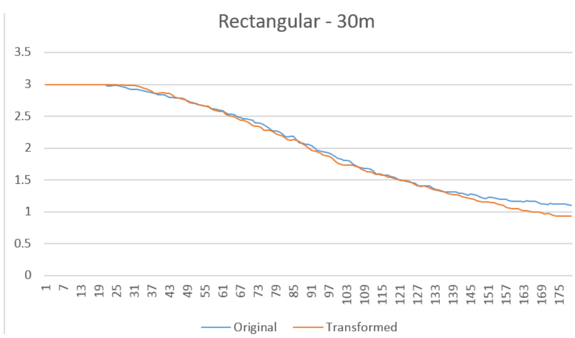

L shape - 20m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

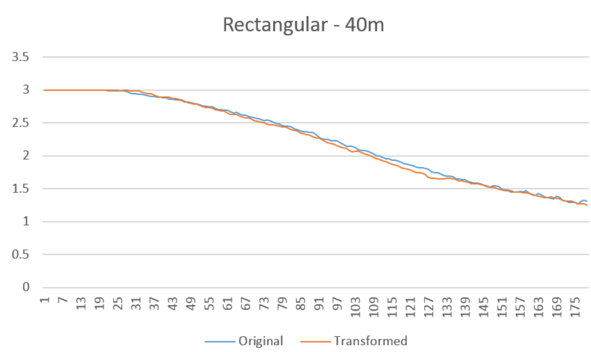

L shape - 30m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed


Rectangular - 10m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed


Rectangular - 15m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed


Rectangular - 20m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed


Rectangular - 30m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed


Rectangular - 40m
3.5
3
2.5
2
1.5
1
0.5
0
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85 91 97 103 109 115 121 127 133 139 145 151 157 163 169 175
Original
Transformed

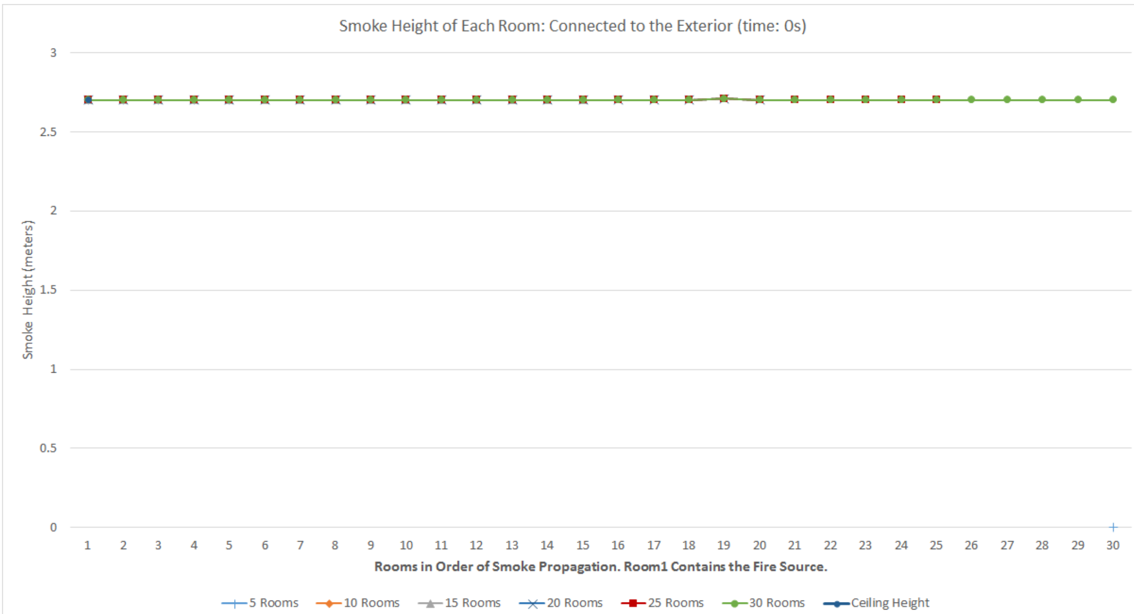
APPENDIX B

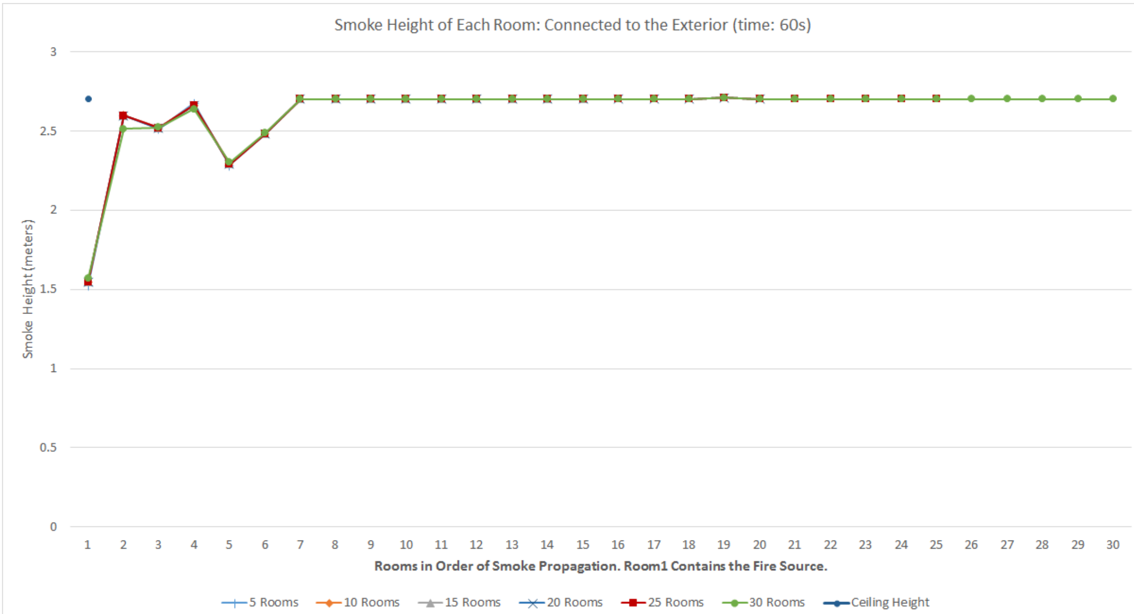
VALIDATION TEST RESULTS FOR THE ROOM SELECTION ALGORITHM

To investigate the validity of the room selection algorithm, a set of validation tests have been performed. A Revit model with exactly 30 rooms was built as the test model. First, the entire model of 30 rooms was simulated using CFAST, the results of which were set as the baseline that all following simulations were compared to. Then, part of the rooms were selected from the 30 rooms using the room selection algorithm: 25, 20, 15, 10, and 5 rooms respectively. The results of the selected rooms were compared with the baseline as shown in the following graphs. Among the simulation results, two of the most critical indicators were selected for comparison: smoke height and CO concentration.

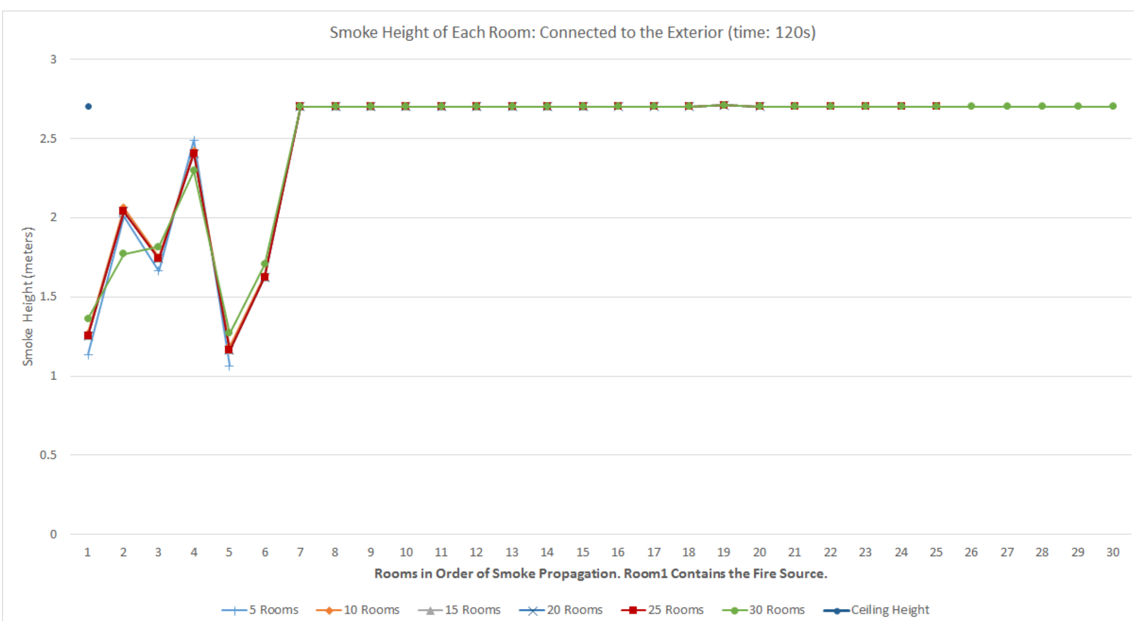
B.1 Smoke Height

B.1.1 Ignoring Scheme/ Connected to the Exterior

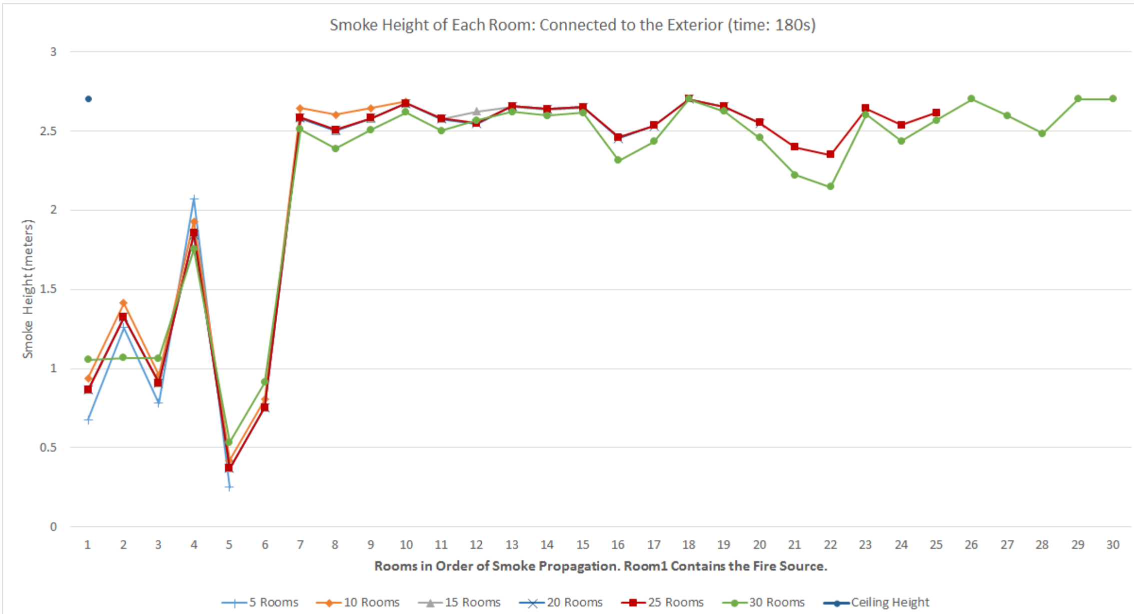


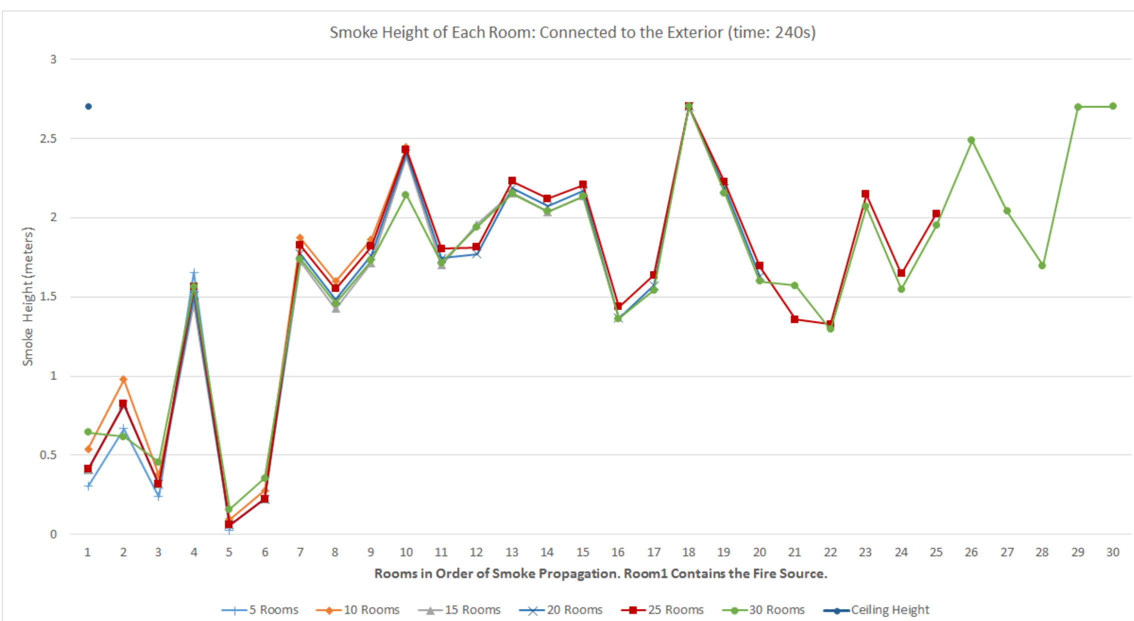


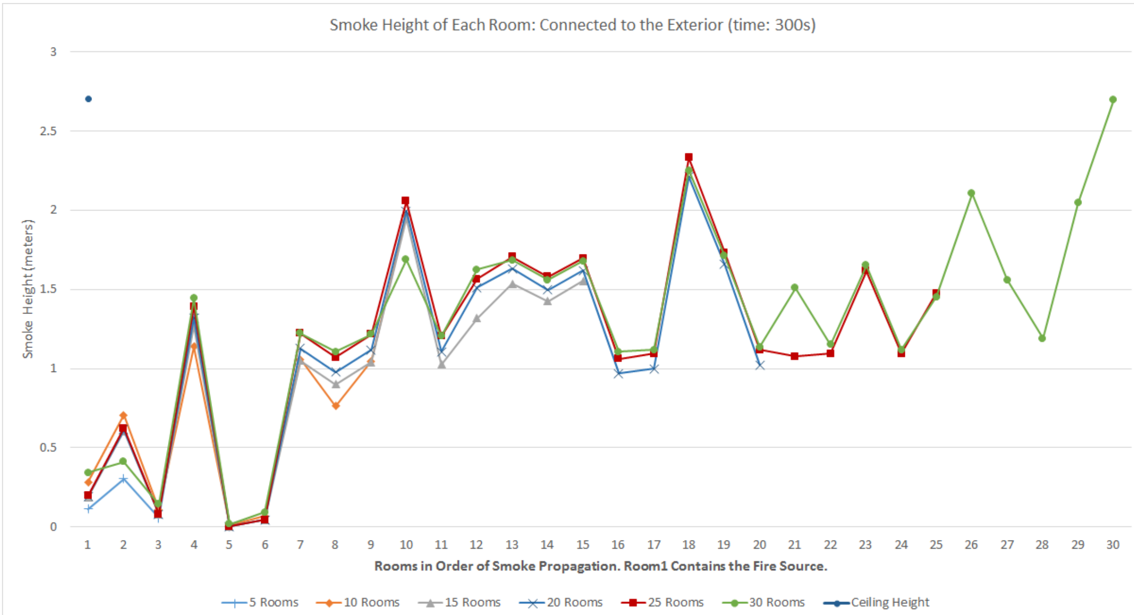
Smoke Height of Each Room: Connected to the Exterior (time: 60s)
Smoke Height (meters)
3
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height



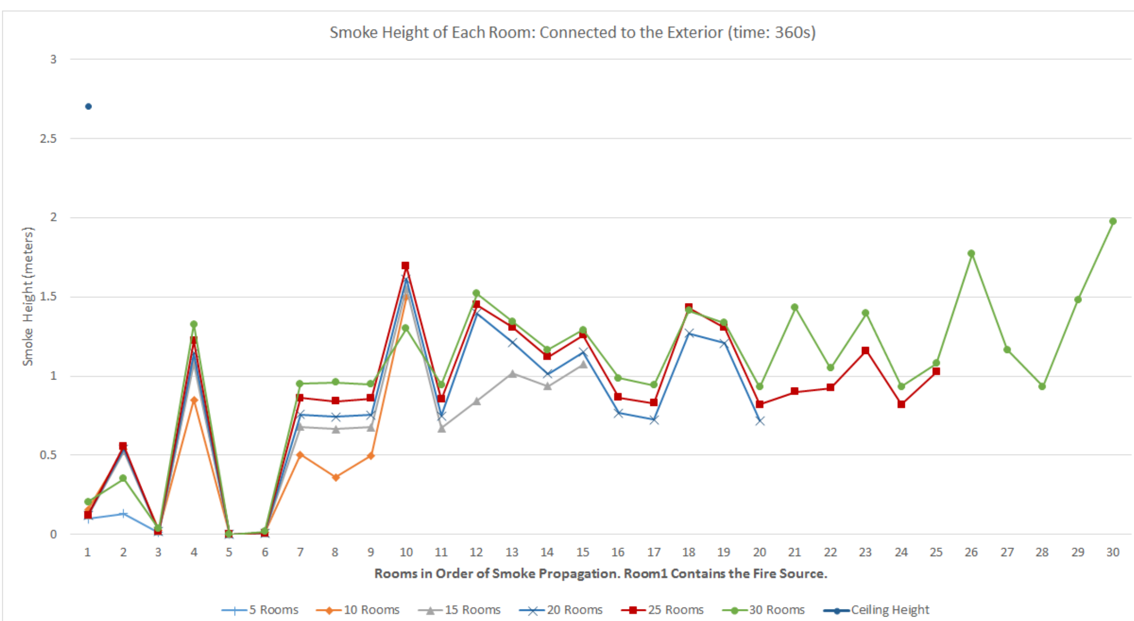
Smoke Height of Each Room: Connected to the Exterior (time: 120s)
Smoke Height (meters)
3
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height


Smoke Height of Each Room: Connected to the Exterior (time: 180s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

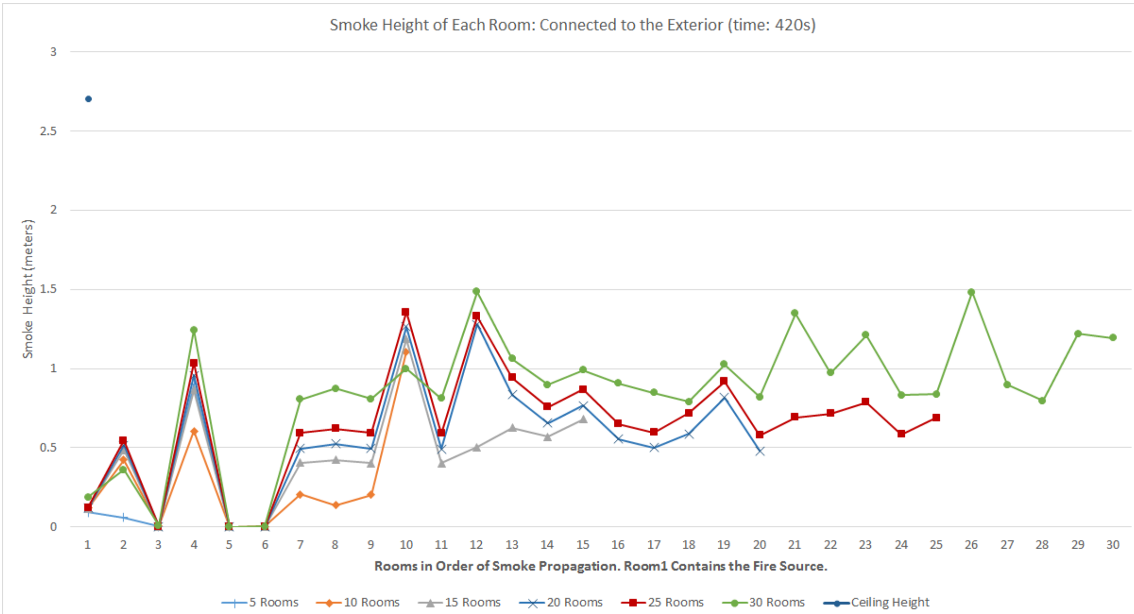

Smoke Height of Each Room: Connected to the Exterior (time: 240s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height



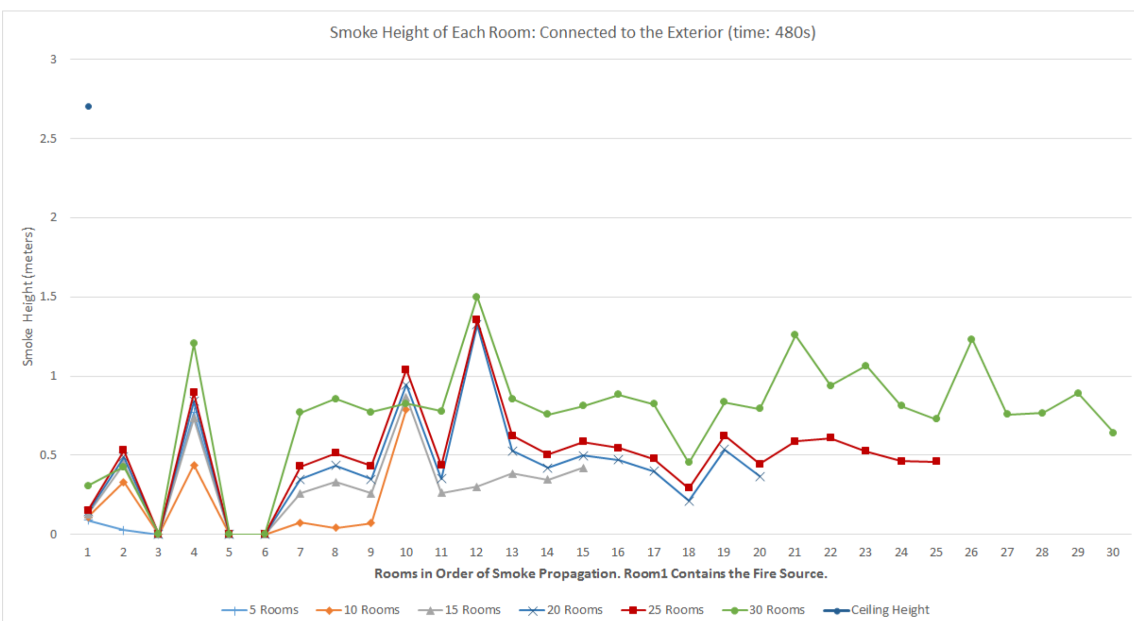
Smoke Height of Each Room: Connected to the Exterior (time: 300s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height



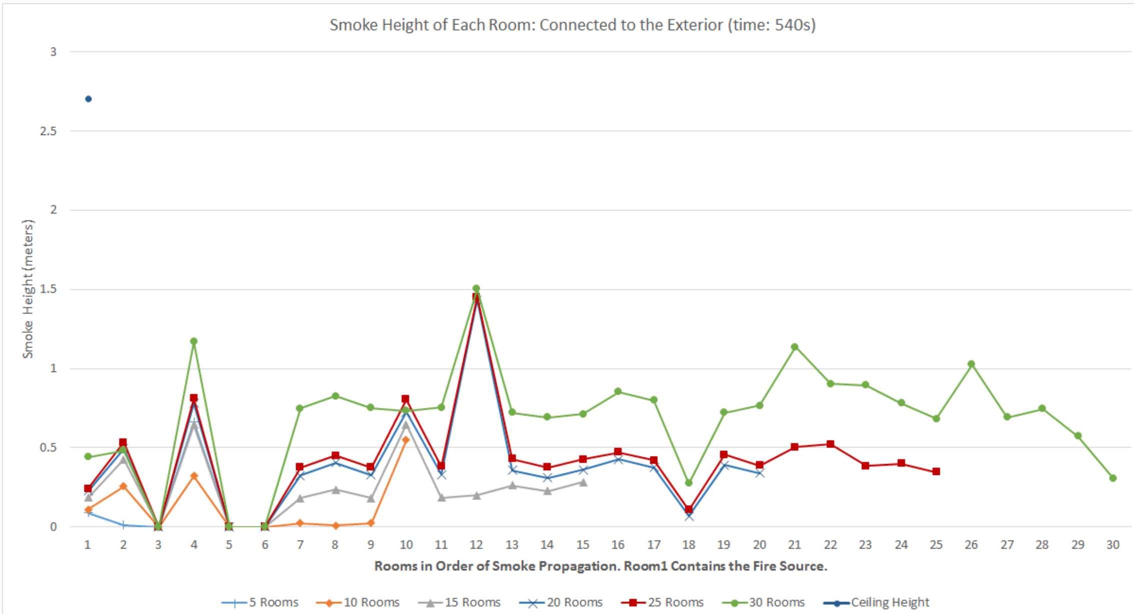
Smoke Height of Each Room: Connected to the Exterior (time: 360s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

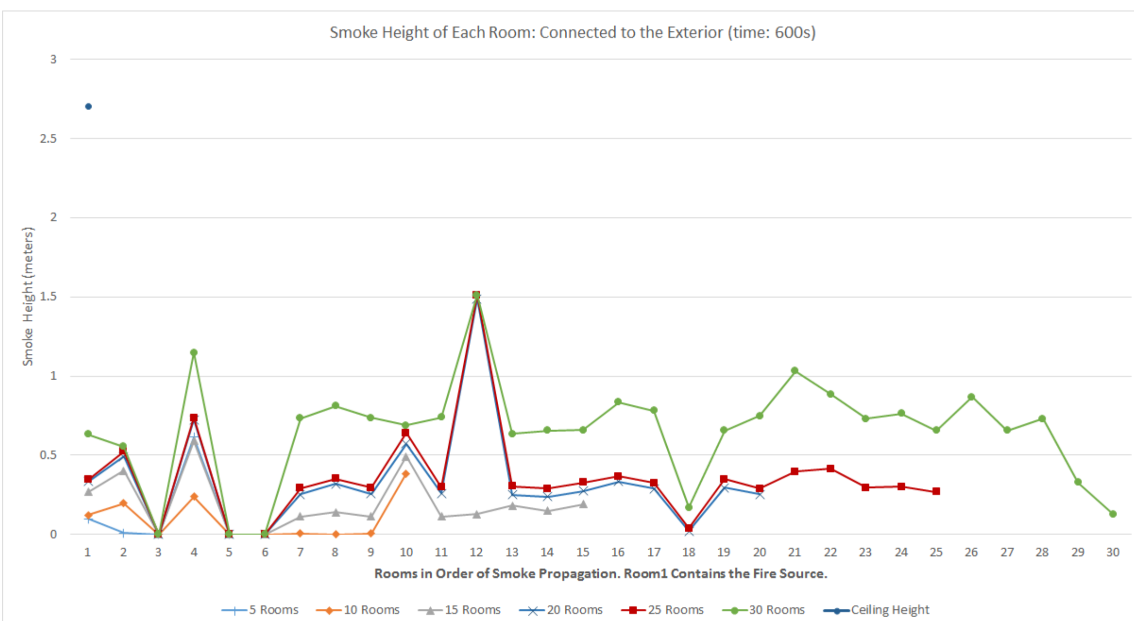


Smoke Height of Each Room: Connected to the Exterior (time: 420s)
Smoke Height (meters)
3
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

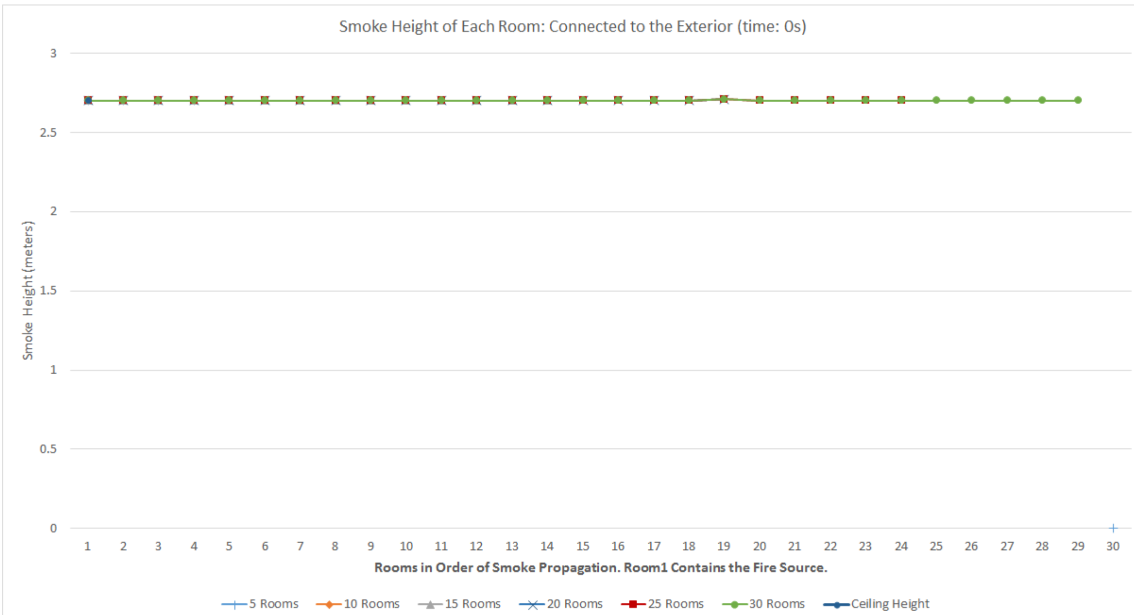


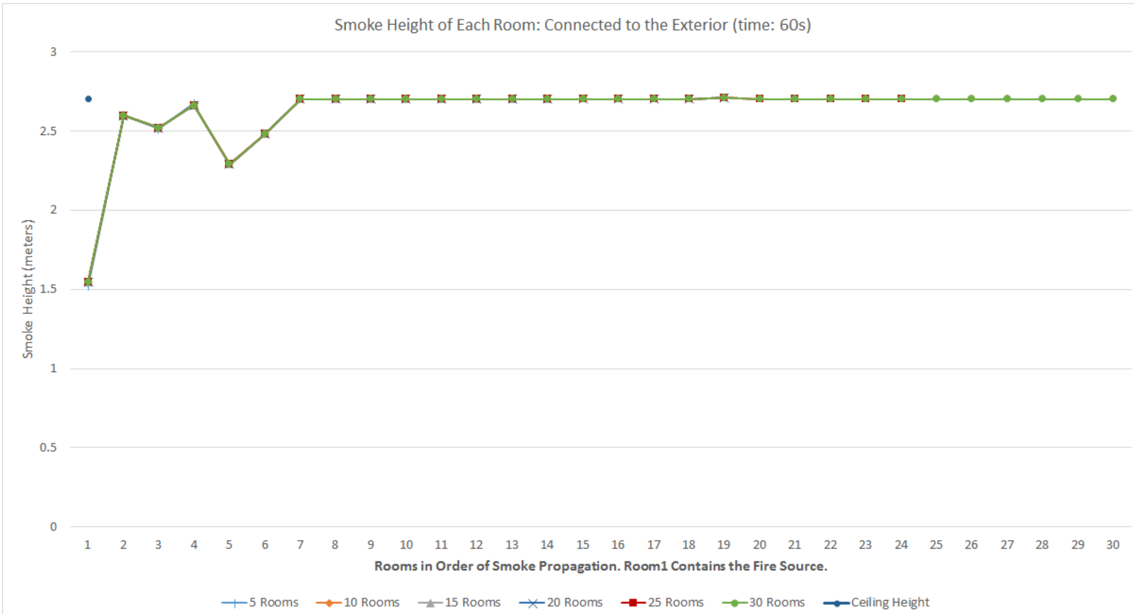
Smoke Height of Each Room: Connected to the Exterior (time: 480s)
Smoke Height (meters)
3
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

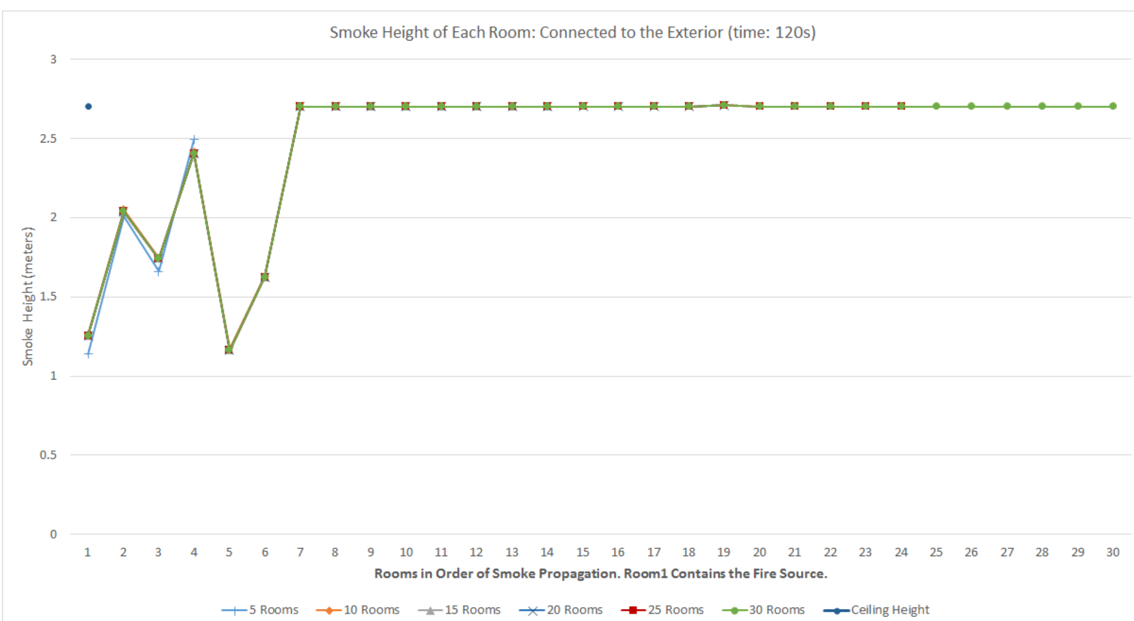

Smoke Height of Each Room: Connected to the Exterior (time: 540s)
Smoke Height (meters)
3
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

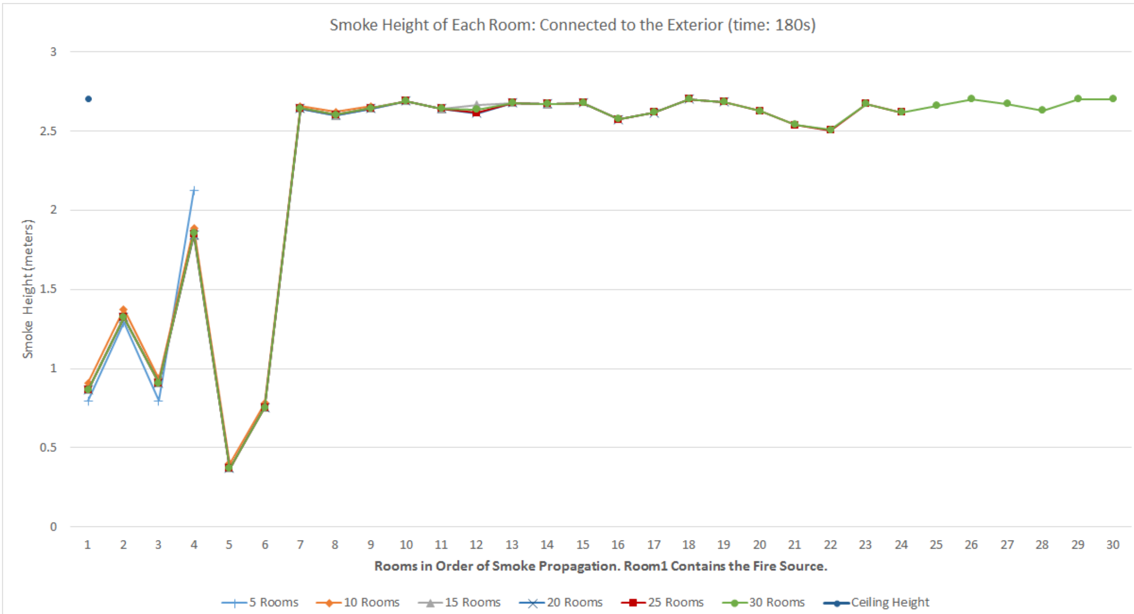

Smoke Height of Each Room: Connected to the Exterior (time: 600s)
Smoke Height (meters)
3
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

B.1.2 Merging Scheme/ Connected to the Exterior

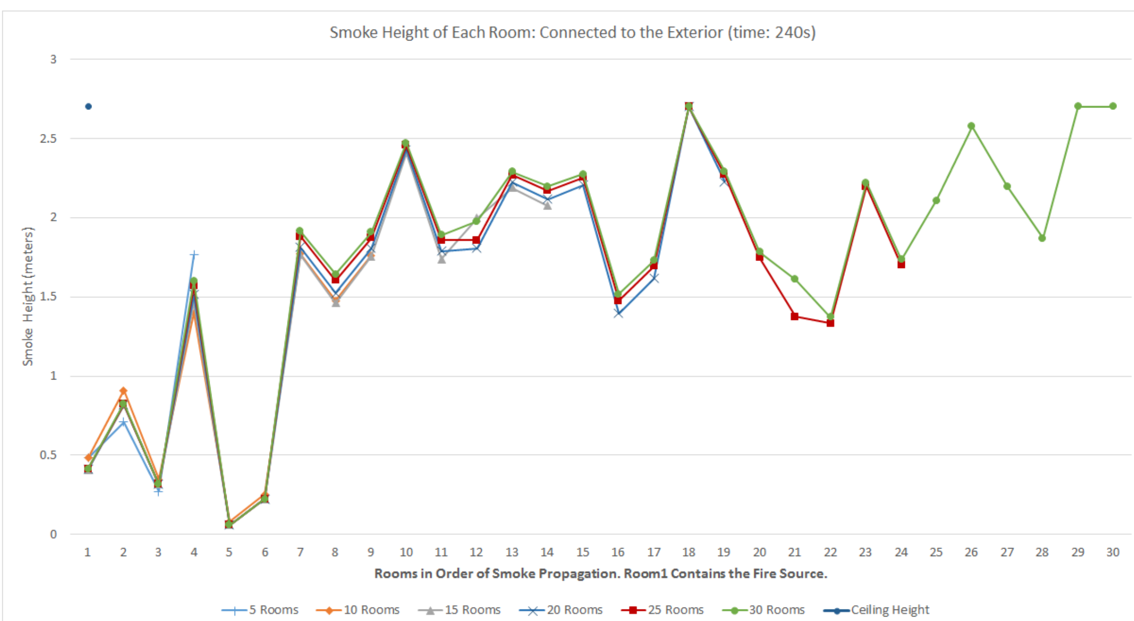



Smoke Height of Each Room: Connected to the Exterior (time: 60s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

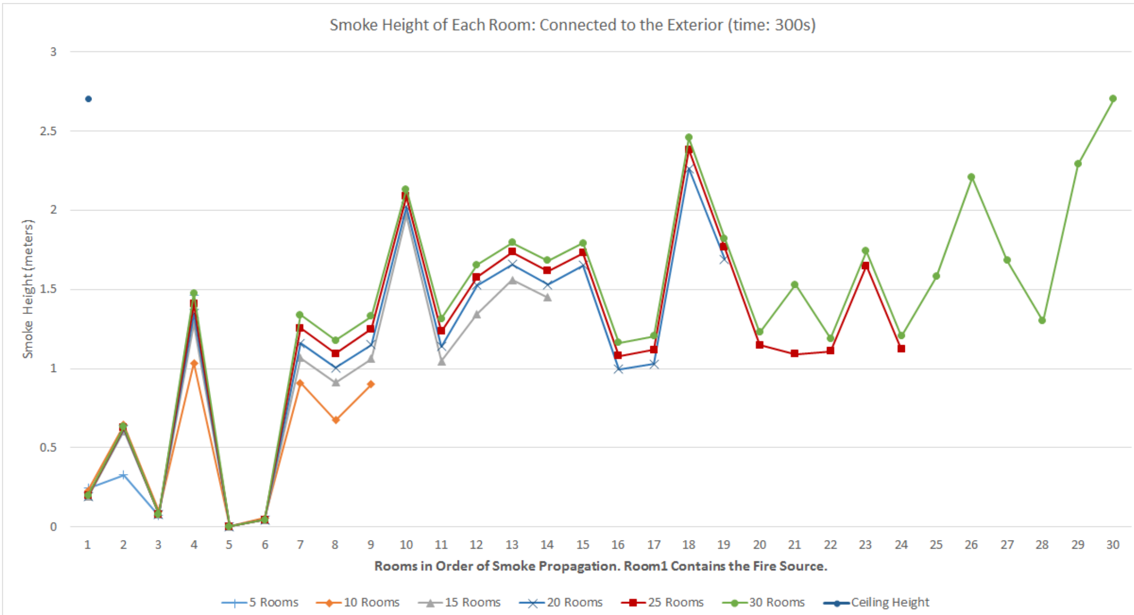

Smoke Height of Each Room: Connected to the Exterior (time: 120s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height



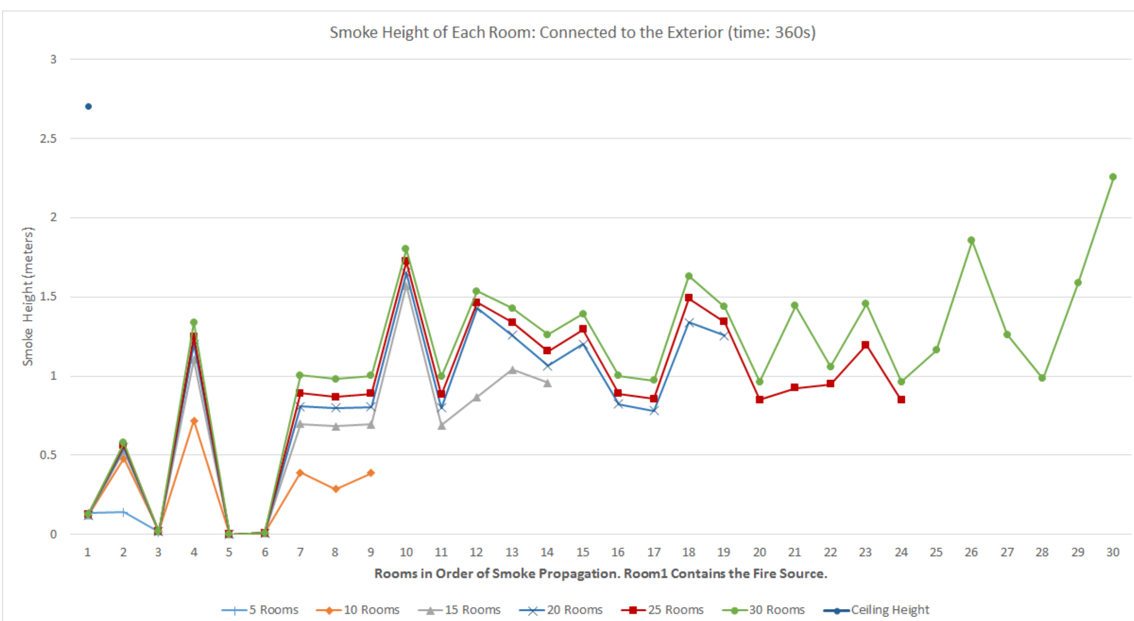
Smoke Height of Each Room: Connected to the Exterior (time: 180s)
Smoke Height (meters)
3
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height



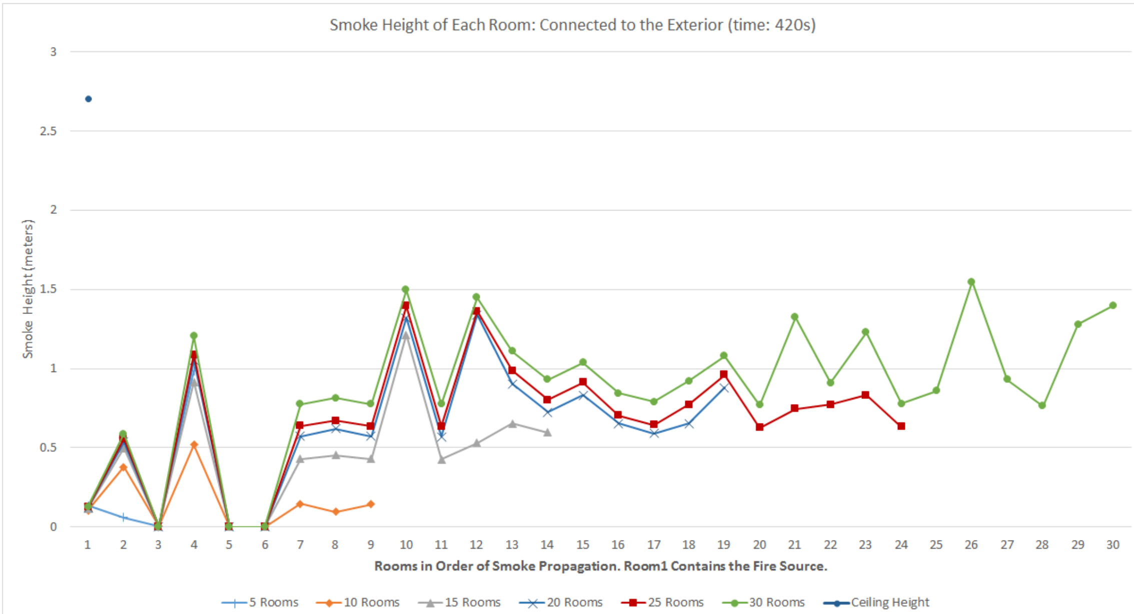
Smoke Height of Each Room: Connected to the Exterior (time: 240s)
Smoke Height (meters)
3
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

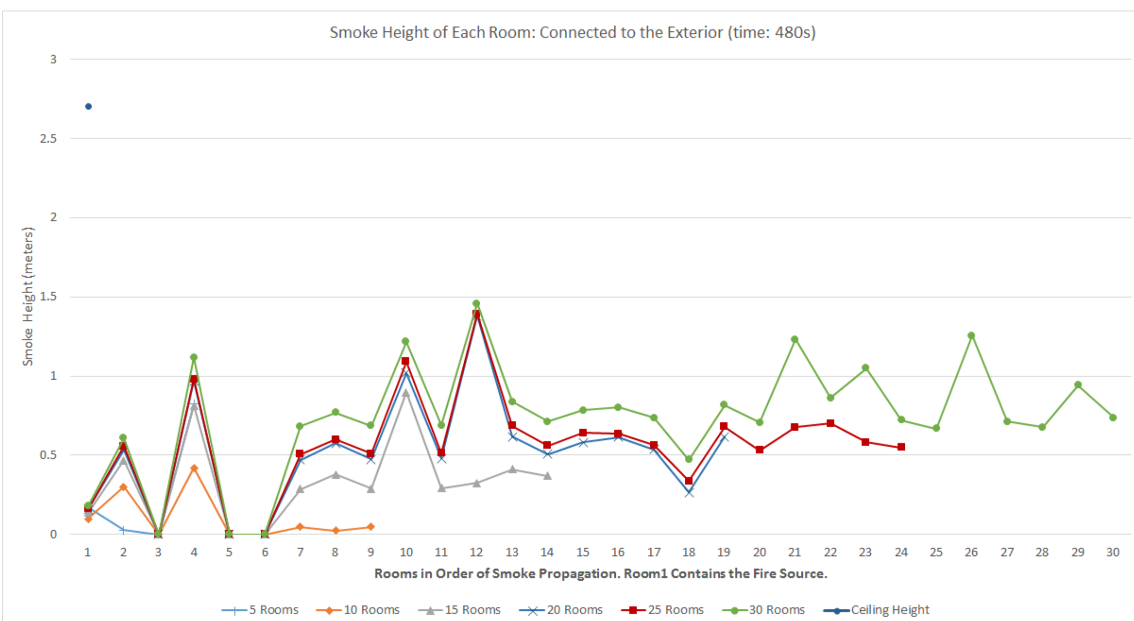


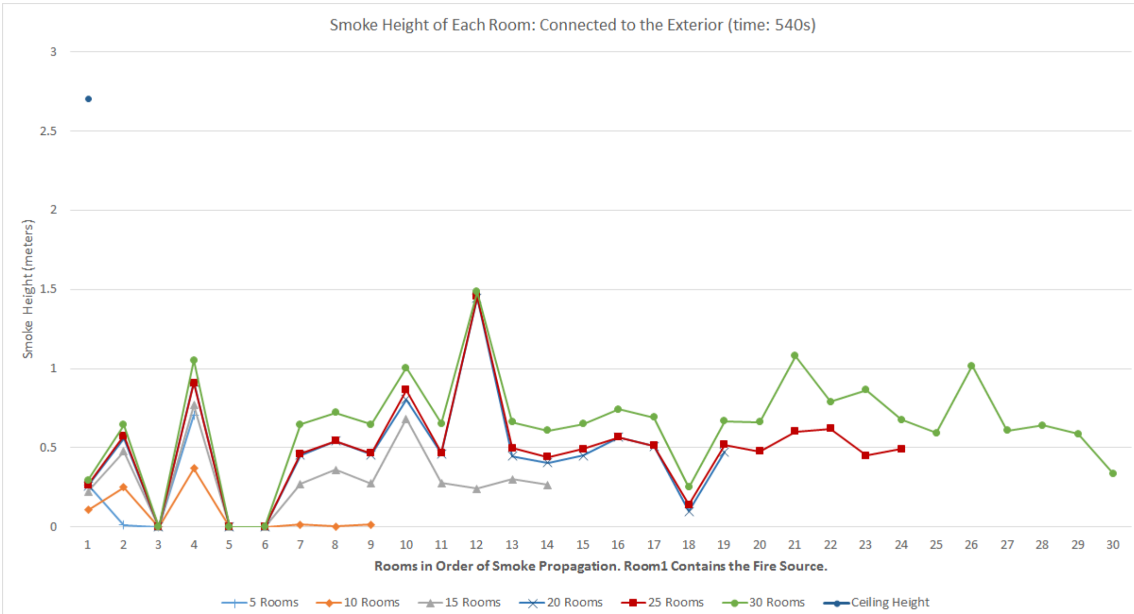
Smoke Height of Each Room: Connected to the Exterior (time: 300s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

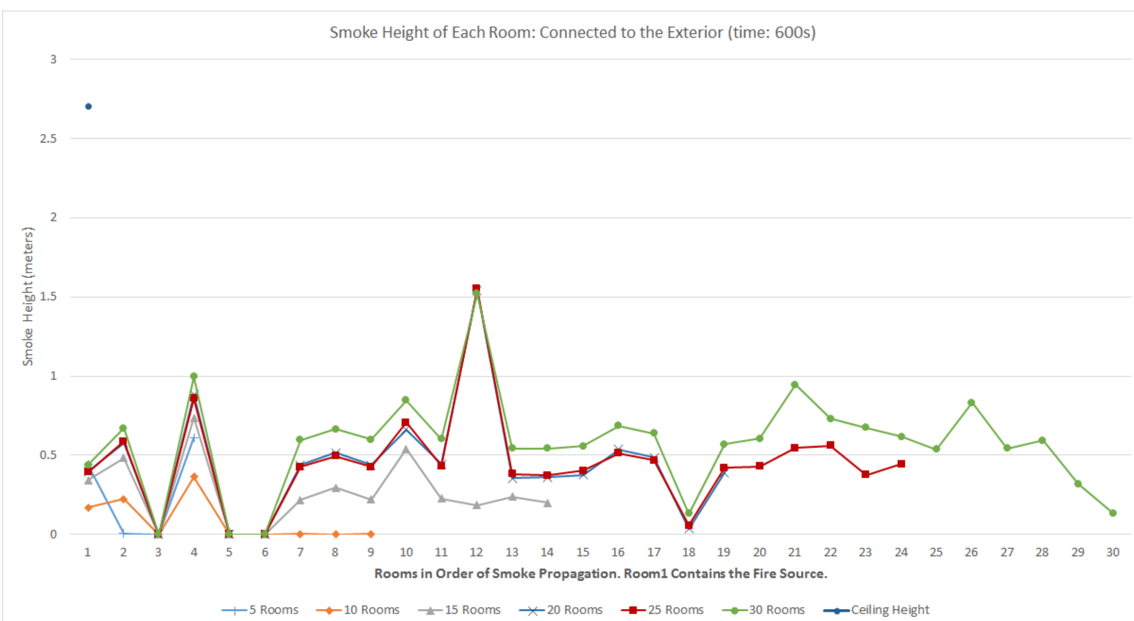


Smoke Height of Each Room: Connected to the Exterior (time: 360s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

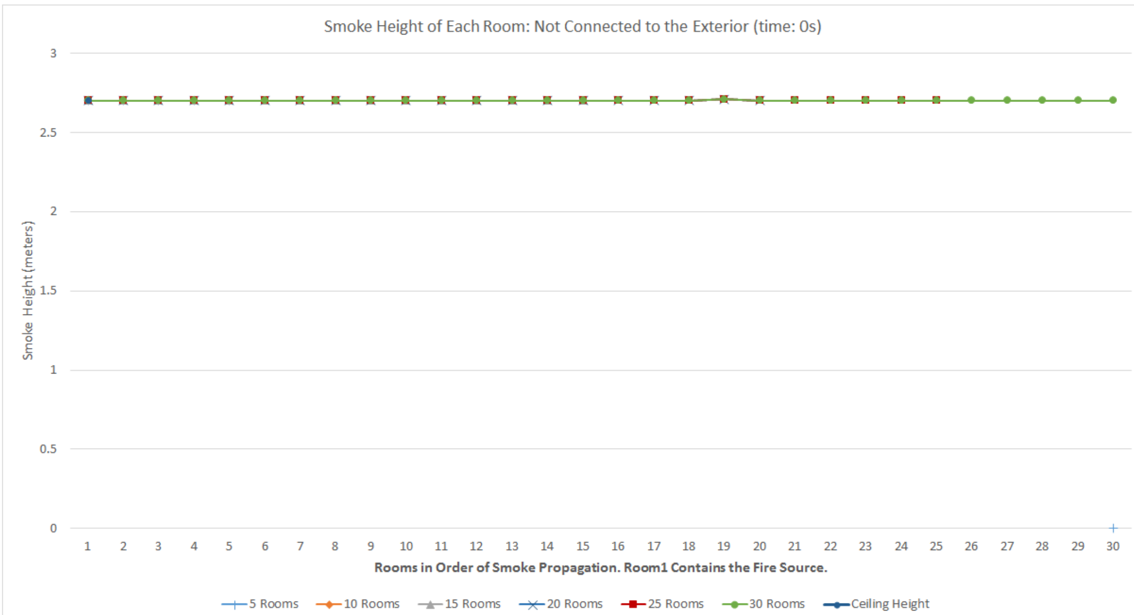

Smoke Height of Each Room: Connected to the Exterior (time: 420s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

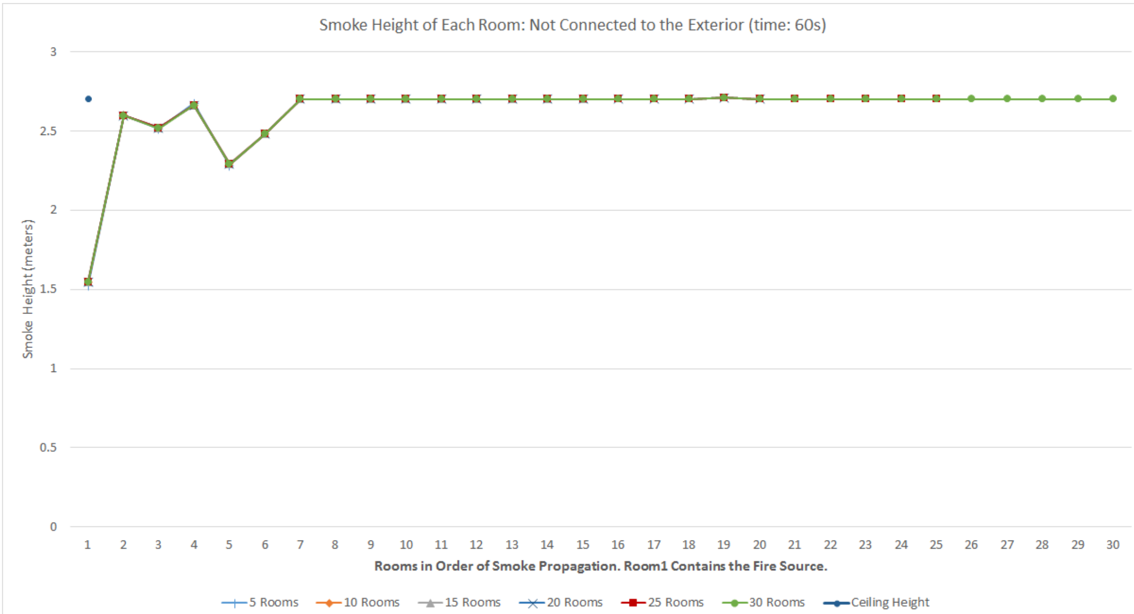

Smoke Height of Each Room: Connected to the Exterior (time: 480s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

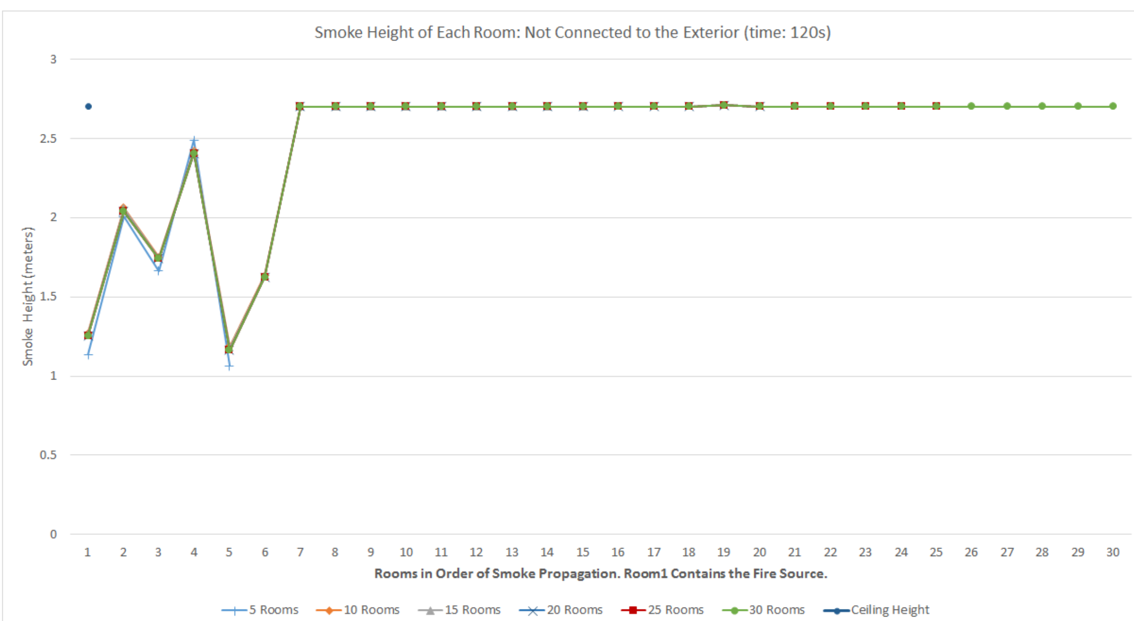

Smoke Height of Each Room: Connected to the Exterior (time: 540s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

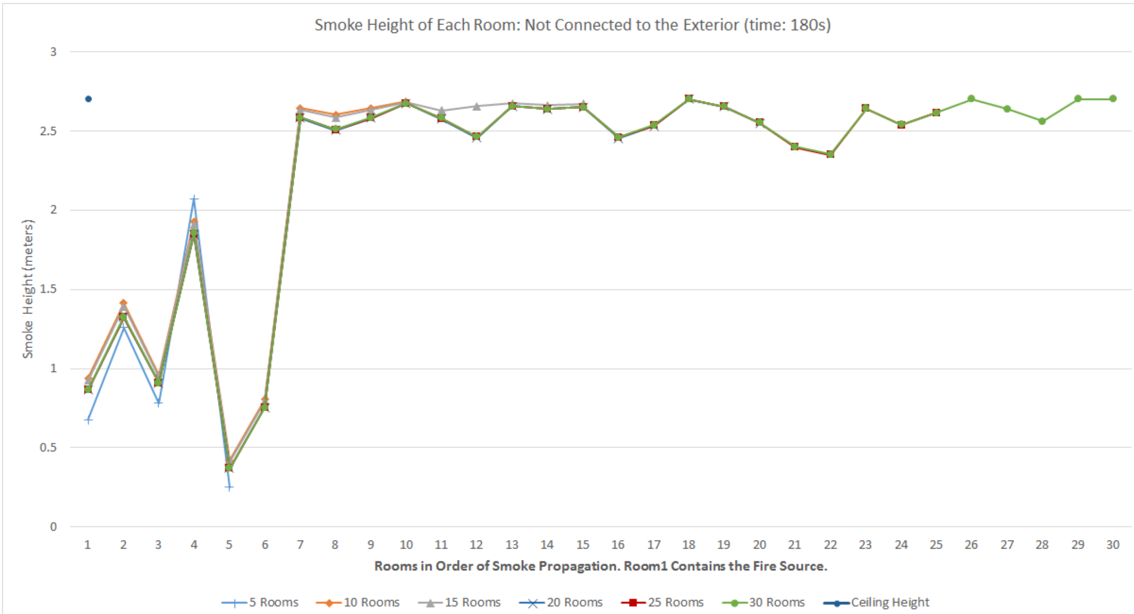

Smoke Height of Each Room: Connected to the Exterior (time: 600s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

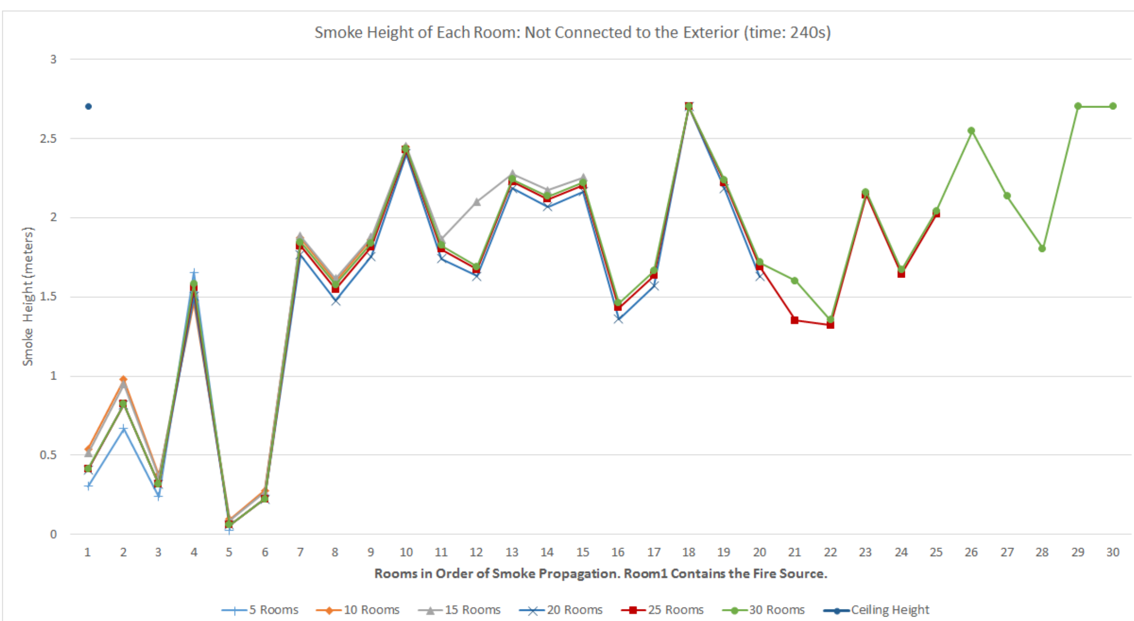
B.1.3 Ignoring Scheme/ Not Connected to the Exterior

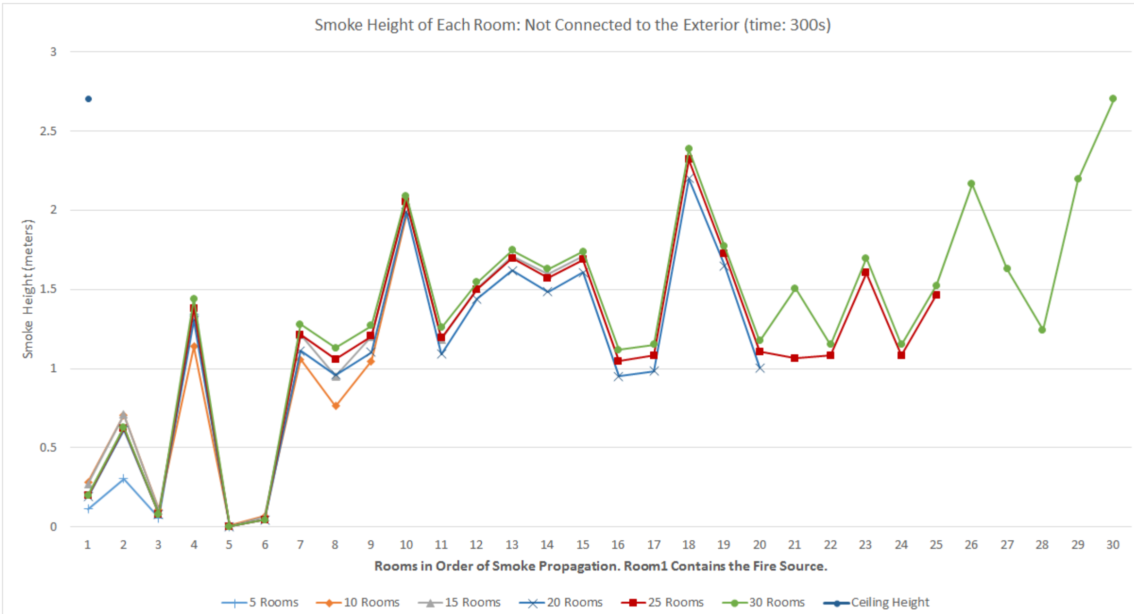


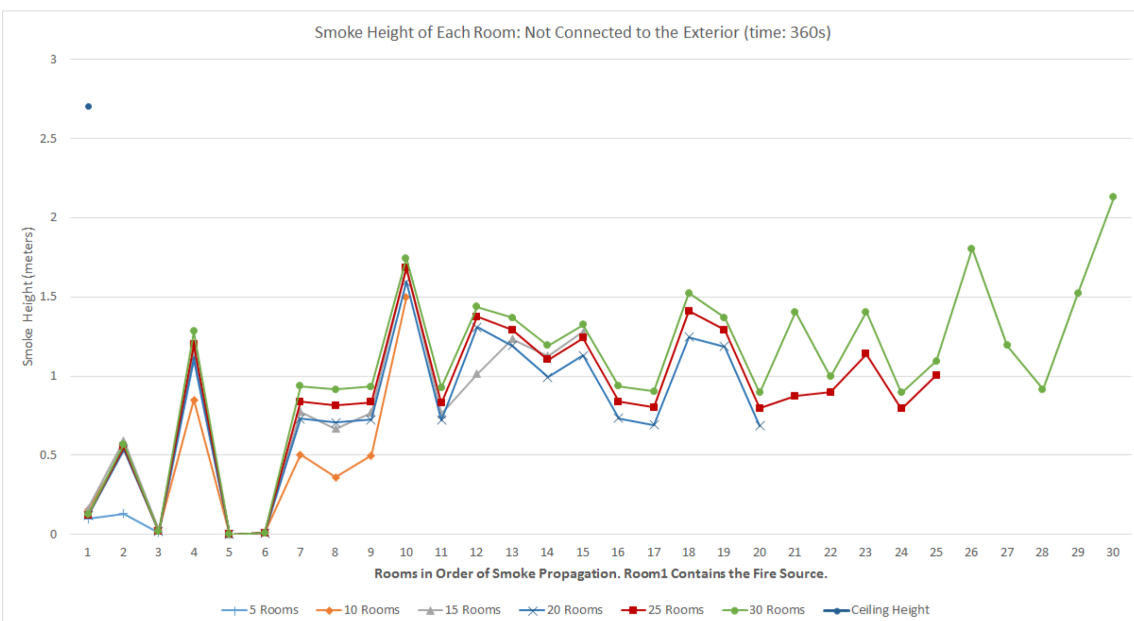

Smoke Height of Each Room: Not Connected to the Exterior (time: 60s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

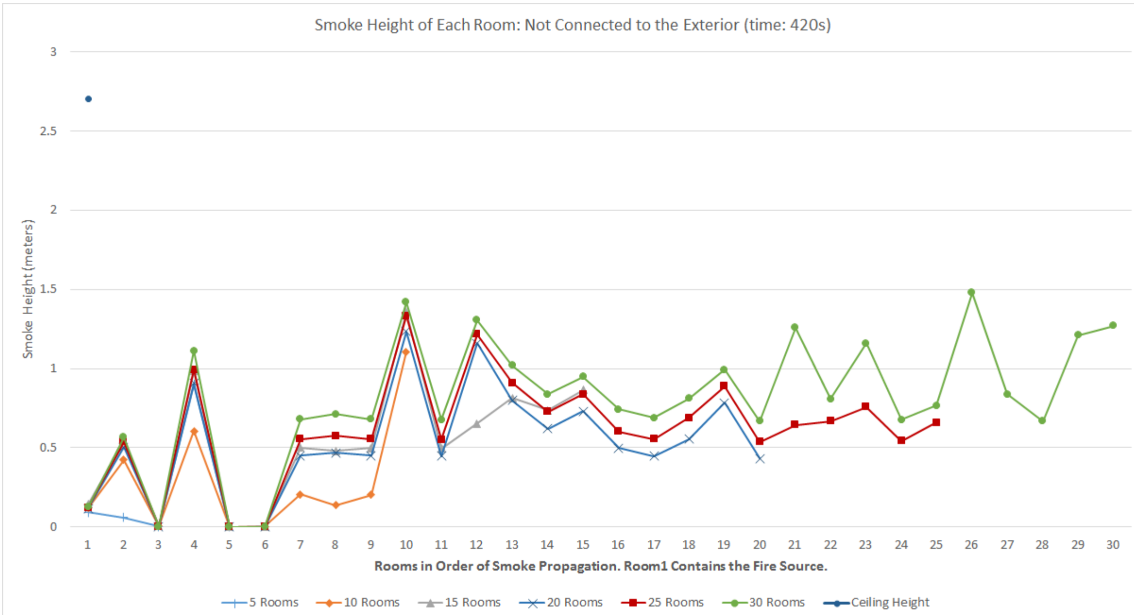

Smoke Height of Each Room: Not Connected to the Exterior (time: 120s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

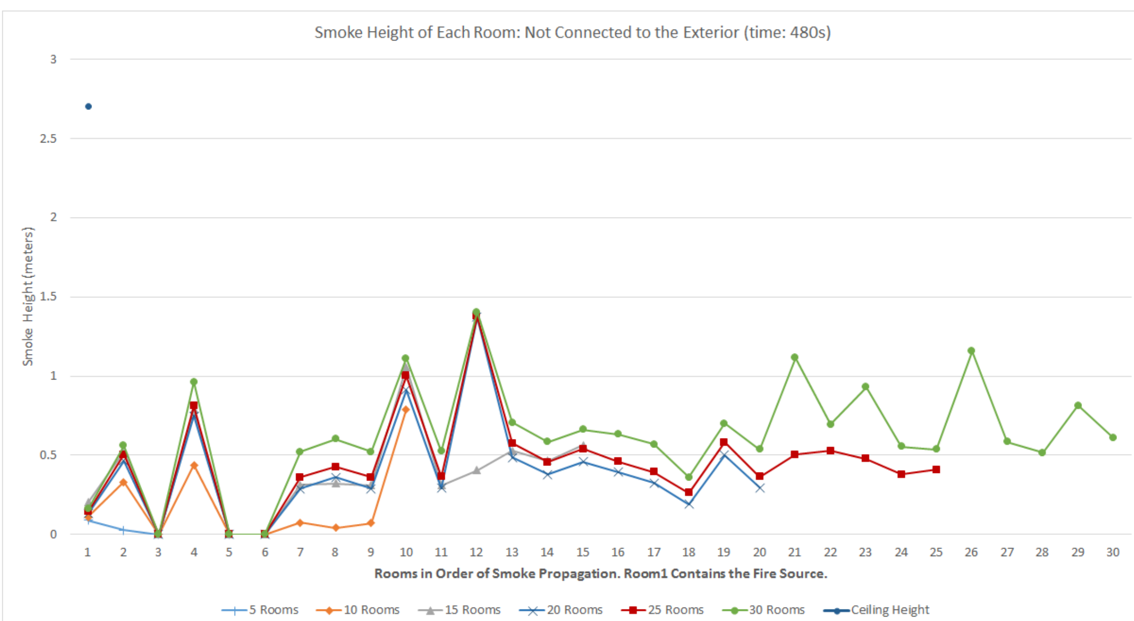

Smoke Height of Each Room: Not Connected to the Exterior (time: 180s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

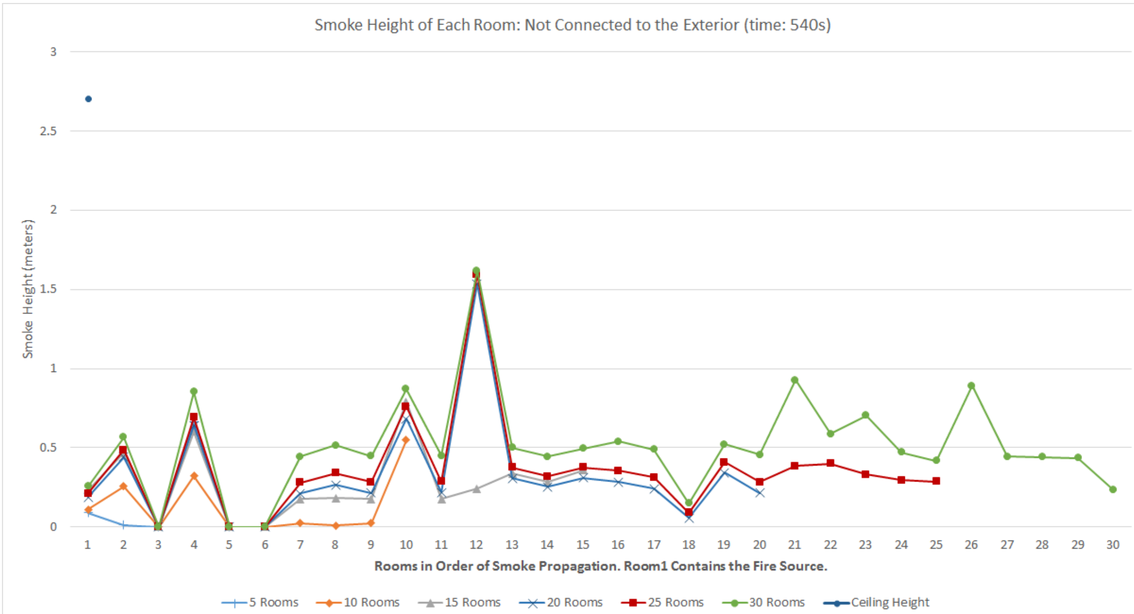

Smoke Height of Each Room: Not Connected to the Exterior (time: 240s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

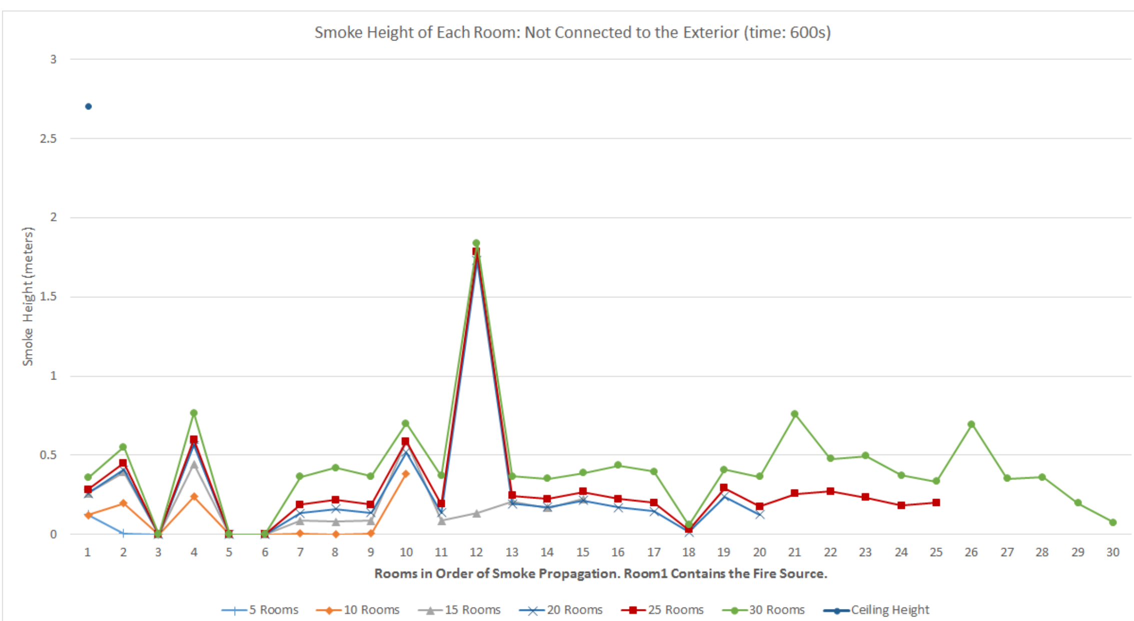

Smoke Height of Each Room: Not Connected to the Exterior (time: 300s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height


Smoke Height of Each Room: Not Connected to the Exterior (time: 360s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

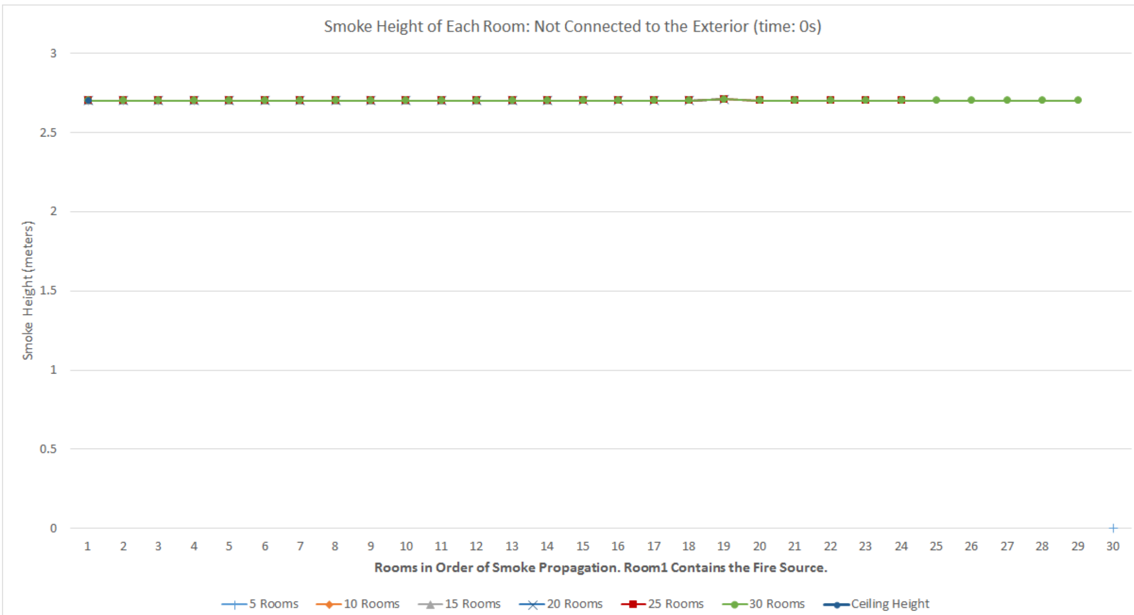

Smoke Height of Each Room: Not Connected to the Exterior (time: 420s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

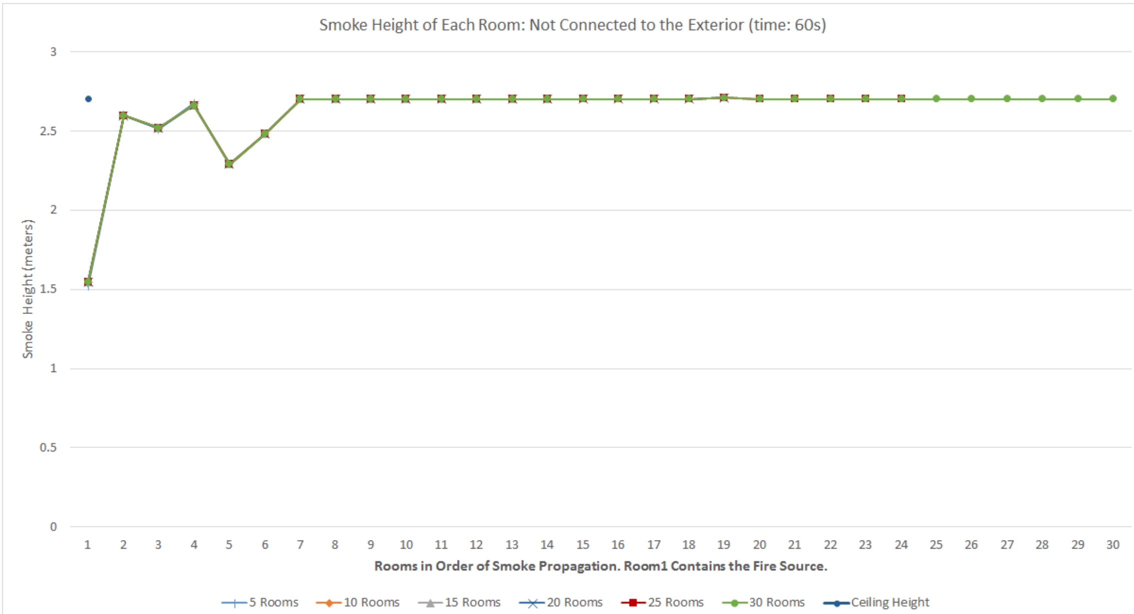

Smoke Height of Each Room: Not Connected to the Exterior (time: 480s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

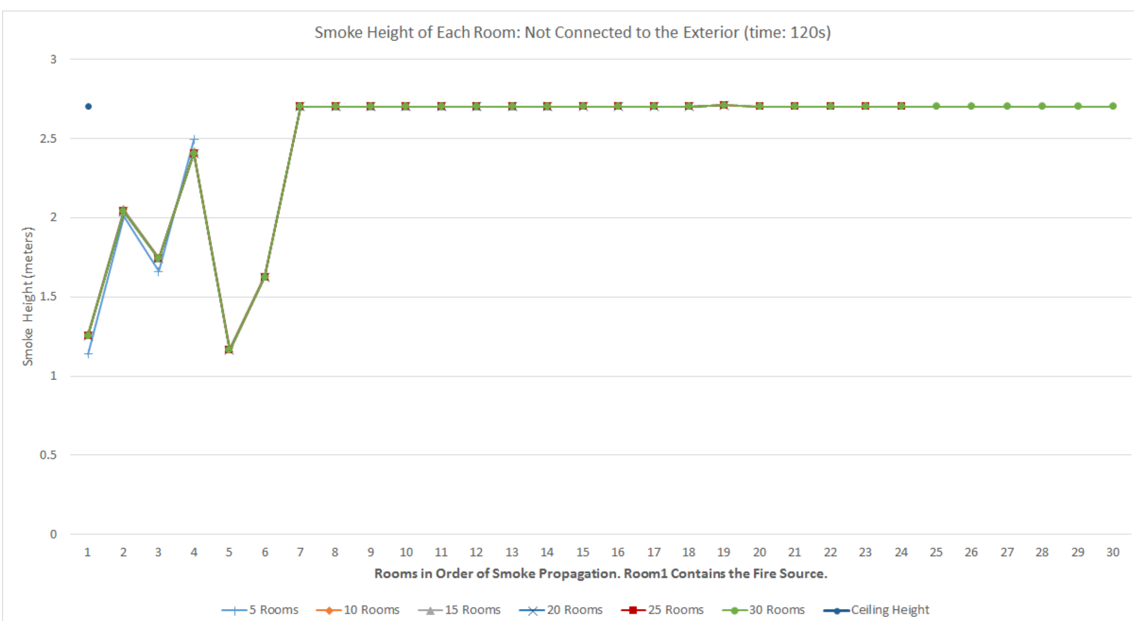

Smoke Height of Each Room: Not Connected to the Exterior (time: 540s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

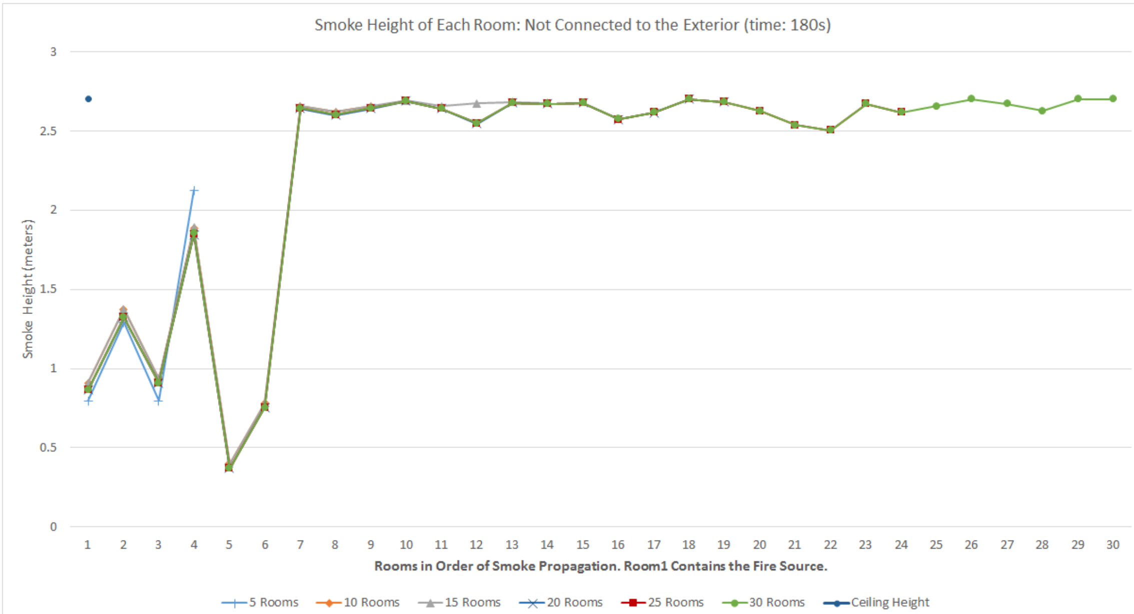

Smoke Height of Each Room: Not Connected to the Exterior (time: 600s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

B.1.4 Merging Scheme/ Not Connected to the Exterior

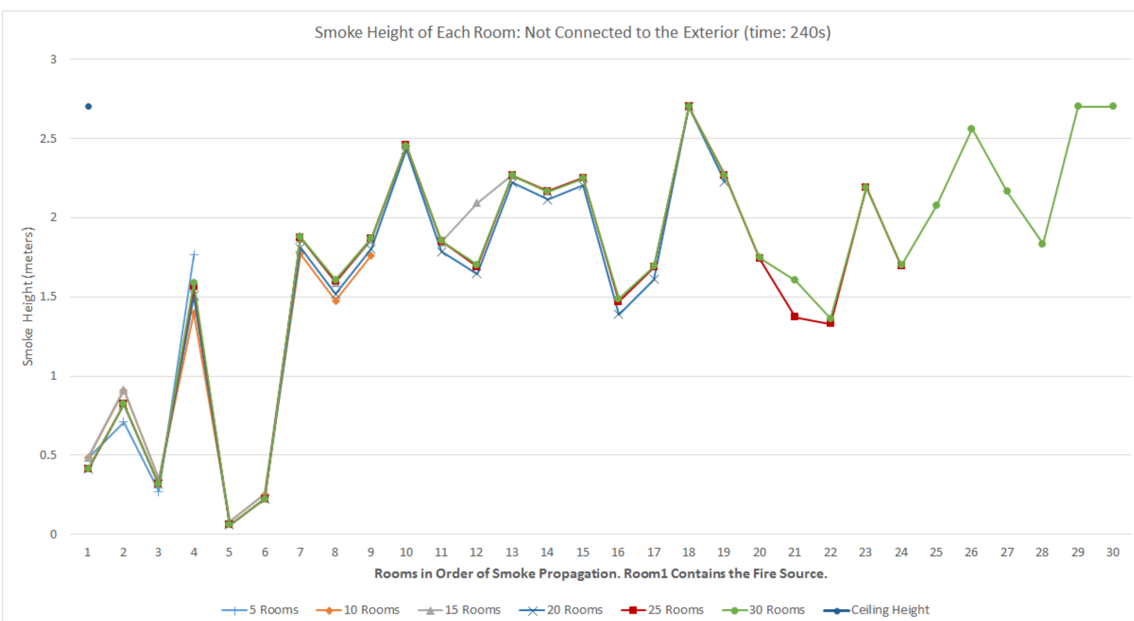



Smoke Height of Each Room: Not Connected to the Exterior (time: 60s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

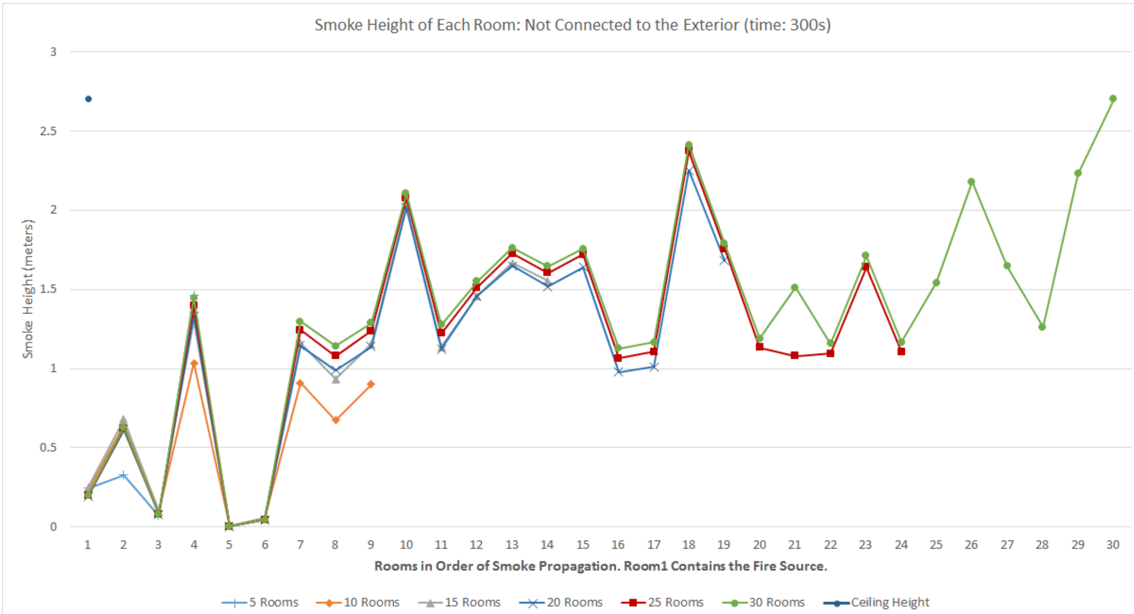

Smoke Height of Each Room: Not Connected to the Exterior (time: 120s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height



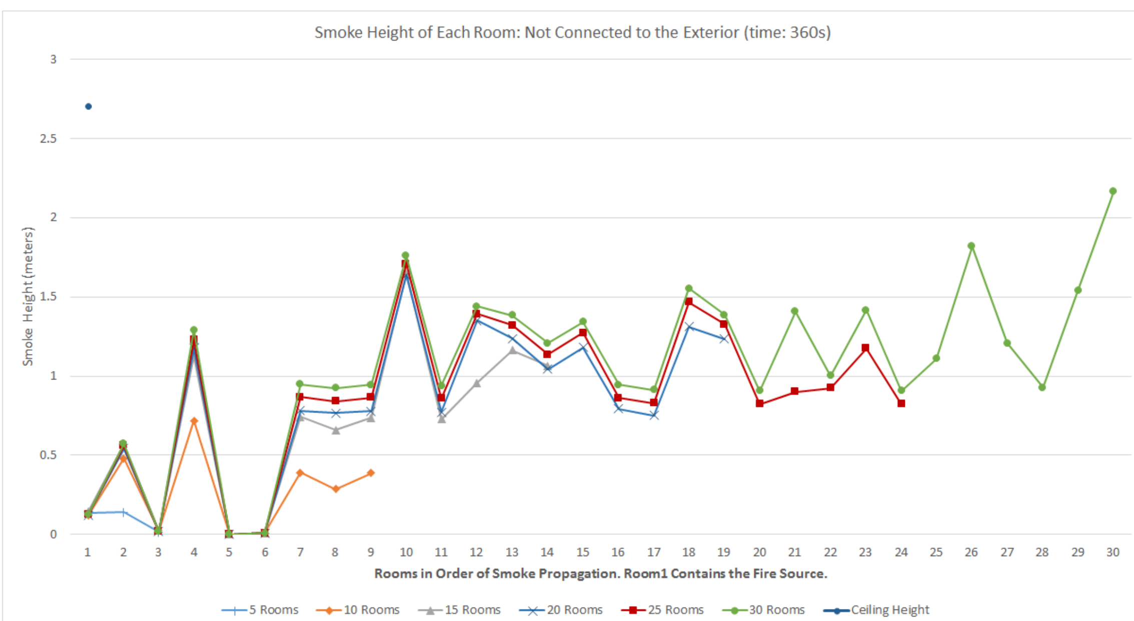
Smoke Height of Each Room: Not Connected to the Exterior (time: 180s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height



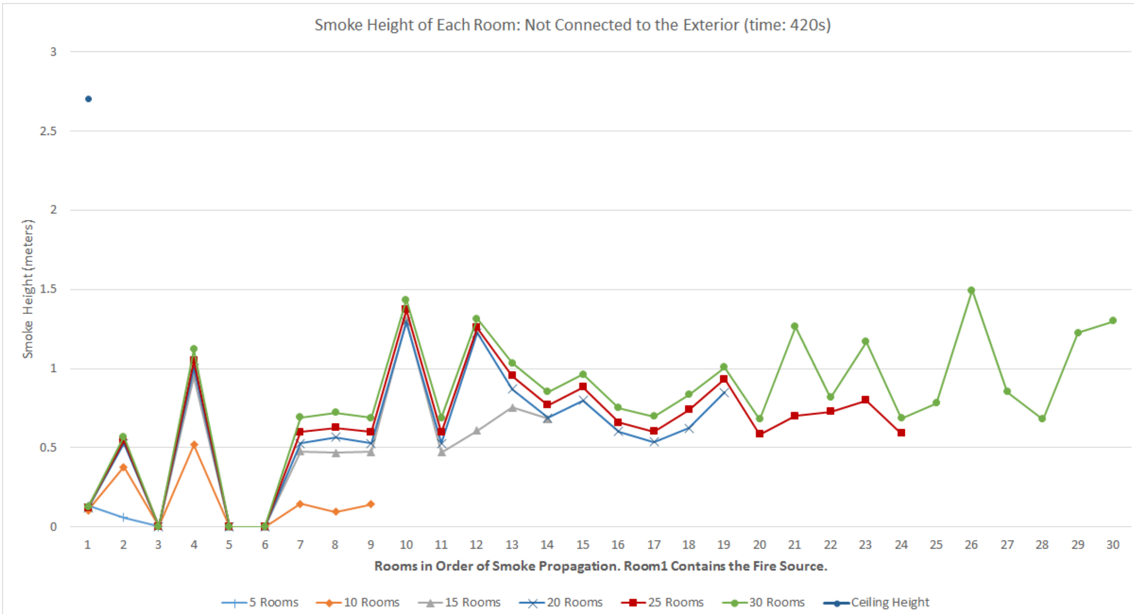
Smoke Height of Each Room: Not Connected to the Exterior (time: 240s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

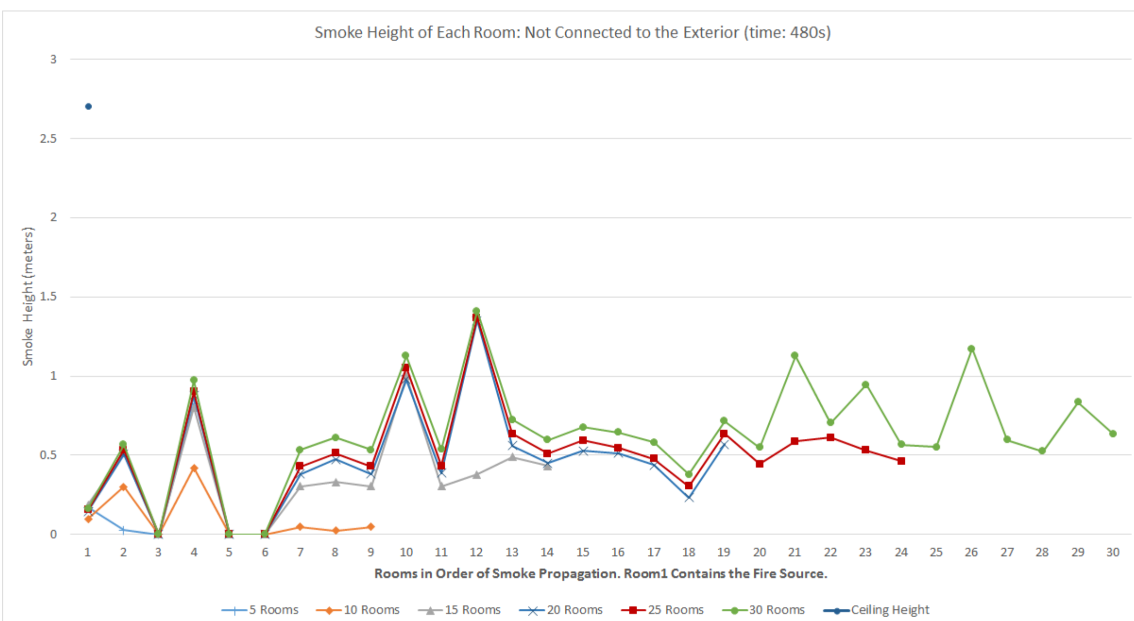


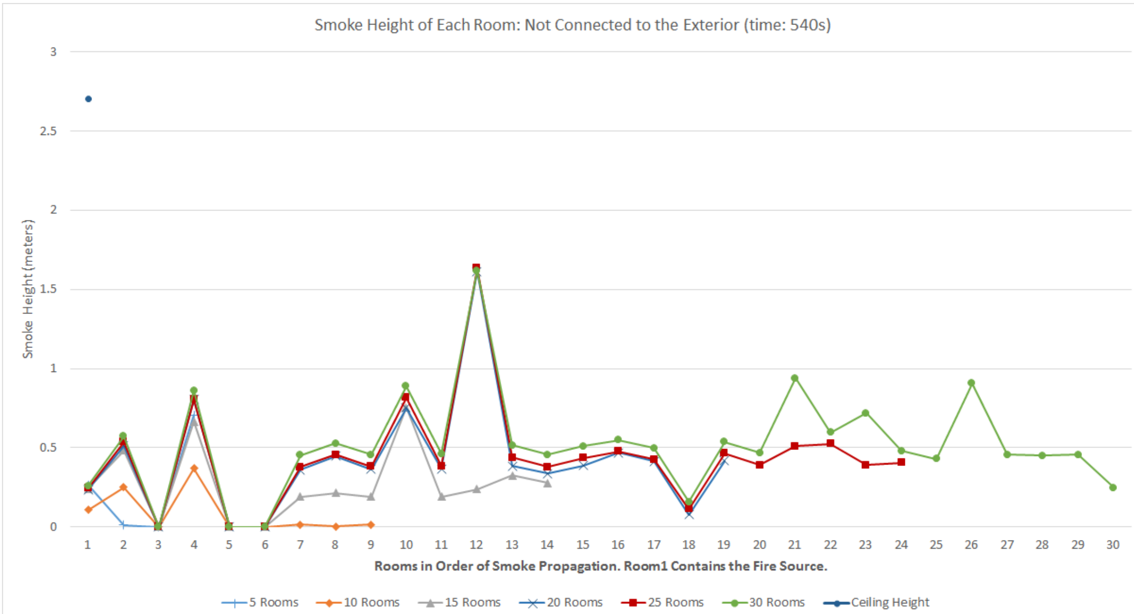
Smoke Height of Each Room: Not Connected to the Exterior (time: 300s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

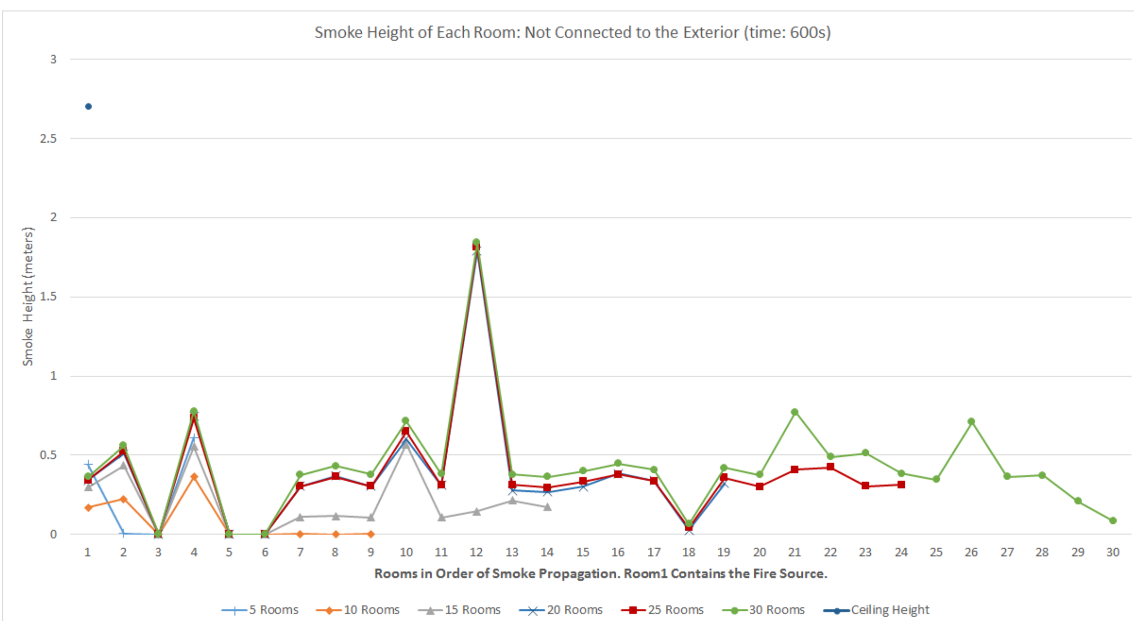


Smoke Height of Each Room: Not Connected to the Exterior (time: 360s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height


Smoke Height of Each Room: Not Connected to the Exterior (time: 420s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

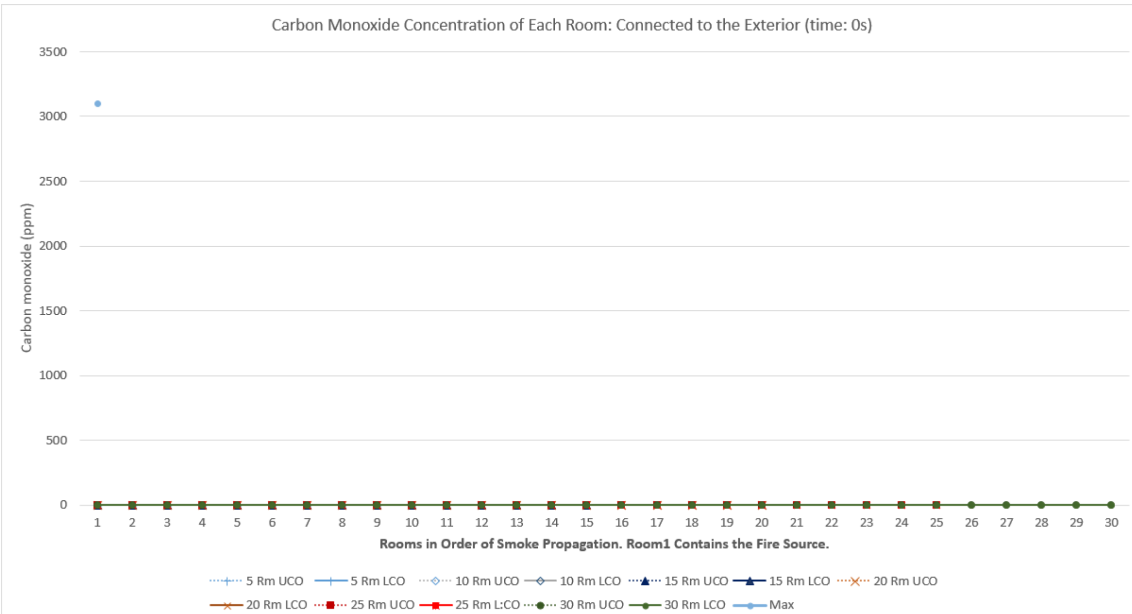

Smoke Height of Each Room: Not Connected to the Exterior (time: 480s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

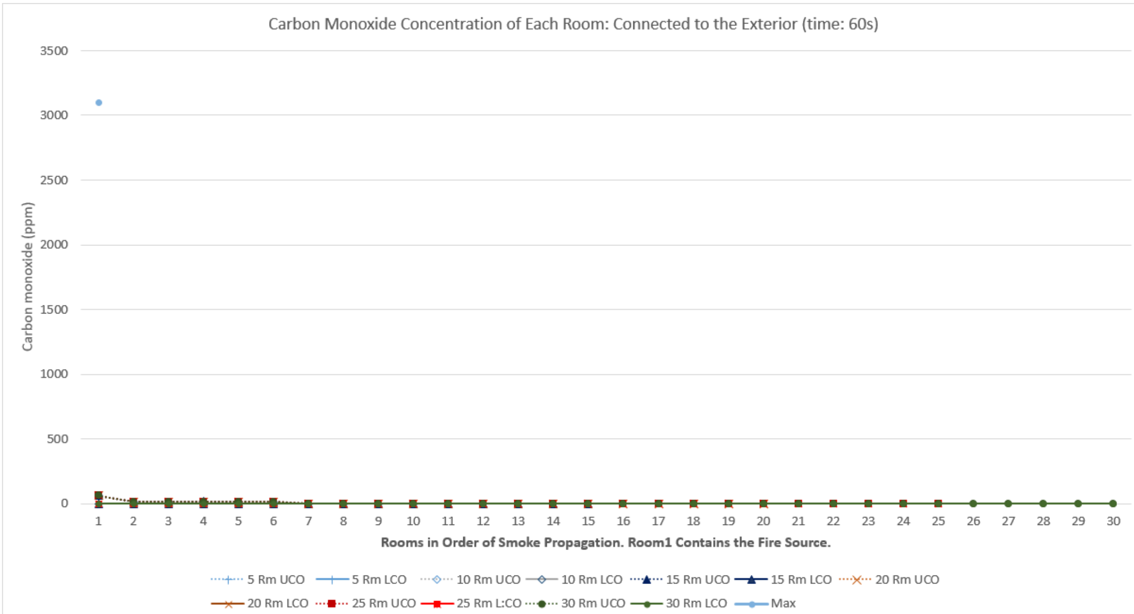

Smoke Height of Each Room: Not Connected to the Exterior (time: 540s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height


Smoke Height of Each Room: Not Connected to the Exterior (time: 600s)
Smoke Height (meters)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rooms
10 Rooms
15 Rooms
20 Rooms
25 Rooms
30 Rooms
Ceiling Height

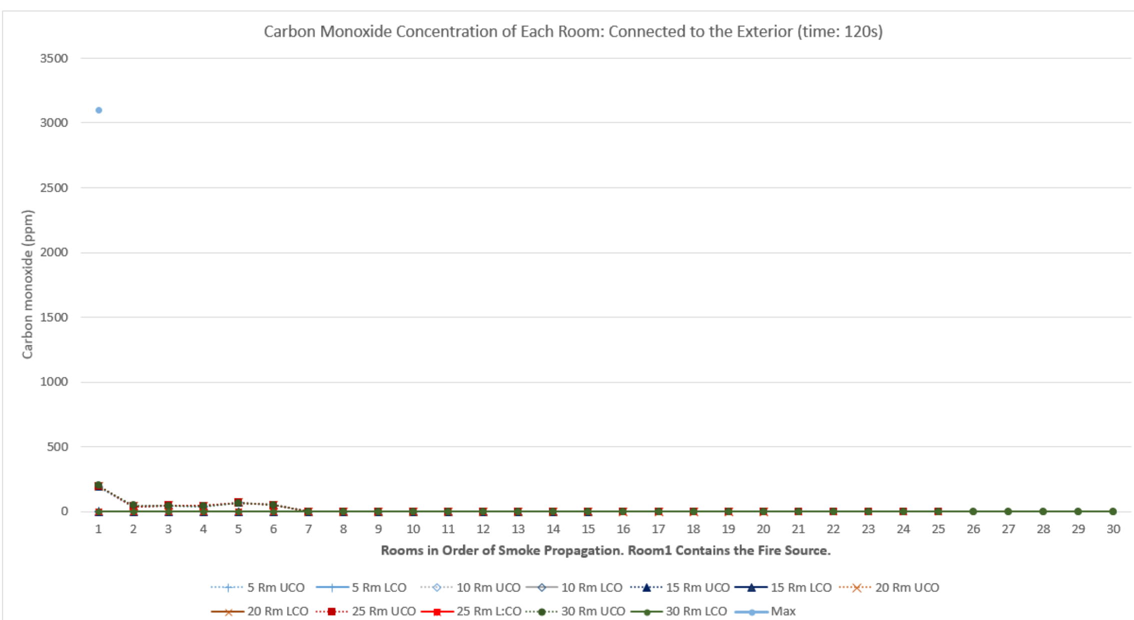
B.2 CO Concentration

B.2.1 Ignoring Scheme/ Connected to the Exterior

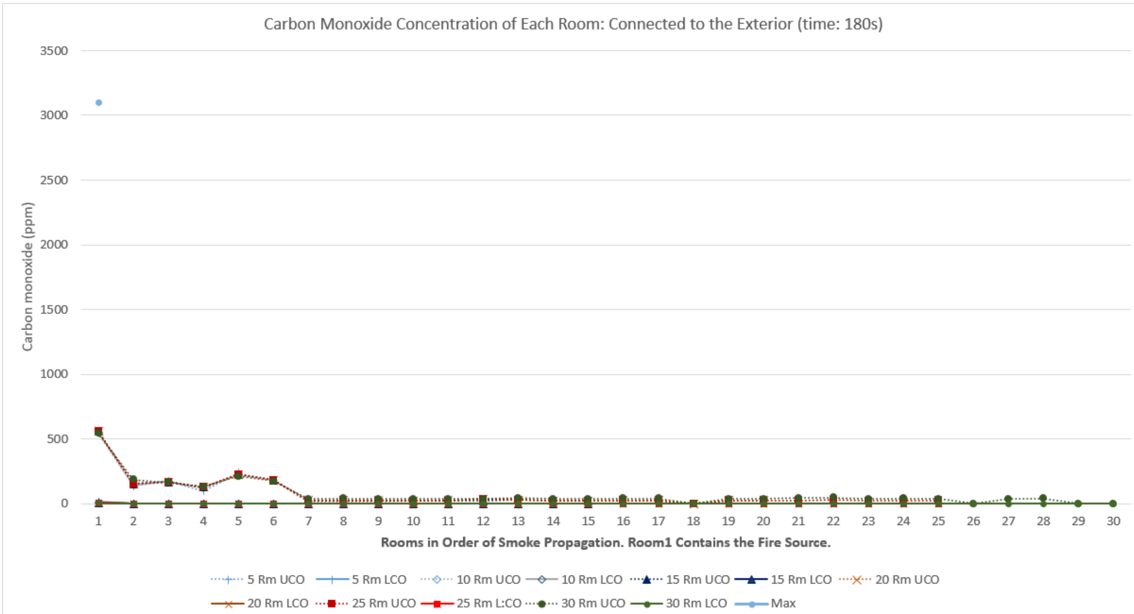


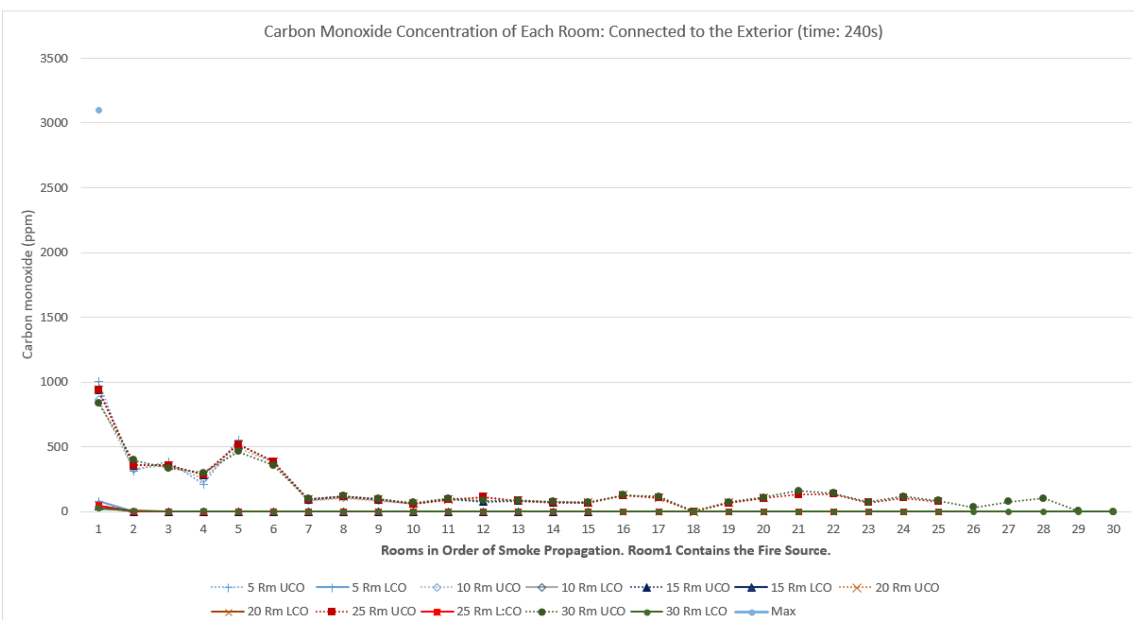


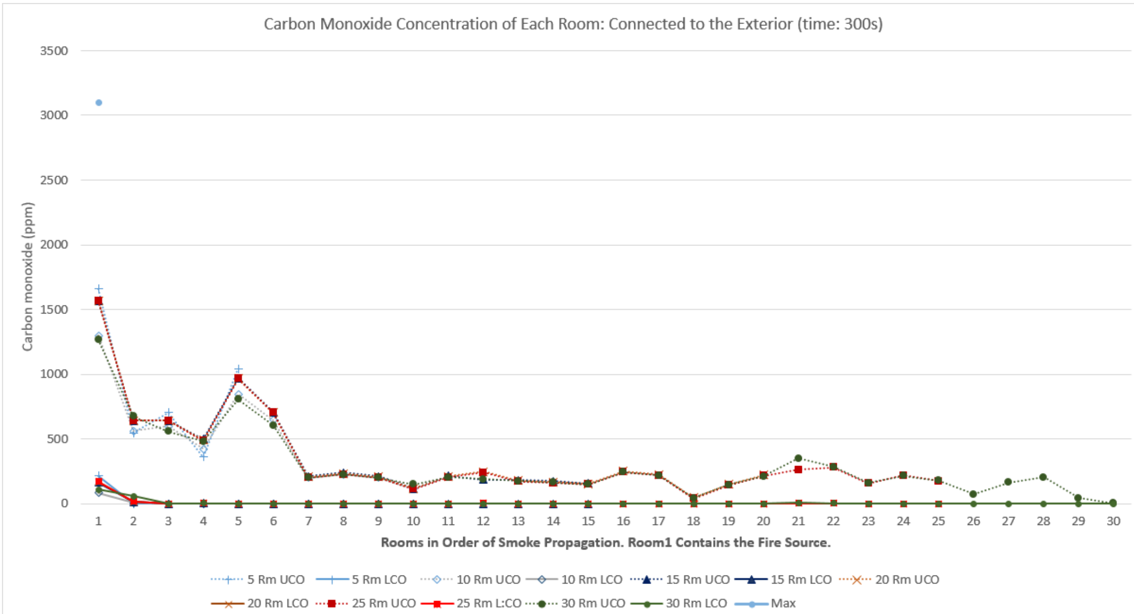
Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 60s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

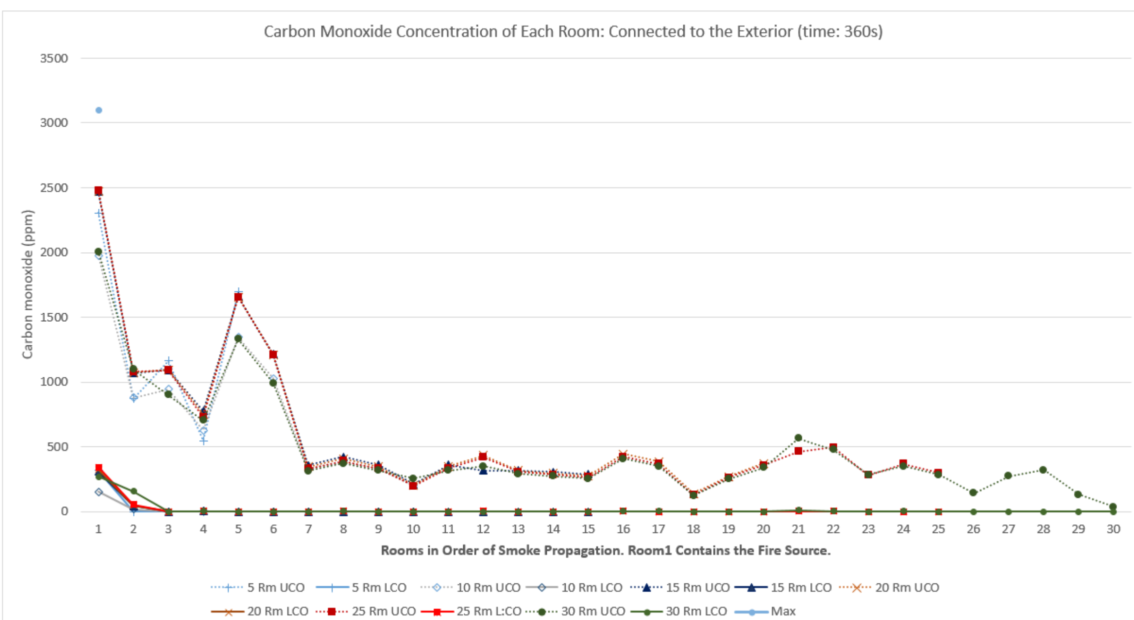


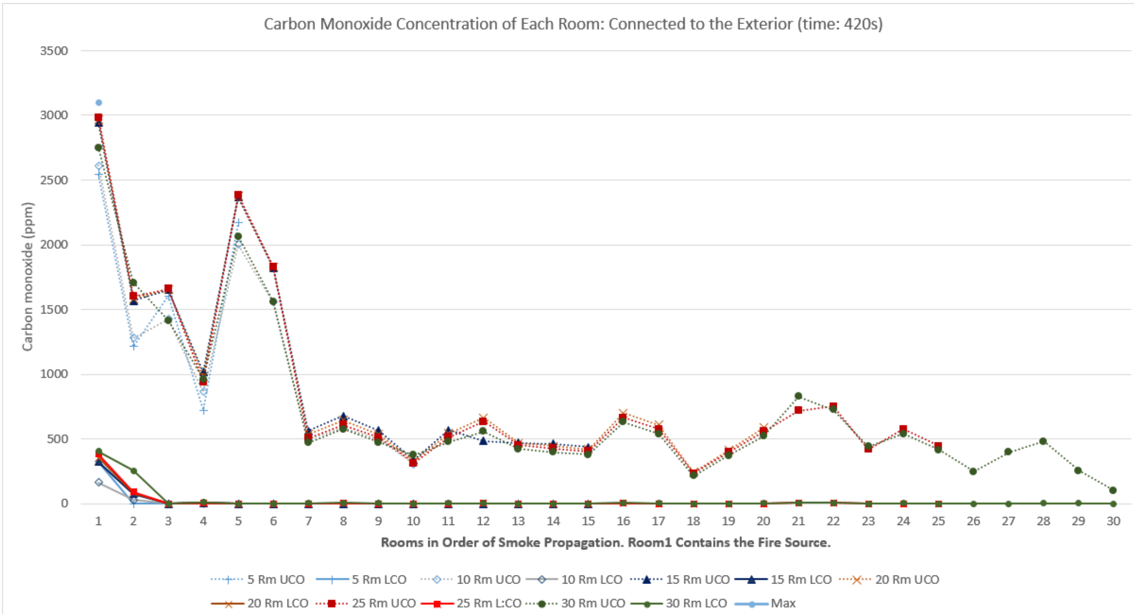
Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 120s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

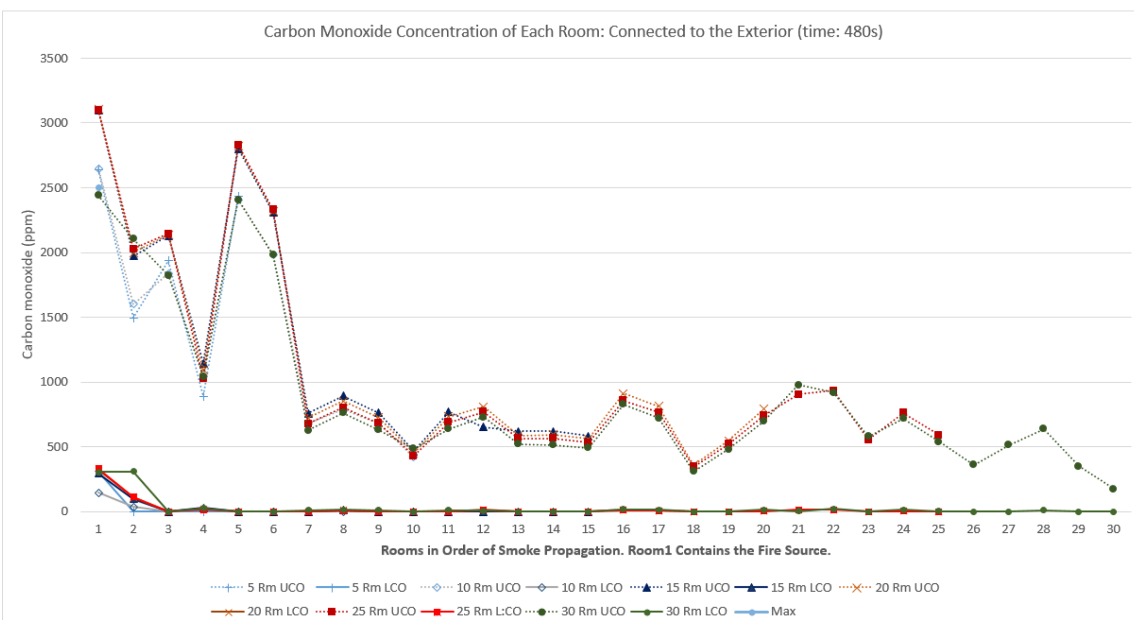

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 180s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

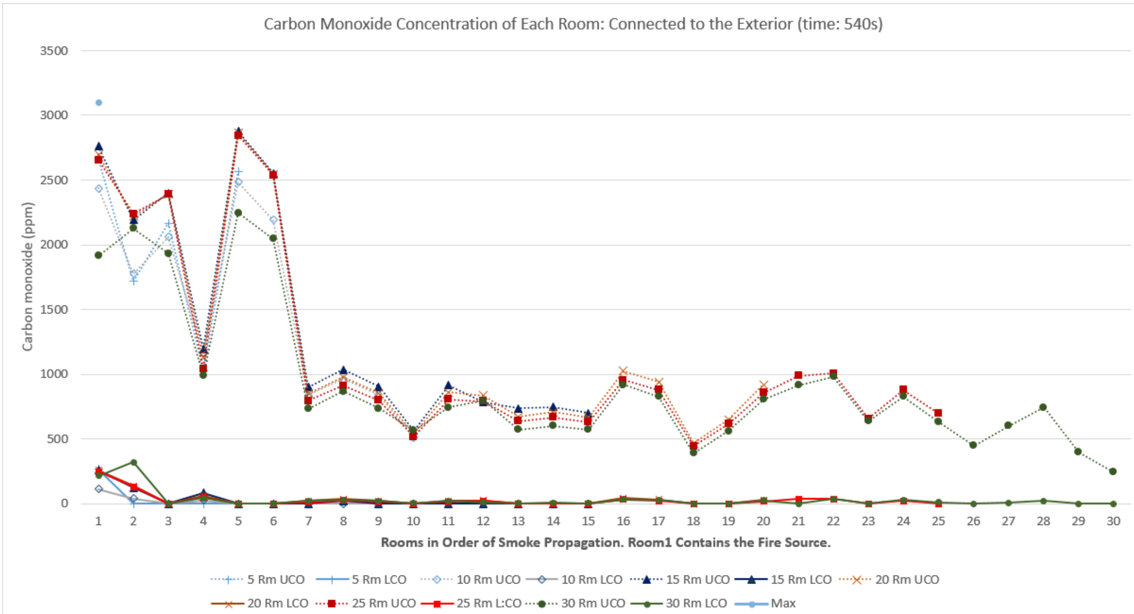

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 240s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 300s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

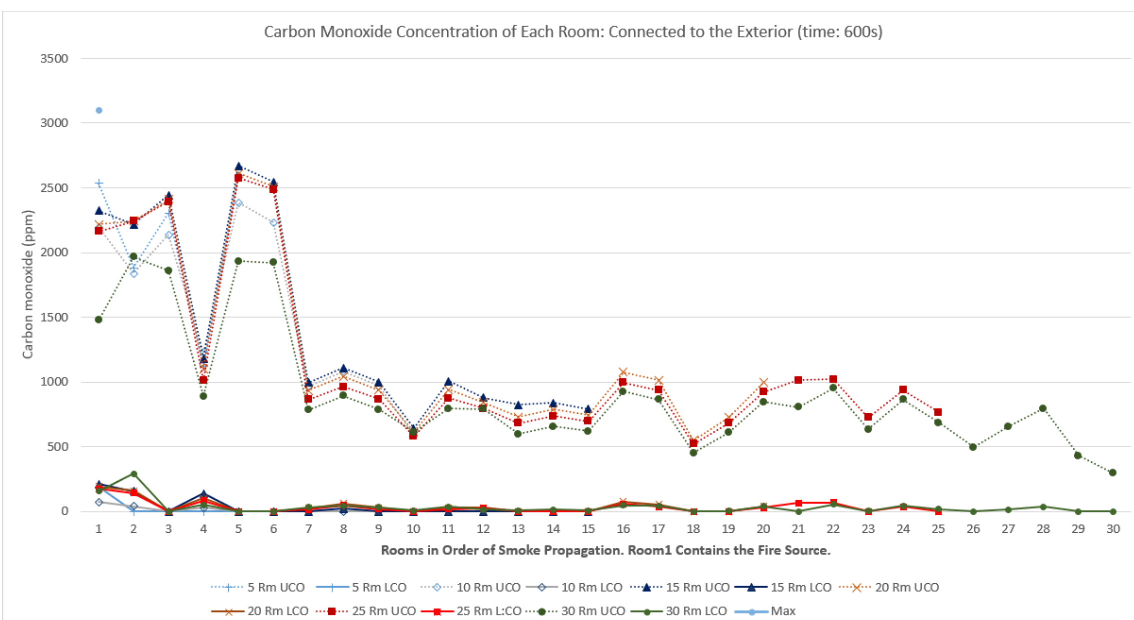

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 360s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 420s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 480s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

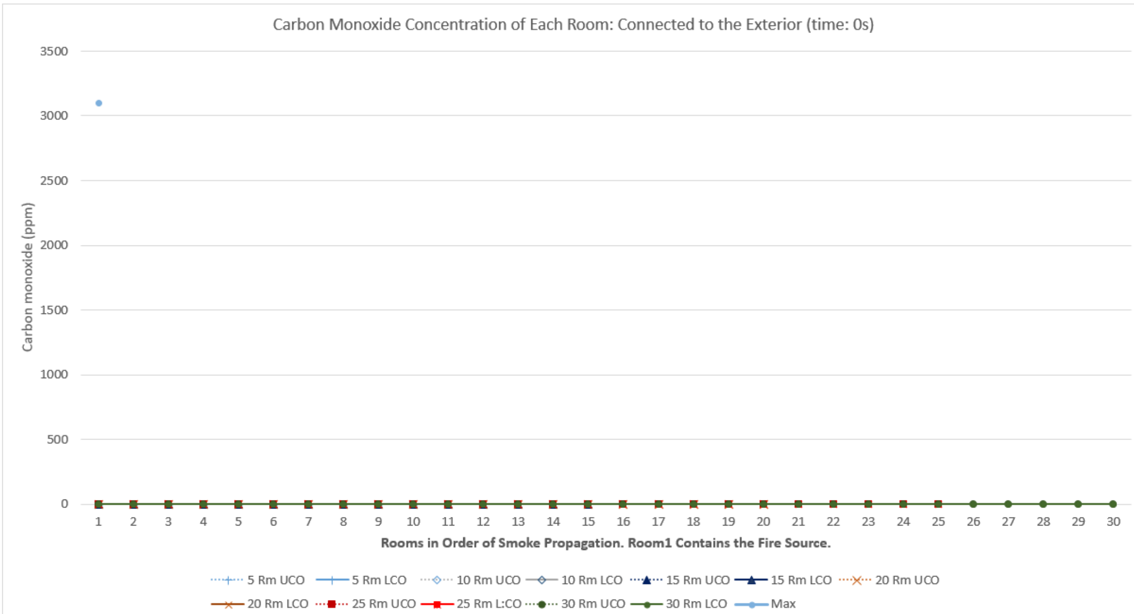


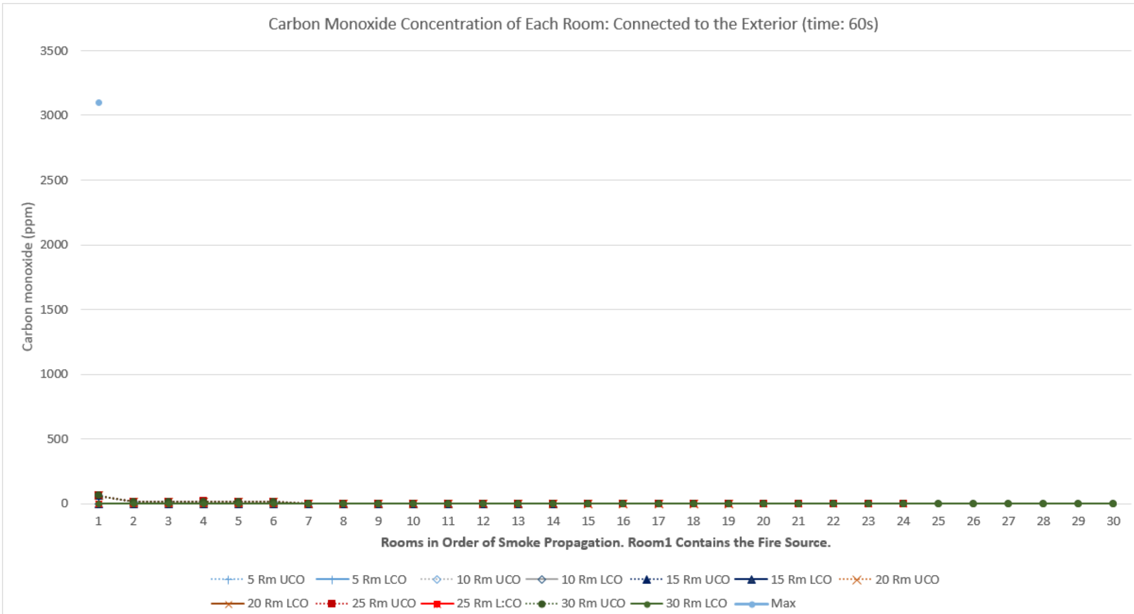
Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 540s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

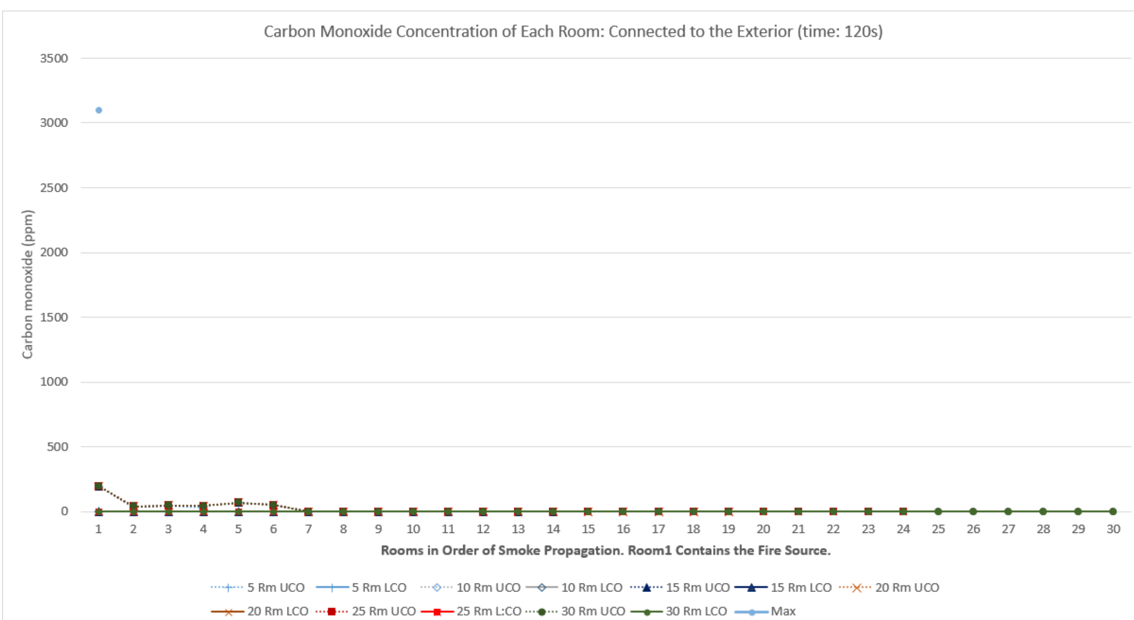


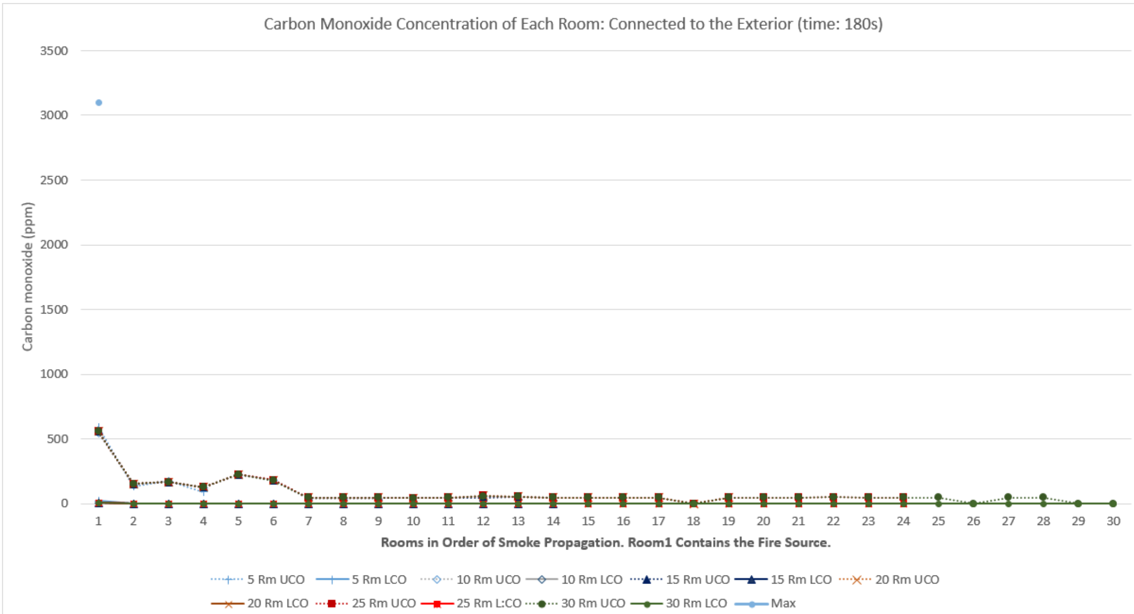
Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 600s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

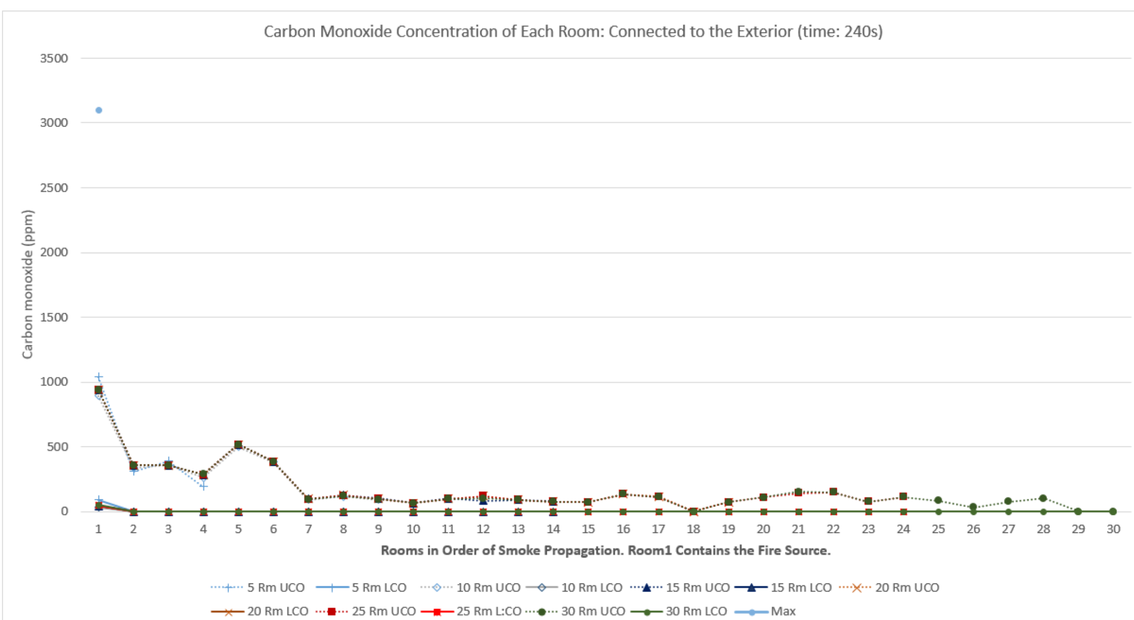
B.2.2 Merging Scheme/ Connected to the Exterior

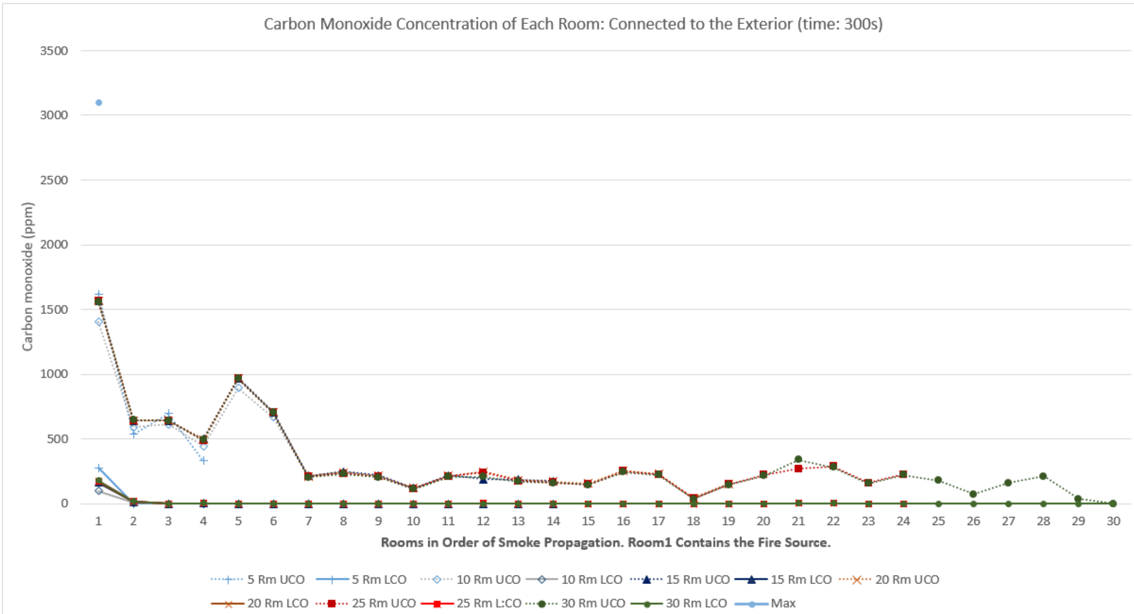


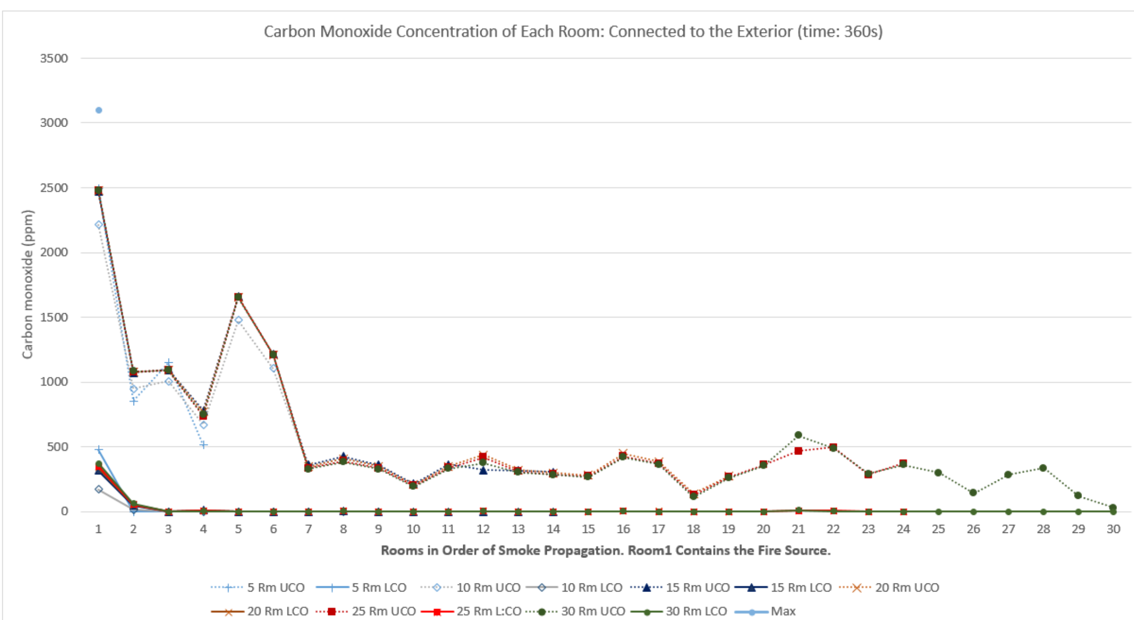

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 60s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

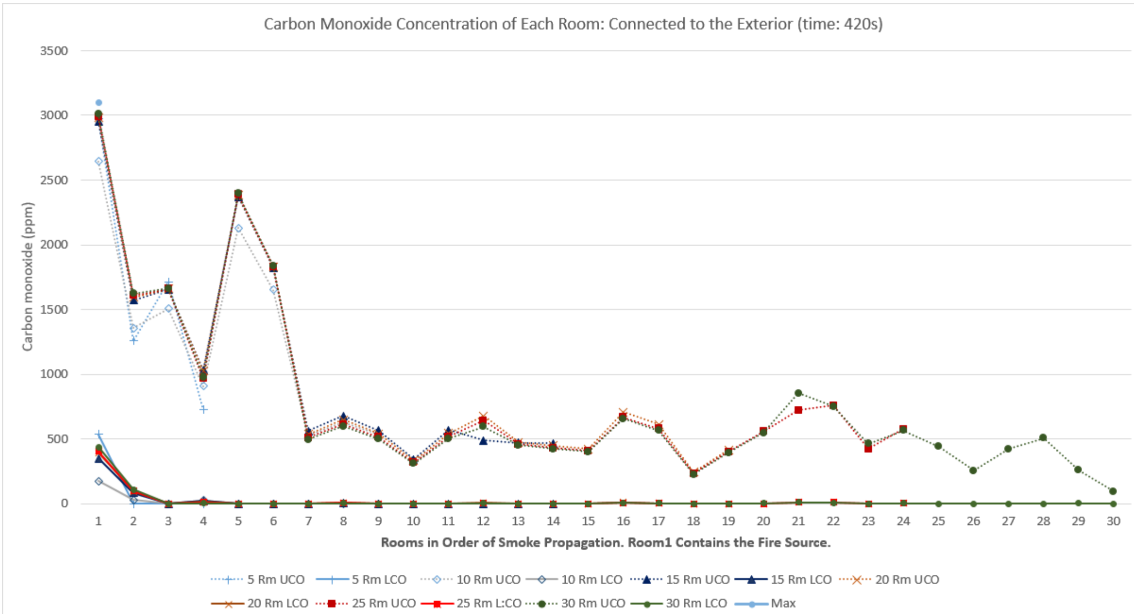

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 120s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

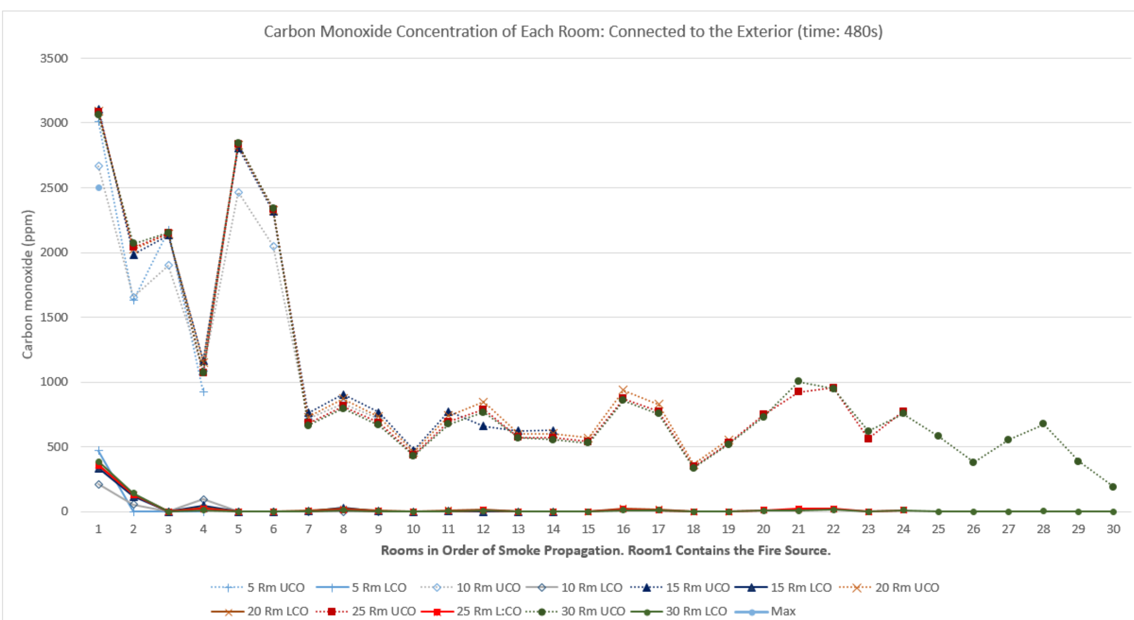

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 180s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

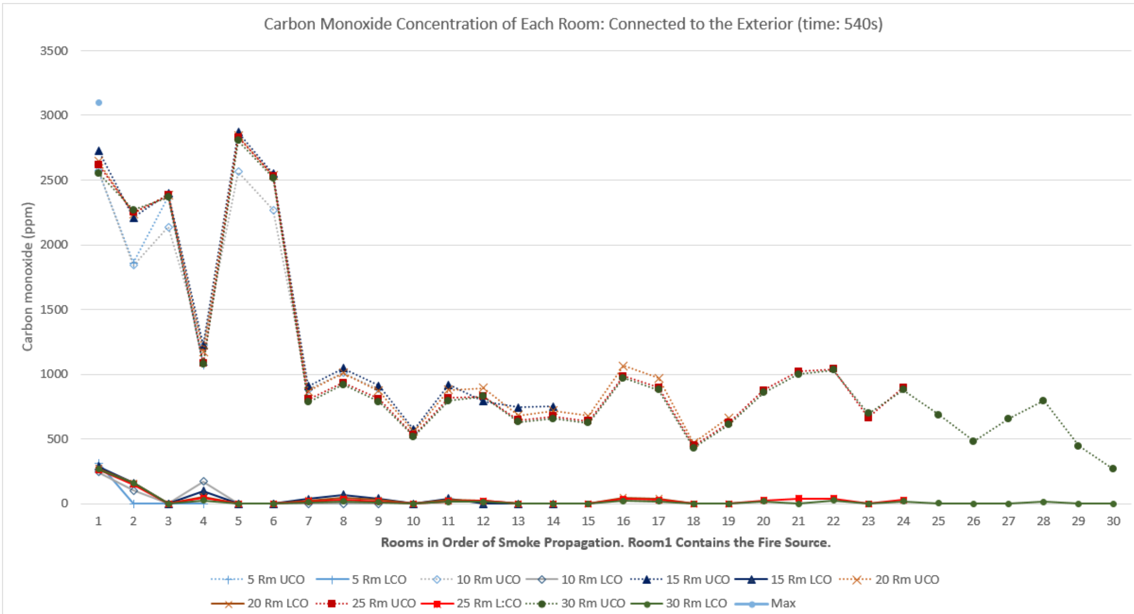

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 240s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

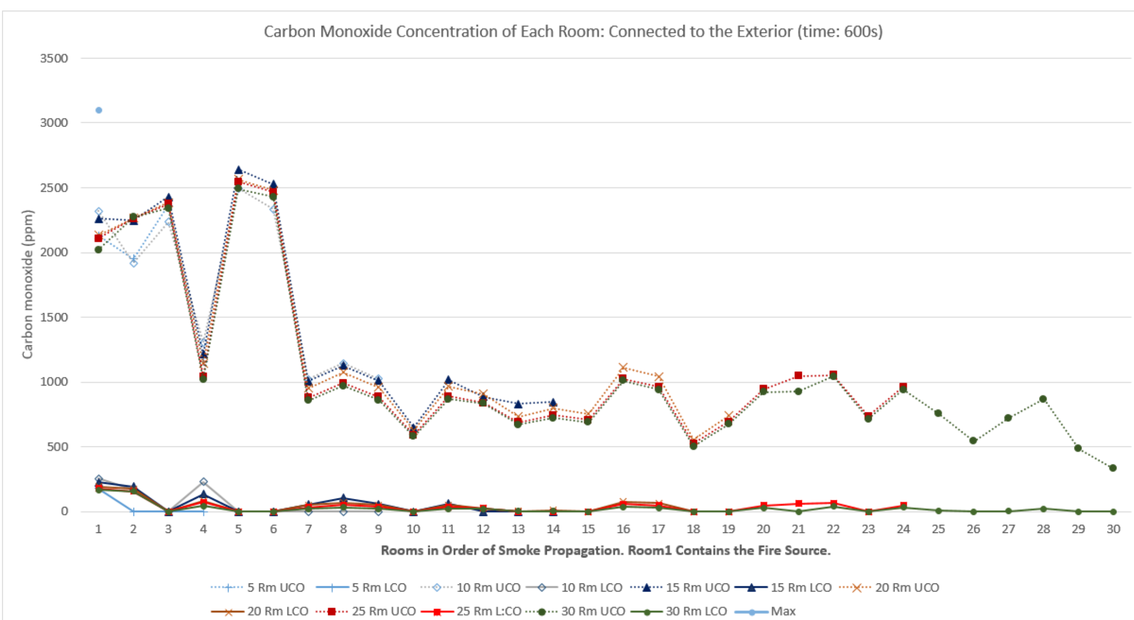

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 300s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 360s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

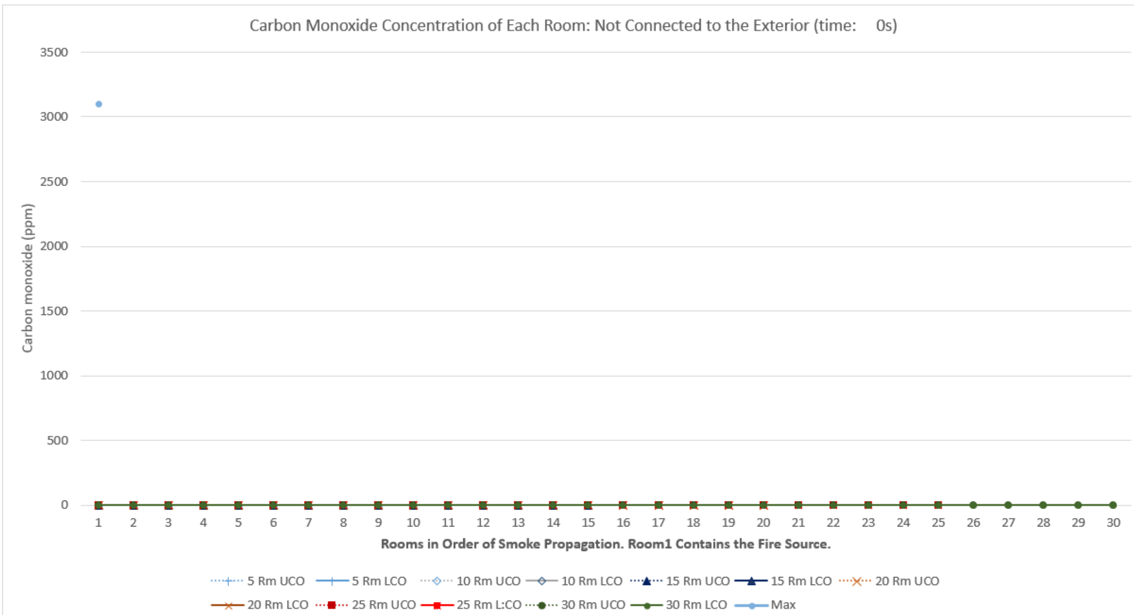

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 420s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

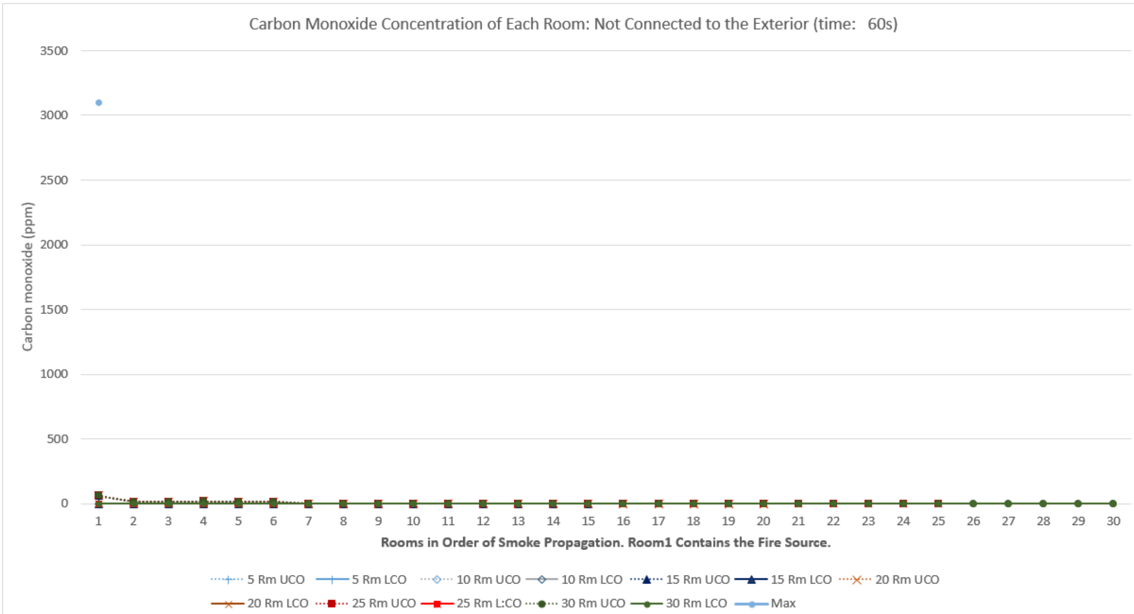

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 480s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

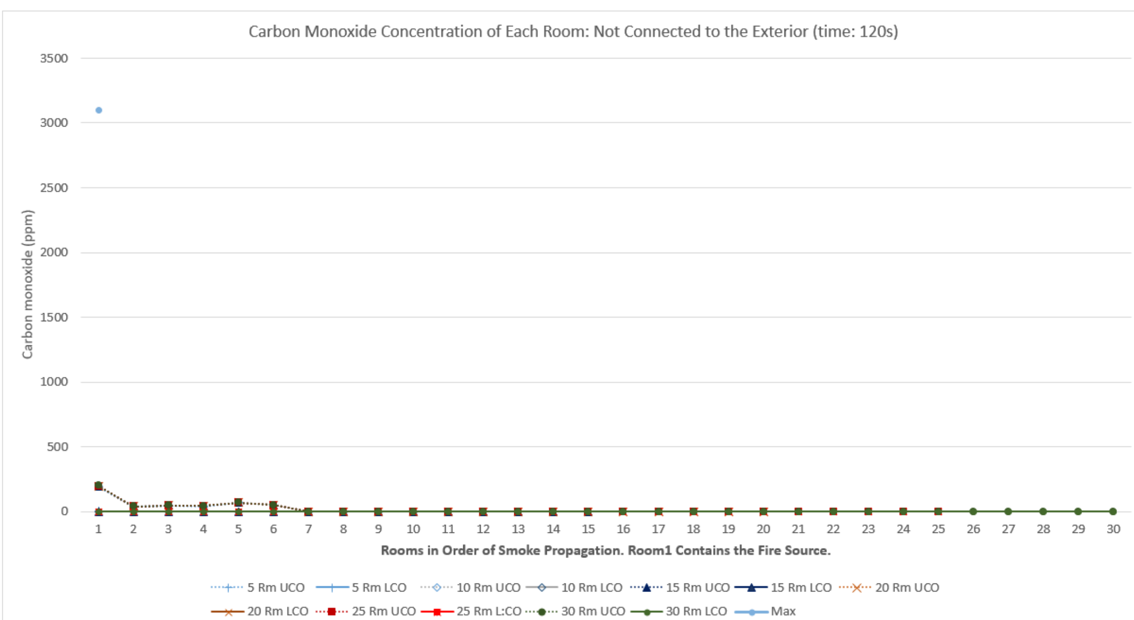

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 540s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

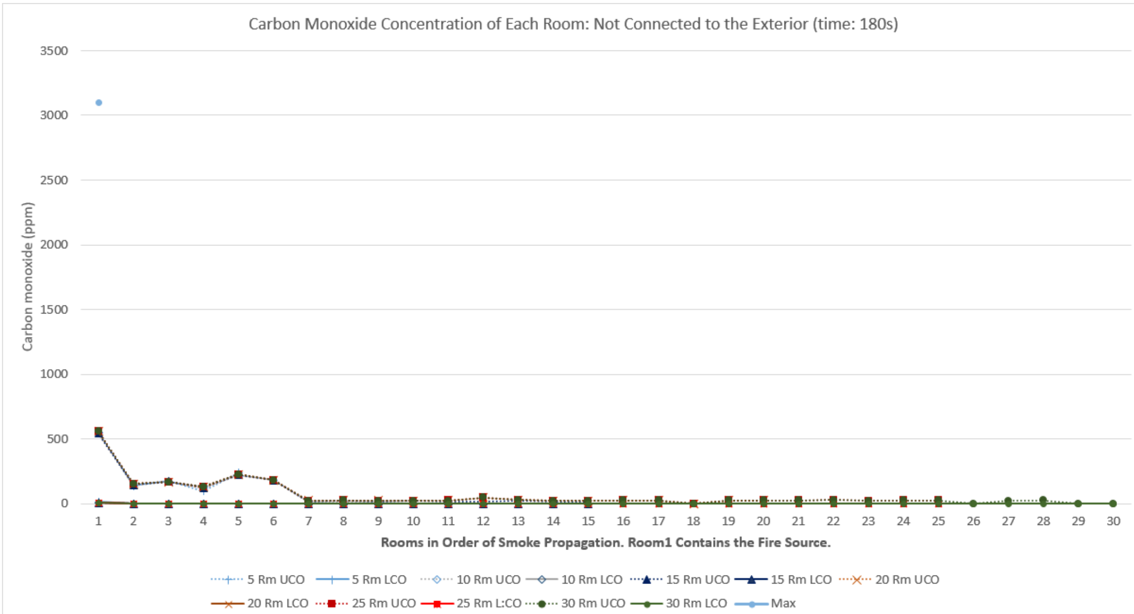

Carbon Monoxide Concentration of Each Room: Connected to the Exterior (time: 600s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

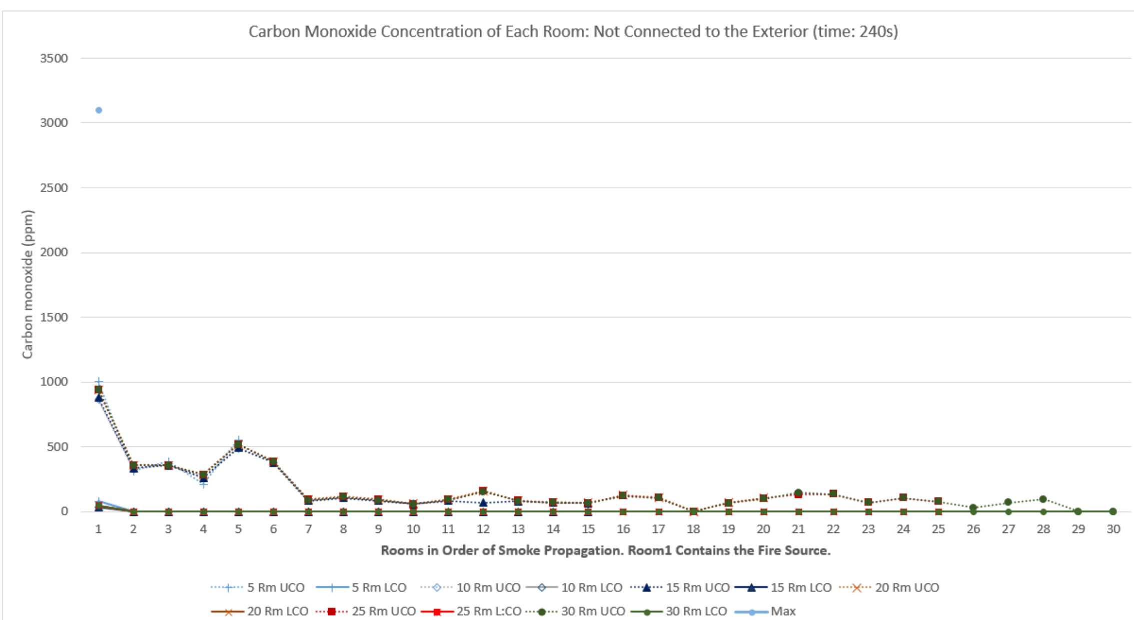
B.2.3 Ignoring Scheme/ Not Connected to the Exterior

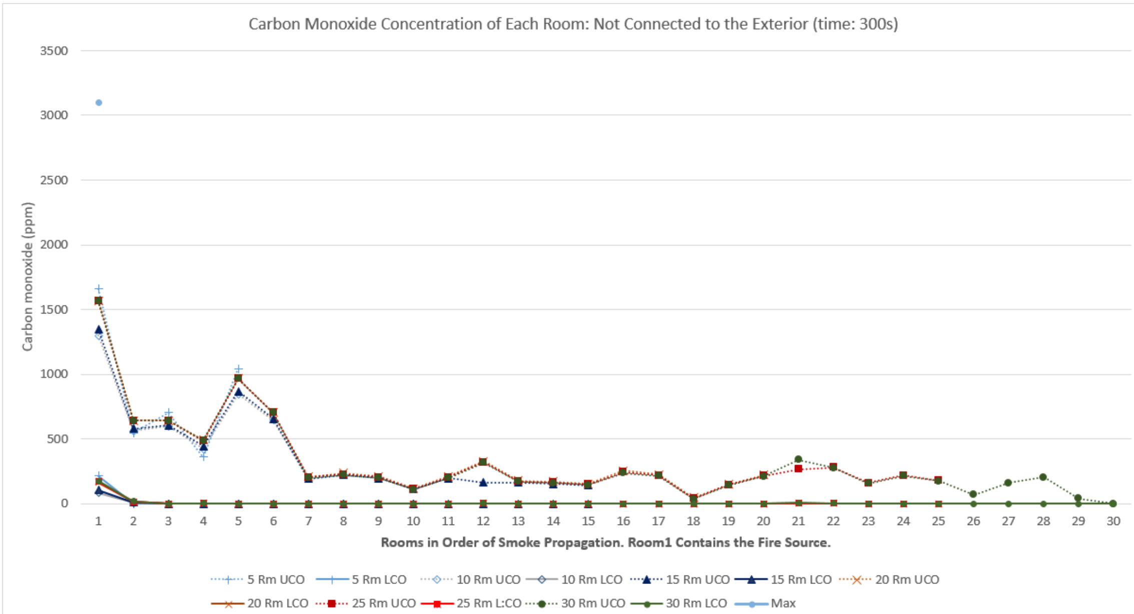


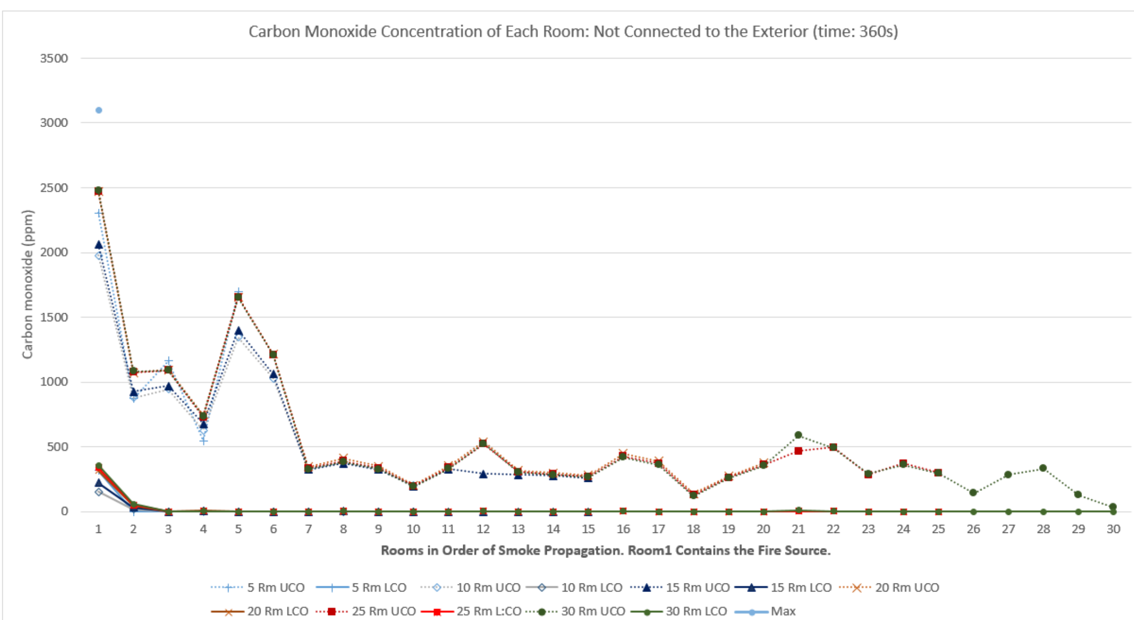

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 60s)
Carbon monoxide (ppm)
0
500
1000
1500
2000
2500
3000
3500
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

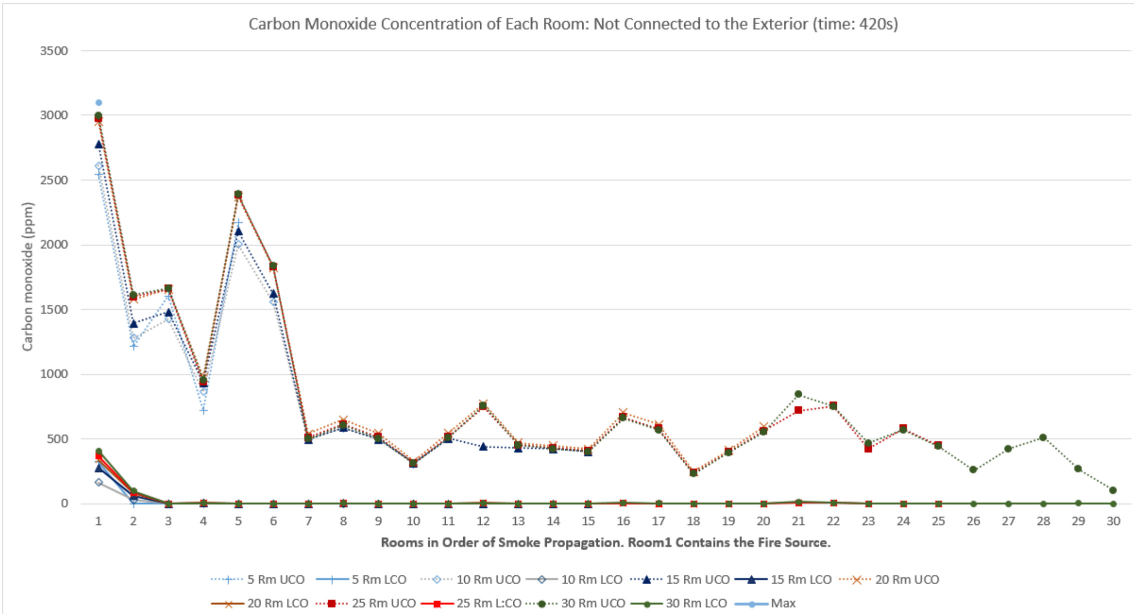

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 120s)
Carbon monoxide (ppm)
0
500
1000
1500
2000
2500
3000
3500
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

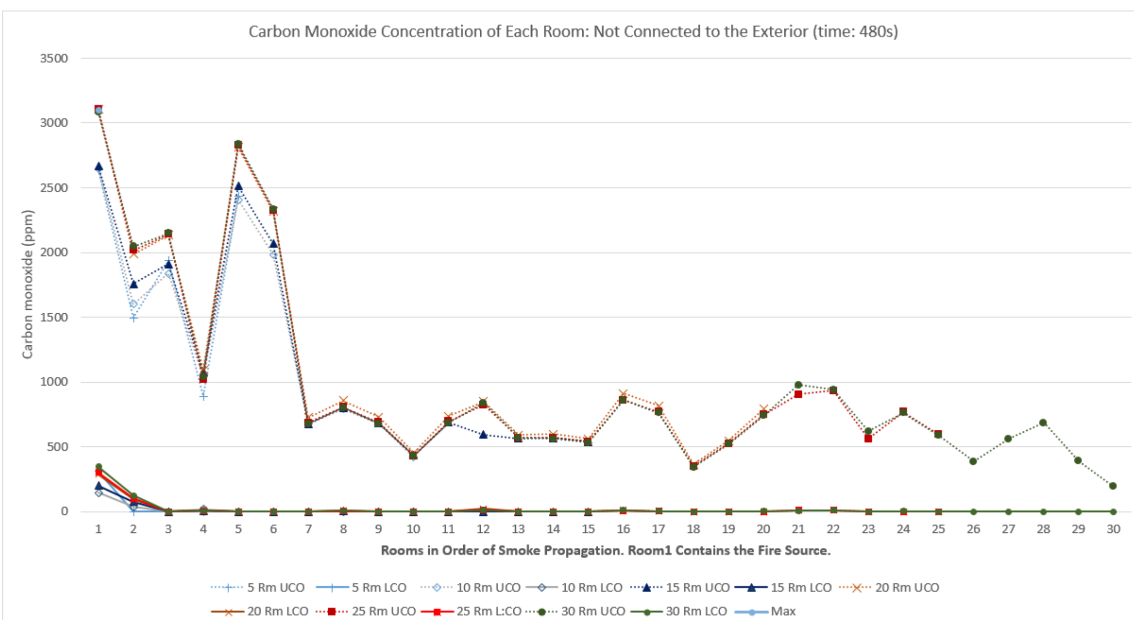

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 180s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

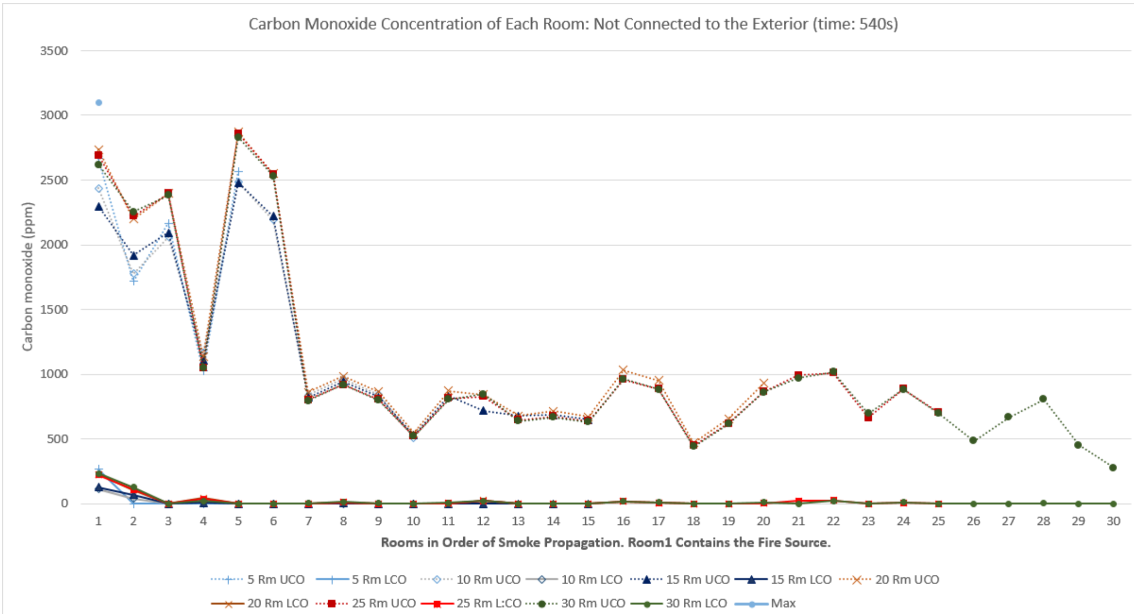

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 240s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 300s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

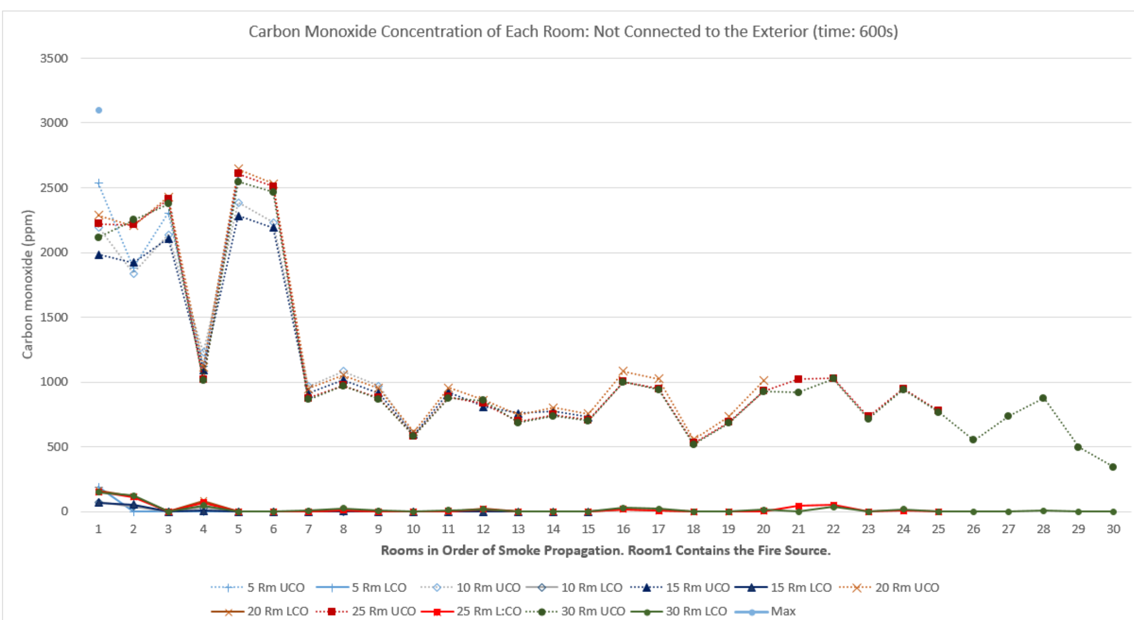

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 360s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 420s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 480s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

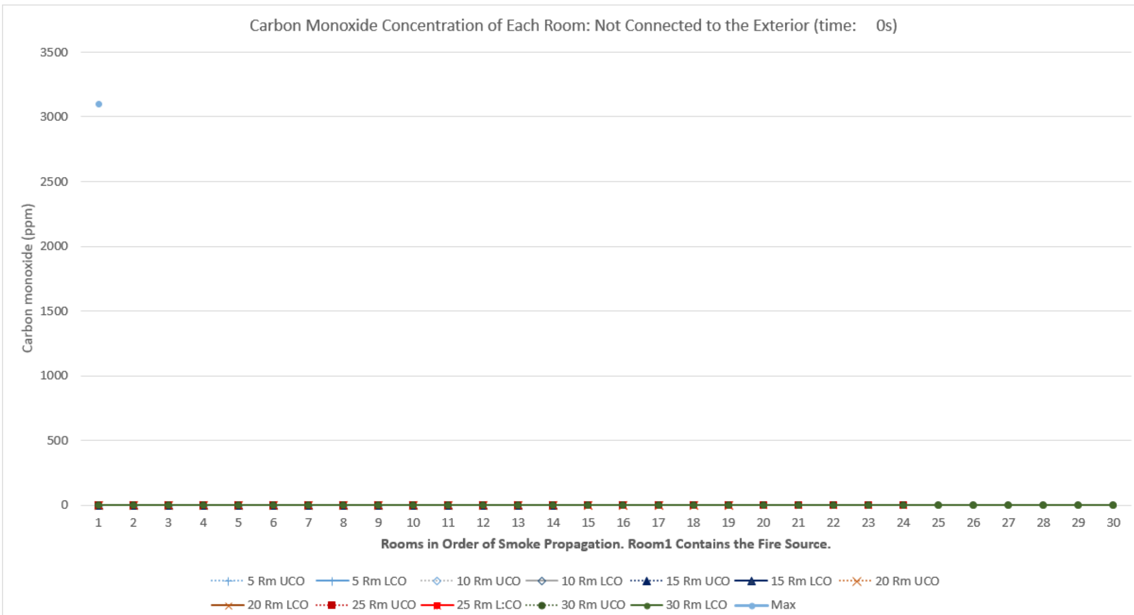


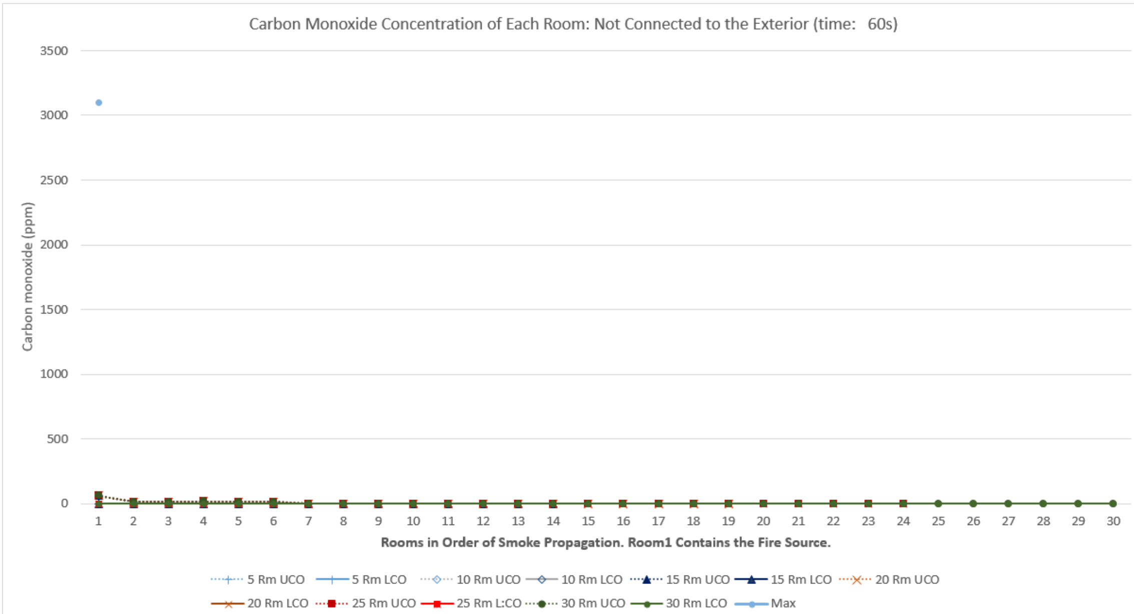
Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 540s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

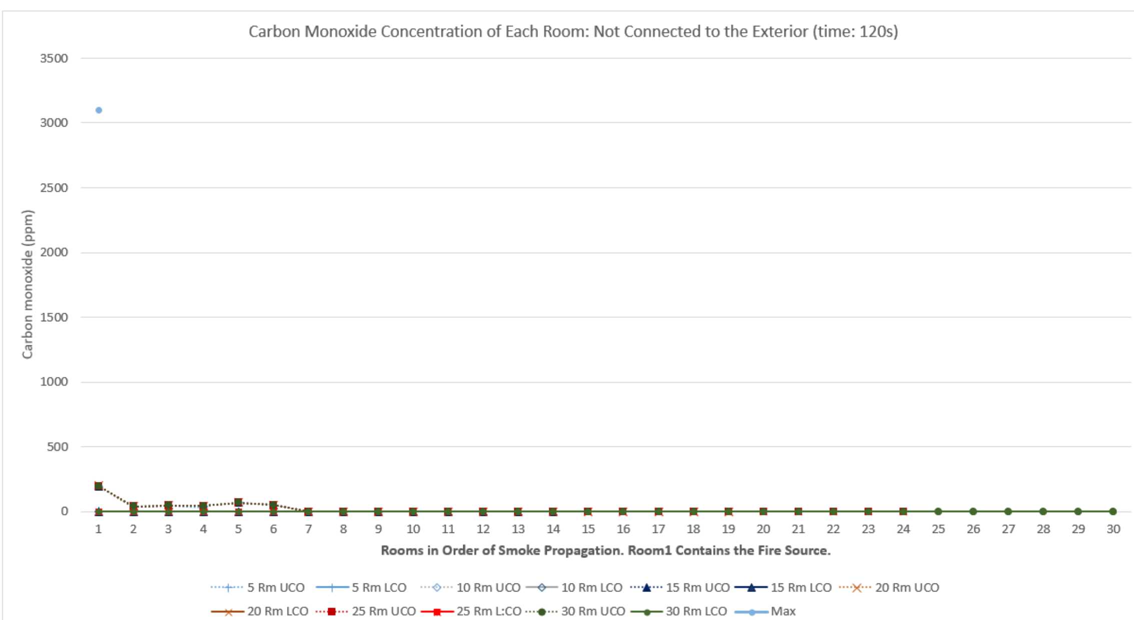


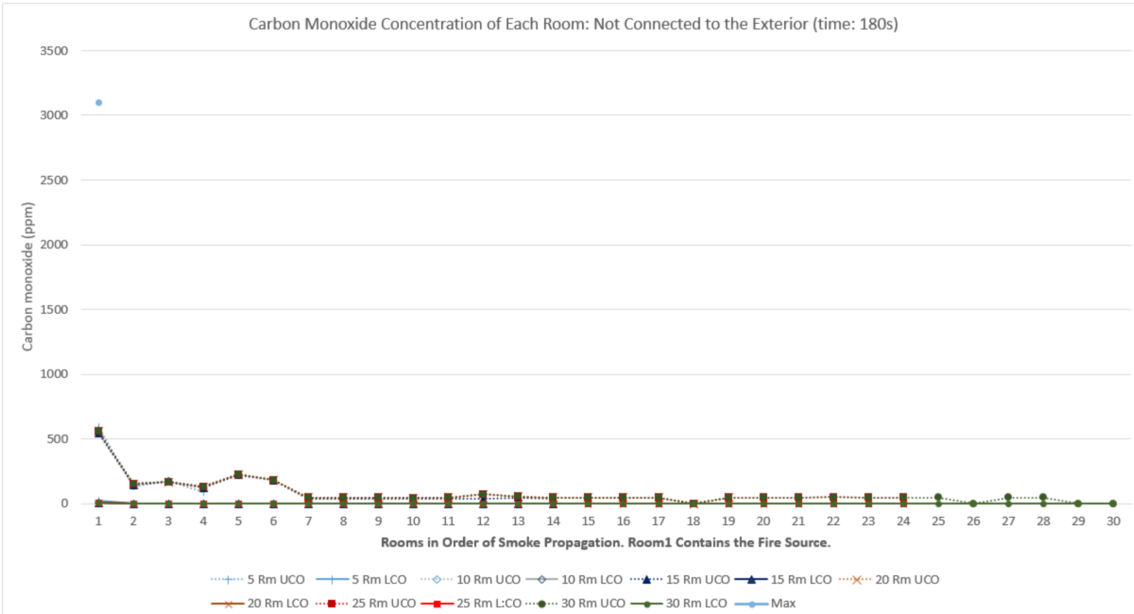
Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 600s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

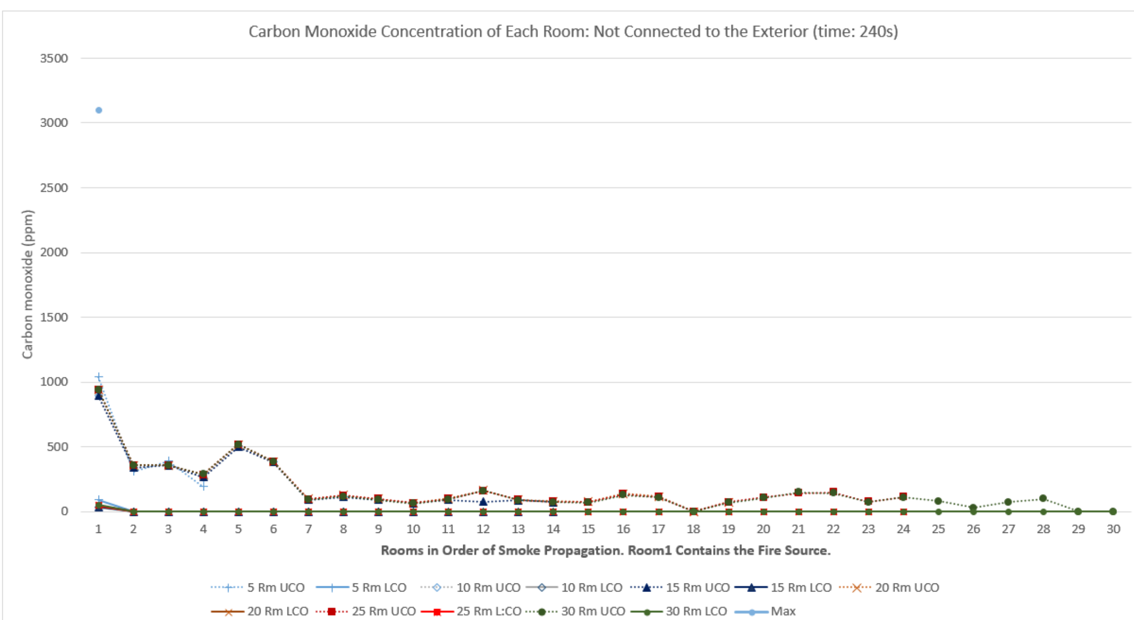
B.2.4 Merging Scheme/ Not Connected to the Exterior

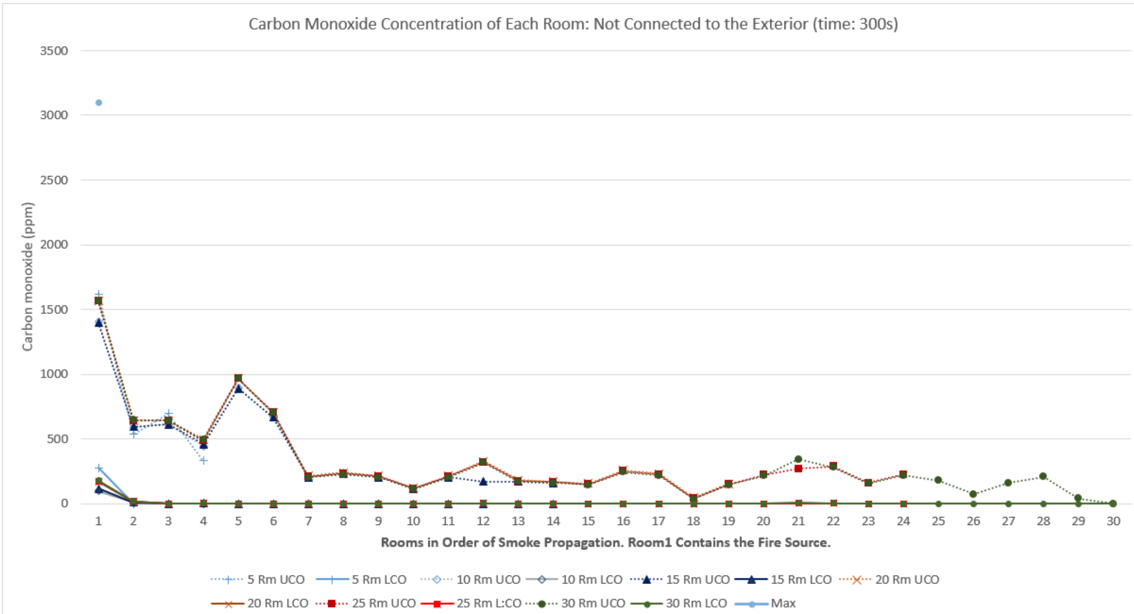


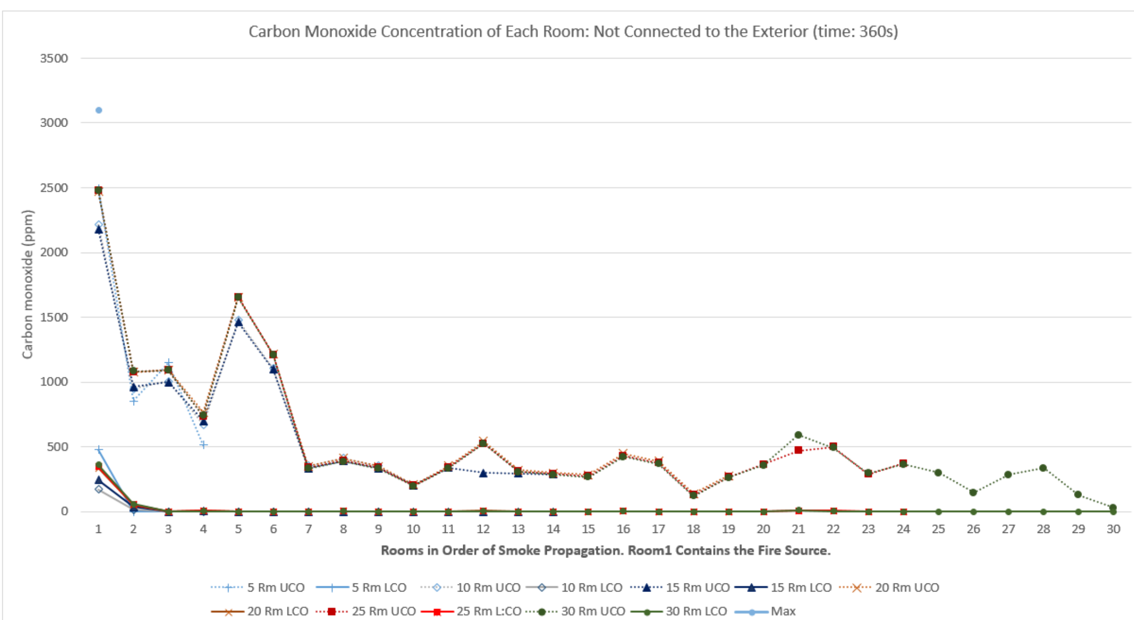

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 60s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

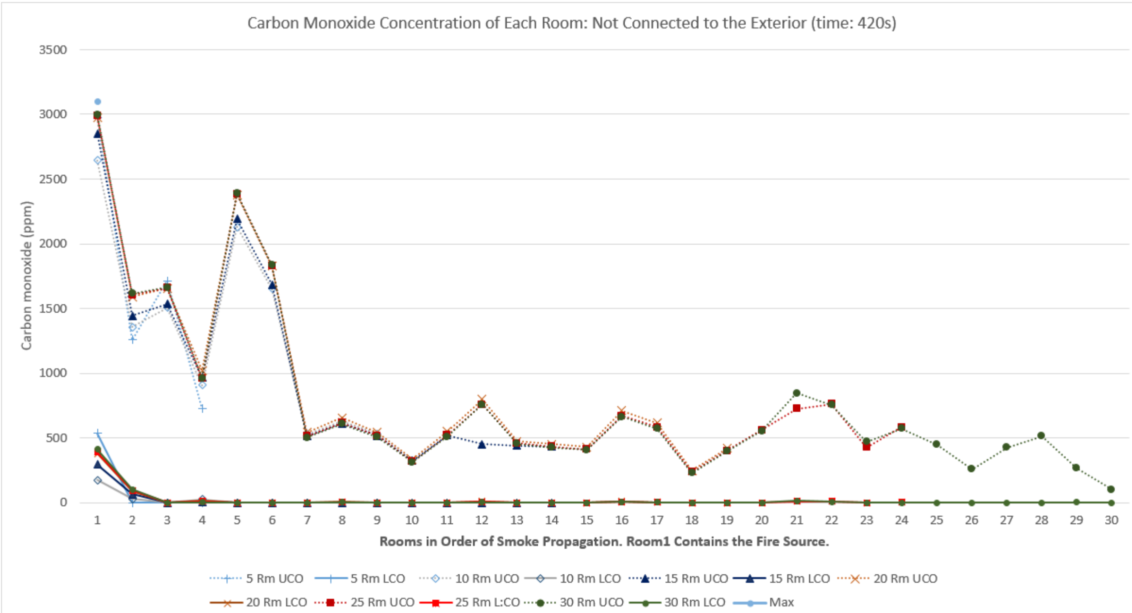

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 120s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

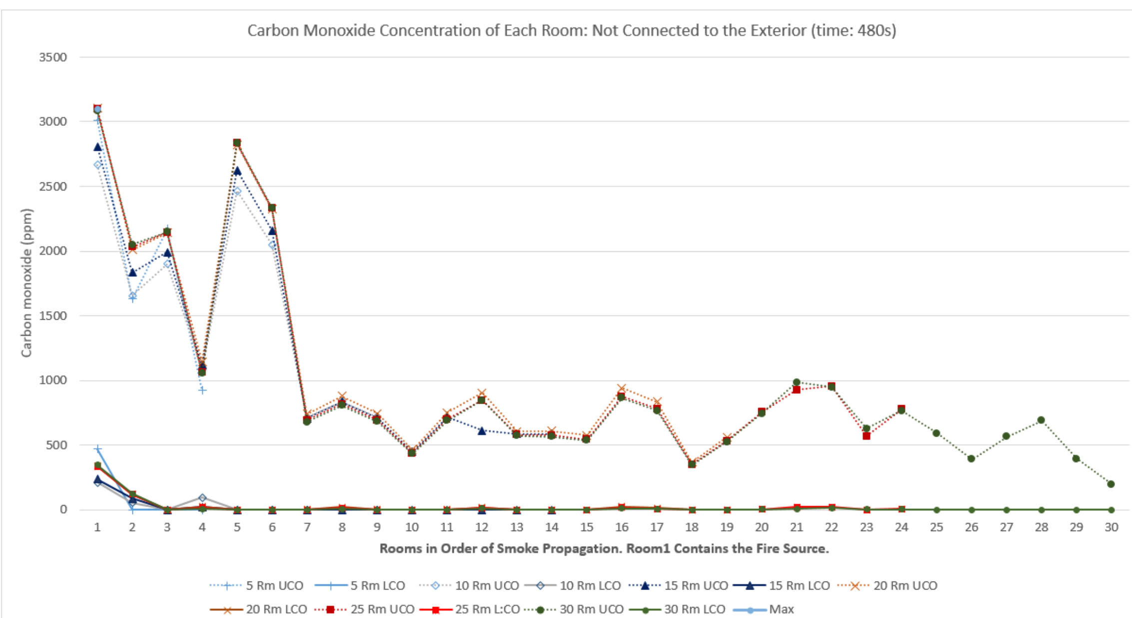

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 180s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

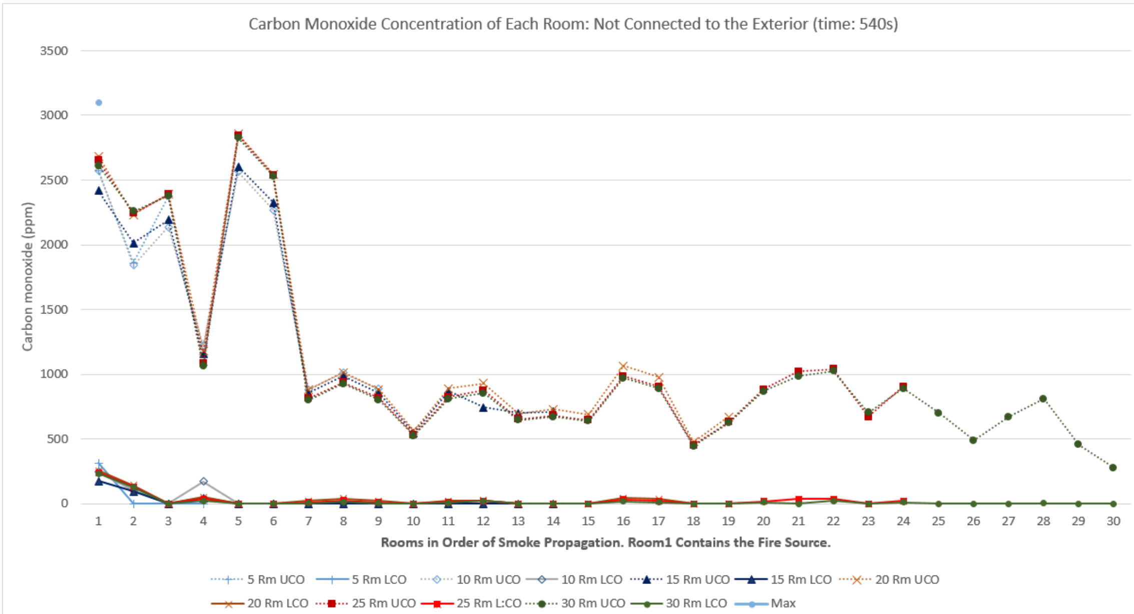

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 240s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max

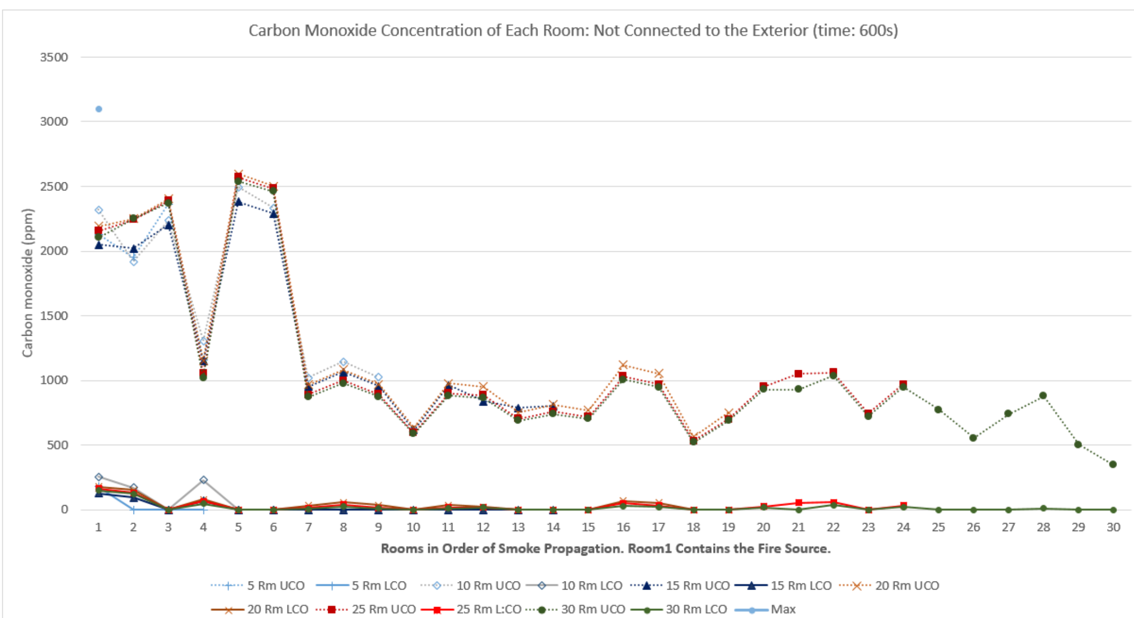

Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 300s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 360s)
Carbon monoxide (ppm)
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 420s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 480s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 540s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max


Carbon Monoxide Concentration of Each Room: Not Connected to the Exterior (time: 600s)
Carbon monoxide (ppm)
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Rooms in Order of Smoke Propagation. Room1 Contains the Fire Source.
5 Rm UCO
5 Rm LCO
10 Rm UCO
10 Rm LCO
15 Rm UCO
15 Rm LCO
20 Rm UCO
20 Rm LCO
25 Rm UCO
25 Rm L:CO
30 Rm UCO
30 Rm LCO
Max