Adaptive or absent: A critical review of building system resilience in the LEED rating system

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Abstract

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With time spent indoors dominating the lives of individuals across developed nations particularly within Europe, North America, and Australia, protecting indoor environmental quality becomes critical to protecting human health, and building systems play a critical role in doing so. As stressors like COVID-19 appear, conflicting system priorities can underline the need for resilience in all building systems. Sustainability rating frameworks are used in the engineering and architectural fields to motivate and reward the use of sustainable practices. As such, it is crucial to ensure these frameworks genuinely encourage resilience in building systems. This paper conducts a review of the LEED BD+C v4.1 framework for New Construction through a credit-level analysis. This is done to determine the extent to which resilience of building systems beyond the scope of structure is encouraged. In order to do so, relevant credits were identified, tabulated and deconstructed according to four key resilience properties: diversity, efficiency, adaptability, and cohesion. This analysis is expanded to the LEED Gold certified Husky Union Building on the University of Washington’s Seattle campus. Specifically, the ventilation systems and the related awarded credits are evaluated along the same resilience properties to better understand how the LEED framework rewards resilience in practice. An analysis of the ventilation performance in terms of indoor CO_2 concentration over three academic quarters is also conducted to determine how the LEED certification relates to performance. The findings conclude that while efficiency is well supported in LEED, diversity, adaptability, and cohesion can be enhanced. The HUB is found to reflect diversity and efficiency within the ventilation design but performs inadequately, failing to maintain healthy CO_2 levels 9.8% and 22.4% of the time during the Autumn and Winter quarters respectively. The author concludes that the existing rating system does not adequately encourage the wide adoption of resilience needed for long-term sustainability but provides a strong base upon which improvements can be made. In short, LEED proffers credits that would reward resilient designs but does not yet actively inspire them.

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ACKNOWLEDGEMENTS

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DEDICATION

This work is dedicated to my parents, who made a year plagued by a pandemic and crammed with an entire graduate degree seemingly comfortable. Mom, thank you for supplying me with so many meals as I holed up at my desk like a crazed hermit. Papa, thank you for being my biggest fan. I love you both.

Chapter 1. INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Human health and the natural environment are inescapably influenced by the built environment. The vast amount of time we spend inside makes the indoor environment particularly significant [1], [2]. As our understanding of these relationships has grown, so has our desire to improve them. Consequently, the concept of sustainability has reemerged. Sustainability is a broad concept that in the context of buildings is both relatively new to modern discussion and often equated with environmental protection. Yet, amongst those actively concerned with the subject, it is widely understood that "sustainability" does not, and by necessity cannot, be bound to such a narrow scope. Indeed, the concepts of social and financial well-being are consequently included in discussion within the field while the concept of resilience extrapolates these considerations over a longer time frame. Rating systems are the leading mechanisms by which these concepts of sustainability are incentivized within the industry.

These rating systems act as grading schemes by which projects voluntarily seeking certification for sustainability or healthfulness are evaluated. Typically, the rating system is organized as a framework comprised of categories that reflect a general theme or element of building design. Individual credits under these categories specify a particular desired intent or outcome and provide a set of requirements that must be met to earn points towards the credit. A threshold defined by the achievement of prerequisites, credits and a specified point total or percentage customarily determines if certification is reached.

These rating systems have been developed and employed all over the globe. The first among them was BREEAM in the UK back in 1990. Thereafter more and more systems developed as interest in sustainability grew. While BREEAM remains popular in the UK it is now deployed internationally [3] as well as are other well-known rating systems including the Living Building Challenge, WELL, and LEED.

The Leadership in Energy and Environmental Design (LEED) framework is currently the most widely adopted globally [4]. Certainly, it plays a key role in influencing what is defined as sustainable design. The framework was first launched by the United States Green Building Council (USGBC) back in 1998 and has since been periodically updated to better reflect developing strategies [5]. Nine credit categories define the structure of the framework. These categories span Integrative Process (IP), Location and Transportation (LT), Sustainable Sites (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Materials and Resources (MR), Indoor Environmental Quality (EQ), Innovation (IN), and Regional Priority (RP) [6]. Pilot credits presented in the online credit library on the USGBC website are introduced on a trial basis to reflect emerging practices. Achievement of these pilot credits can earn a project points under the Innovation credit category. In this way, the USGBC has consistently shown an understanding of the need for continuous evolution and evaluation of rating systems.

Researchers too have recognized this need. Studies that evaluate the performance of LEED-certified buildings are appearing more frequently in published literature. Assessments of energy performance in LEED buildings and comparisons between LEED and non-LEED buildings such as that conducted on Navy buildings by Menassa et al. [7] and in Arizona by Oates and Sullivan (Oates and Sullivan 2012), and Tilton and El Asmar [8] highlight a need to inspect the substance of the LEED framework to ensure the achievement of sustainability goals. In the same vein, the structures of rating systems are being brought under scrutiny as well. Particularly under prescriptive based rating systems it is possible for the desired outcomes of certification to be muted in projects that bypass impactful practices. This has been found to be a problem in LEED through Orr's position paper [9] and Amiri [10].

The concept of resilience is another issue that has gained popularity in research. Often discussed under the context of natural disasters and climate-change hazards, resilience is described as a building's ability to withstand and rebound from stressors. As climate change brings rising sea levels and increasingly frequent severe storms, floods have unsurprisingly proved a common focus of resilience discussion. Papers such as those presented by Barabaro et al. [11] and Chester et al. [12] present findings focused on physical and structural design to improve pre- and post-disaster flood risk mitigation. While these findings and similar investigations are significant, they often lack formal consideration of building systems. Recently, this gap in the literature was identified by Abraham and Anumba in 2020 who identified a need to approach resilience "from an interdisciplinary perspective" so that "every component of the building … can absorb disturbance," [13].

Building systems are critical components responsible for the performance of many building functions. The broad ambit of building systems traditionally encompasses lighting, ventilation, heating, and plumbing but is growing as new systems and technologies develop. While building systems vary, four key properties of resilient systems were defined by Fiksel back in 2003: namely diversity, efficiency, adaptability, and cohesion. Under this context, diversity is characterized as "the existence of multiple forms and behaviors," efficiency as "performance with modest resource consumption," adaptability as "the flexibility to change in response to new pressures," and cohesion as "the existence of unifying forces or linkages," [14].

Table 1.1 RBSPs relating to the four properties of resilient systems.

Diversity	**Efficiency**	**Adaptability**	**Cohesion**
• Multiple energy sources (onsite) • Multiple water sources (onsite) • Daylighting • Passive survivability (supplemental to mech.) • Variable settings	• Reducing energy load • Reducing water consumption (esp. potable)	• Modular design • Monitoring with response plan or automation • Consideration of future trends (eg. hazard assessment) • Renewable energy (onsite)	• Building management systems • Centralized controls • Centralized data collection • Inter-system coordination

For example, we may consider redundancies such as back-up generators as a diversity tactic or using LEDs instead of incandescent bulbs as efficiency. Feedback loops would be one adaptability characteristic, and modularity which allows change and re-configuration would be another. Finally, cohesion might be exemplified by a central control station. Resilient building system practices (RBSPs) that exemplify these four resilience properties can be found amongst the growing literature in research and industry. Table 1.1 presents some of the most common.

Upon examining RBSPs the interrelationships between the resilience properties becomes apparent. Passive survivability for example creates a redundancy in behavior when designed as a supplement to mechanical system operations. In this way it can fall under diversity as well as the immediately obvious adaptability. In fact, diversity can be thought of as a specific subset of adaptability. Yet, when used as typical operation, passive designs contribute to reducing energy loads and thus efficiency as well. Similarly monitoring and responding to system performance supports adaptability but is often integrated into building management systems and thus can tie to cohesion as well.

The need for building systems that embody these characteristics is perhaps most starkly shown by the convergence of COVID-19 and natural disasters over the past year. Indeed, the shroud of wildfire smoke that blanketed many skies in recent summers is set to become a permanent addition to these hot months stressing ventilation systems in homes and buildings. COVID-19 in 2020 presented a conflicting stressor to ventilation systems in these regions. While management of smoke ingress called for the separation of outdoor and indoor air, management of COVID-19 called for the opposite – instead in-creasing outdoor air intake [15], [16]. Both responses however increase energy demand of mechanical ventilation systems while dense overhead smoke cloaks the sun and impedes solar power. In California the wildfires from 2020 resulted in a decrease of about 30% in solar power generation [17].

These issues are representative of the western coast of North America and Australia in particular, but air quality is an issue dealt with in many countries. London has long struggled with air pollution and while local policies are improving the issue [18], other places are still grappling with it. Air pollution from China for example affects local cities and presents a transboundary problem for neighboring countries like South Korea [19]. Furthermore, it is imperative to understand that such conflicts seen in ventilation systems between COVID-19 and pollution are not the only instance of multiple-hazard events we are likely to see in the future. This paper does not intend to identify a comprehensive list of such events but rather to identify how well LEED is preparing for them. Designing resilience into systems can prepare buildings and occupants to better manage similar pressures.

The Husky Union Building on UW’s Seattle campus is, as its acronym suggests, a HUB for campus activity. This means that the systems that service it cover a variety of spaces including a cafeteria, a bowling alley, offices, meeting rooms, and entryways. Student populations on campus fluctuate throughout the year and its geographical location means it has been and will be subject to the aforementioned issues of wildfire smoke. After a major renovation in 2013, the HUB was awarded LEED Gold standard under the previous LEED 2009 version of the rating system. Data collected through an indoor environmental quality evaluation during the following year provide an apt opportunity to investigate the relationship between three factors: LEED, resilience, and building system performance.

1.2 THESIS OVERVIEW

1.2.1 *Objectives and Scope of Research*

This research covers the intersection between building system resilience properties, building system performance, and the LEED rating system. The goals of this evaluation are twofold. Firstly, to inform the integration of resilience practices into the LEED framework, and secondly to better understand the relationship between resilience properties and performance.

A critical evaluation of the LEED BD+C v4.1 rating system for New Construction aims to determine whether the four properties of resilient systems are intentionally encouraged by LEED, and whether they are fully or partially integrated within credits. The properties of resilience that are supported and areas of improvement are identified to inform future advancement of the framework.

A case study of the ventilation systems in the Husky Union Building is conducted by delving into official building documents, the building's LEED Gold score card and associated LEED manual, and a statistical analysis of CO_2 level within the building. In so doing the case study aims to answer the following questions:

- Does the HUB feature RBSPs in ventilation?
- Does LEED reward RBSPs in ventilation?
- Do RBSPs translate to good performance?

1.2.2 *Organization*

The following sections of this thesis are broken up to present the two portions simultaneously. The methods for each evaluation are presented under Methodology separated by subheadings, likewise with the Results. In this sense, the process descriptions and results for the three subsections of evaluation needed for the HUB case study are presented separately. The Discussion however is used to combine the findings and nuances identified in each evaluation in order to lead to the Conclusions.

Chapter 2. METHODOLOGY

2.1 EVALUATIVE PROCESS FOR LEED BD+C V4.1

In order to analyze the LEED Building Design and Construction v4.1 framework for New Construction, three phases of evaluation were conducted:

1. Evaluation of relevant credits;
2. Identification of overall correlation and patterns; and
3. Identification of possible improvements.

In phase 1, using the rating system manual and the accompanying online credit library, the literature for each credit therein was used as the basis for analysis. This examination probed qualitatively for RBSPs that support the four fundamental properties of resilience. The listed practices provided in Table 1 were collected from existing literature on resilience in buildings including papers by Mallawarachchi [20], Awadh [4], and Phillips et al. [21] as well as the authors' own knowledge. Where appropriate, practices were reframed in the context of building systems. The list is not designed to be exhaustive but representative of the field's current understanding of resilient practices and features. As discussed in the introduction, the RBSPs can overlap with more than one resilience principle. In order to address this complexity and standardize the evaluation process for each credit, each RBSP was sorted under a single resilience property. In particular, RBSPs that addressed adaptability through creating diversity were sorted under diversity only.

Both credit requirements and intents were considered. As such, credits that were intentionally designed to directly encourage these properties, and credits that did so inadvertently were noted alike. Specifically, the evaluation determines a credit's support of each property to be one of the following:

- **Intentional, Full (I, F):** at least one RBSP is specified under the credit Intent statement and is required under all possible routes to earning credit points.
- **Intentional, Partial (I, P):** an RBSP is specified under the credit Intent statement but is not required to earn credit points.

- **Unintentional, Full (U, F):** an RBSP is not specified under the credit Intent statement but is required under all possible routes to earning credit points.
- **Unintentional, Partial (U, P):** an RBSP is not specified under the credit Intent statement but is required under at least one requirement route.
- **Not Supported:** no RBSP is specified under the credit Intent statement and no RBSP is required under any requirement route.

The process through which each credit was evaluated to determine the above classifications is illustrated as a decision-based flowchart in Figure 2.1. This analysis was completed and organized into a review table, Table 1.1, where each row marks an individual credit and results are entered under columns corresponding to the four properties.

In phase 2, the results from phase 1 are reviewed to identify which of the four properties are (or not) supported, where in the framework, and in what manner. The number of credits earning each designation under individual properties were counted and graphed comparatively in order to inform the discussion.

Phase 3 forms the discussion and conclusion sections of this paper. Here, the results from both previous phases are considered and most importantly discussed in relation to the details of the credits and RBSPs themselves. As such, conclusions are drawn, and suggestions made that offer the chance to build upon the current rating system framework. These suggestions however are not intended to be exhaustive but are designed to provide a starting point for a more thorough deliberation.

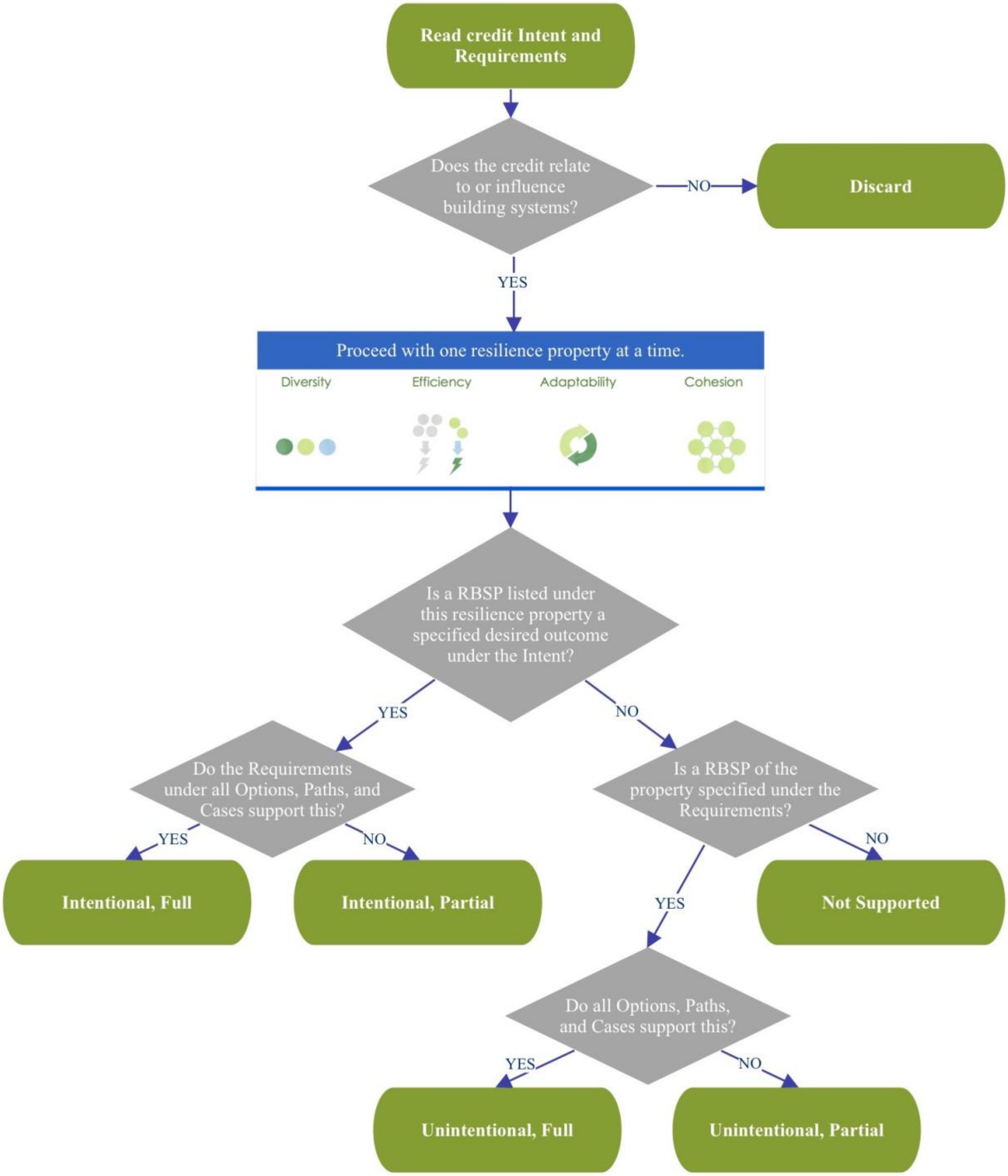


Figure 2.1 A process flowchart showing the evaluation process for determining the type of support given by a credit to a resilience property.

2.2 EVALUATIVE PROCESS FOR HUSKY UNION BUILDING

2.2.1 *Evaluative Process of LEED 2009 NC*

The process used for the evaluation of LEED BD+C v4.1 for New Construction was repurposed for the evaluation of the LEED 2009 for New Construction and Major Renovations manual. However, as this evaluation was expressly concerned with the HUB and ventilation, the questions posed at each decision stage were altered to reflect the change in evaluative scope. These changes apply the system boundary of ventilation for this evaluation and account for specifications within the HUB that limit the paths for credit achievement available to the project. In particular, the size of the project and typology. The resulting evaluation flowchart may be found in Figure 2.2.

The list of RBSPs, Table 2.1, was similarly reframed to be specific to ventilation systems. The system boundary for the scope of ventilation was defined to include systems for natural ventilation (windows and air stacks), mechanically assisted natural ventilation (automated windows and exhaust fans), and mechanical ventilation (air handling units and HVAC). As an extension, because mechanical ventilation systems such as HVAC systems are necessarily entwined and reliant on building energy systems, these were included in the scope of the assessment as well.

Table 2.1 Ventilation RBSPs relating to the four properties of resilient systems.

Diversity	**Efficiency**	**Adaptability**	**Cohesion**
• Multiple energy sources (onsite) • Mixed-mode ventilation • Variable settings	• Reducing energy load	• Modular design • Monitoring with response plan or automation • Consideration of future trends (eg. hazard assessment) • Renewable energy (onsite)	• Building management systems • Centralized controls • Centralized data collection • Inter-system coordination

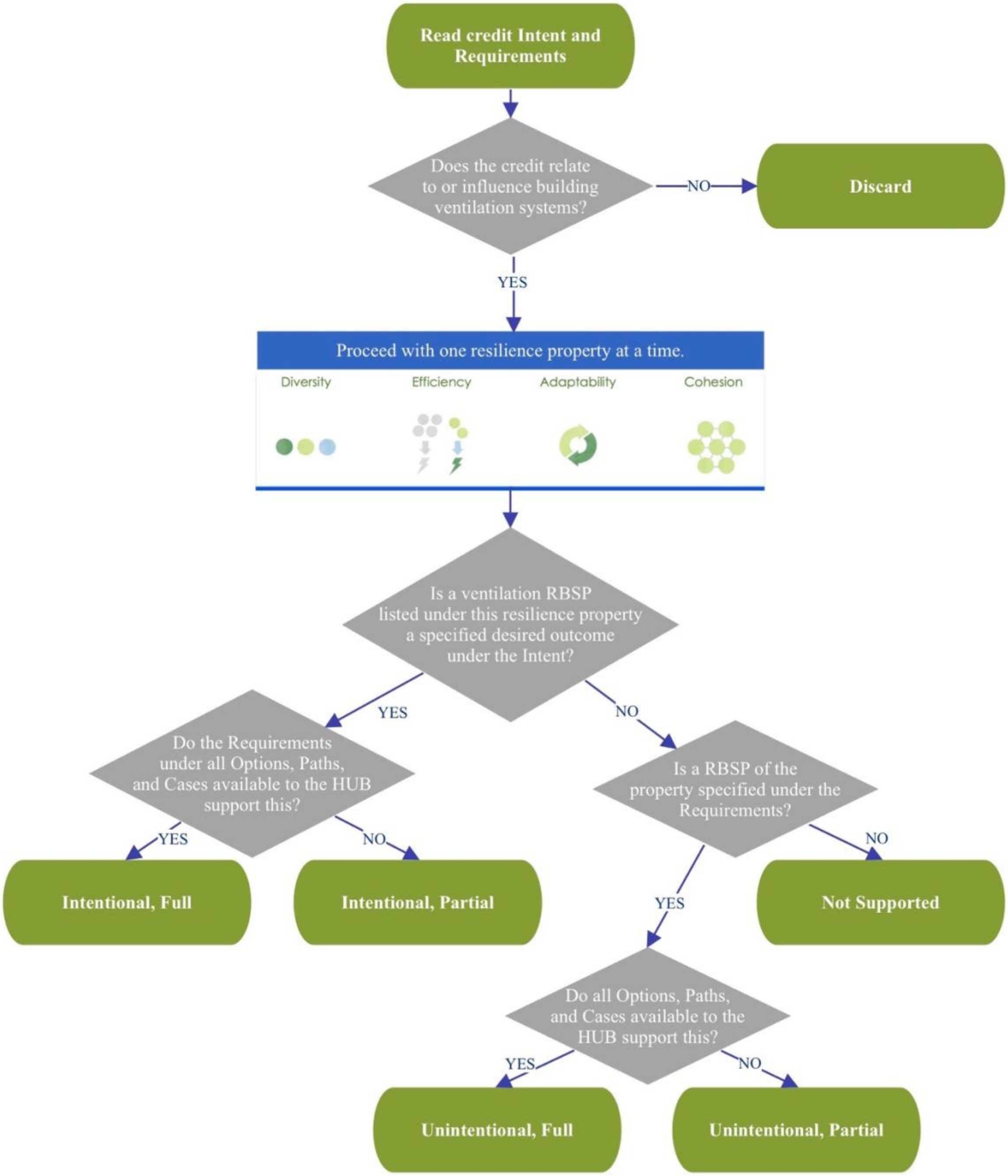


Figure 2.2 A process flowchart reframed for ventilation systems and the HUB's specifications showing the evaluation process for determining the type of support given by a credit to a resilience property.

2.2.2 *Research Process for Characterization of HUB's Ventilation*

Building specifications, commissioning documents, and design schematics regarding the HUB's renovation in 2013 were consulted in order to identify RBSPs exhibited by the ventilation systems. The same system boundary as defined in the evaluation of LEED 2009 were employed. In this way, the different forms natural and mechanical ventilation features throughout the building were noted for diversity along with variable settings or controls. These RBSPs and those under each resilient property were catalogued and summarized. Cohesion was identified through the Sequences of Operations (SOOs).

Particular attention was taken to understand the Sequence of Operations and ventilation features for Room 306 and indoor CO_2 control. A system flow diagram describing the connections between indoor and outdoor variables, the building management, occupants, and the ventilation equipment was thereby laid out.

2.2.3 *Process for Statistical Analysis of HUB's Ventilation Performance*

This portion of the paper will investigate the probability distribution of indoor CO_2 concentrations within the Student Legal Services office in the HUB, also referred to by its room number, Room 306. The concentration of CO_2 over the course of three quarters (Summer 2014, Autumn 2014, and Winter 2015) was logged at one-minute intervals each day for the duration of the building's operating hours. Please note that for the analysis under this project, any days with missing data were removed from consideration. The probability of failure was then defined as the probability that indoor CO_2 concentrations exceeded the maximum acceptable threshold of 1000 ppm noted under ASTM standard D6245-18 [22]. As such the relevant limit state equation, Equation (1), is defined as:

$$g(C) = 1000 - C_{CO_2} \tag{1}$$

where C_{CO_2} is the concentration of carbon dioxide inside the building. It should be noted that the 1000 ppm limit is the most commonly referenced albeit most lenient limit on indoor CO_2.

Epistemic uncertainty associated with the data is rooted in the method of collection. CO_2 monitoring devices vary in accuracy with relation to their quality. However, more importantly, individual devices can only monitor a localized zone. As such the data recorded was particular to the zone in which the monitor was placed. The HUB is a large building consisting of a variety of indoor spaces including offices, an atrium, a food court, and even a bowling alley. The use of natural and mechanical ventilation also varies throughout the building. This means that there is obvious epistemic uncertainty in regard to concentrations throughout the entirety of the building. Of course, aleatoric uncertainty plays a large role in the analysis of this data as well. This is in fact the basis of this portion of the investigation. Indoor CO_2 levels respond to a number of sources, key amongst these in the HUB is the occupants. The number of occupants in the building and how much CO_2 they expel is inherently variable. This is especially true over the course of multiple quarters. The number of students on campus during Summer quarter is significantly lower than that when the traditional school year is in session. To account for this, the data was analyzed separately for each of the three recorded quarters.

To determine the probability of failure, an appropriate probability distribution needed to be fit to the variables of the limit state equation, in this case a single variable: indoor CO_2 concentration. Some existing literature surrounding air pollutants are tabulated in Table 2.2.

Table 2.2 Distributions for air pollutants in literature.

	Distribution/Model	**Reference Title**
Particulate Matter (PM)	• 3-Parameter Lognormal • Generalized Extreme	• *Statistical distributions of particulate matter and the error associated with sampling frequency* [23]
Indoor Air Pollutant	• Lognormal	• *Report to Congress on Indoor Air Quality* [24] • *A Physical Explanation of the Lognormality of Pollutant Concentrations* [25]

The first listed reference was a paper investigating the fit of probability distributions to various particulate matter data collected in Spokane. It considered extreme value, gamma, generalized extreme value, lognormal, three-parameter lognormal, and Weibull distributions. The paper concluded that the goodness of fit varied depending on the PM data collected and sampling rate with the three-parameter lognormal performing best for daily PM2.5 data, and the generalized extreme for high concentrations of PM8 [23]. Both papers that used the lognormal distribution for indoor pollutants were affiliated with the EPA with the latter of the two aimed at explaining the physical processes that justify its ubiquitous use [24], [25].

Table 2.3 Goodness of fit test results.

		Summer	**Autumn**	**Winter**
Normal	KS Test	0.2391 – not valid	0.1251 – not valid	0.1157 – not valid
	AIC	1.1754e+05	3.0991e+05	3.1979e+05
Log Normal	KS Test	0.2094 – not valid	0.0916 – not valid	0.1054 – not valid
	AIC	1.1451e+05	3.0437e+05	3.1700e+05
Weibull	KS Test	0.2530 – not valid	0.1372 – not valid	0.1048 – not valid
	AIC	1.2029e+05	3.0889e+05	3.1836e+05

The references presented suggested the lognormal distribution was an appropriate distribution to fit to the collected CO_2 data, however the normal and Weibull distributions were also considered using the K-S and AIC tests using a developed MATLAB code to verify. The results are tabulated in Table 2.3. The code may be found in the Appendix.

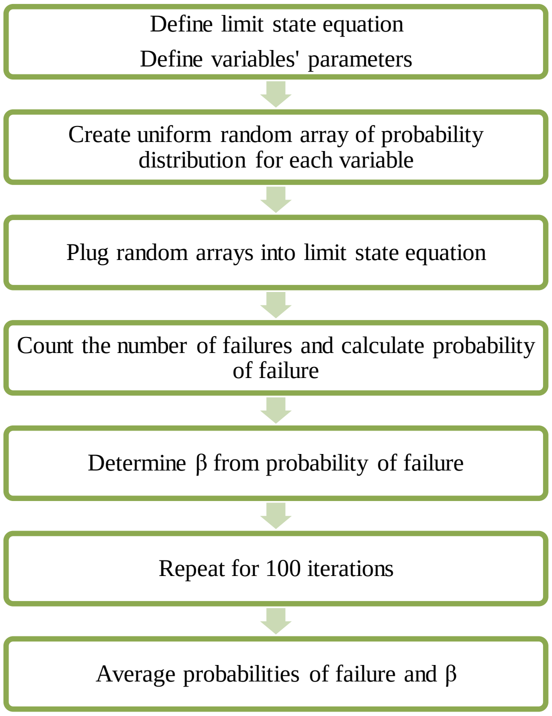


Figure 2.3 Monte Carlo simulation procedure.

The K-S test determined that all three distributions were not appropriate for the data from any of the quarters. This is a common issue with large sample sizes as was true here. Summer had the smallest sample size at 10,080 data points and autumn and winter at 22,320 data points each.

As such, the AIC test was used to determine the best fit of the three wherein the distribution with the smallest AIC value is chosen [26]. For all three quarters, this was the lognormal distribution.

As part of the process of identifying the distribution to be used in analysis, the Distribution Fitter App within MATLAB was used. This allowed the raw data and all three fitted distributions to be plotted together for each term. The resulting graphs and plots may be seen in the Appendix along with the app's analysis of each lognormal fit which provides the relevant mean, variance, and fit parameters. Interesting to note is that the choice of distribution was not clear from the probability plots.

The probability of failure was determined using the Monte Carlo method for all three terms and the Advanced First Order Second Moment method (AFOSM) was used as comparison for the winter quarter.

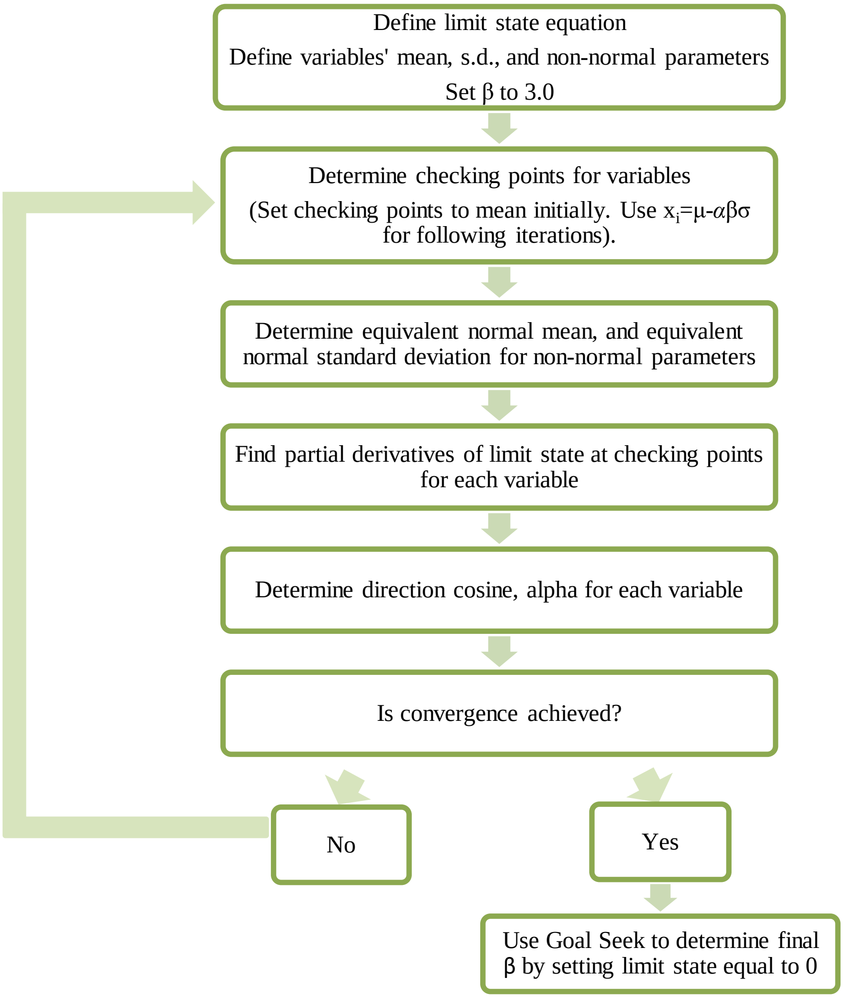


Figure 2.4 AFOSM simulation procedure.

The Monte Carlo procedure was executed using MATLAB code. A loop was used to complete the iterations and the averages were coded to ignore any ‘INF’ results. The steps for the procedure can be seen in Figure 2.3, and the script may be found in the Appendix. The AFOSM method (seen in Figure 2.4) was completed in Excel and made use of the ‘Goal Seek’ feature to change the value of β once convergence was reached. For this particular limit state, the relevant partial derivative was -1 and convergence could not be determined from the alpha value as this did not change between iterations. Instead, convergence was gauged by the limit state equation calculated at the checking points for each iteration.

Chapter 3. RESULTS

3.1 RESULTS OF LEED BD+C V4.1 EVALUATION

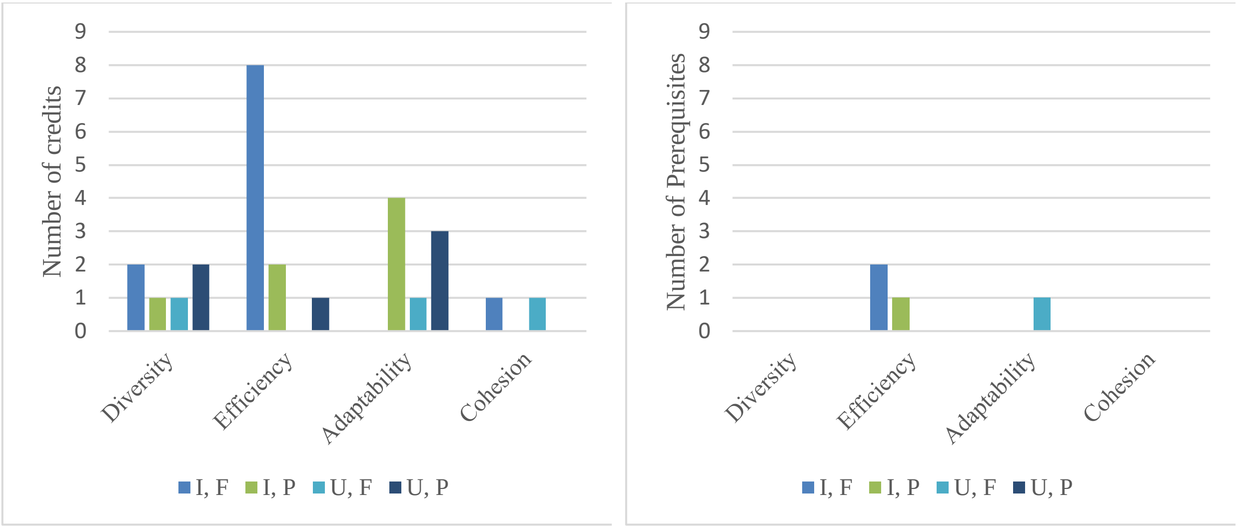
Based on the results of the evaluation seen in Table 2, it can be seen that unintentional, full support (U,F) is not common, only occurring under three credits. In other words, when an RBSP is not specified under the Intent of a credit, it is unlikely that it is fully supported in the credit Requirements. This perhaps is unsurprising; however, it is surprising to note that an RBSP’s presence in the Intent statement does not always translate to full support. Intentional, but partial support (I,P) was encountered seven times in the evaluation, particularly under the adaptability property. This means that either paths to earning credits are offered that allow a project to bypass the RBSP, scope out building systems, or the language alters the practice in a way that diminishes the integrity of the practice in relation to the resilience property.

The evaluation shows that the existing LEED BD+C credits support some properties of resilient building systems very well and others less so. This is seen particularly well in Figure 3.1. Existing energy and water sustainability goals under the framework unsurprisingly advance efficiency for these two major resources in building system operations. Water efficiency is especially supported intentionally and fully both in prerequisites and credits. Adaptability appears the second most frequently throughout the framework behind efficiency but is mostly concentrated in the Energy and Atmosphere (EA) category and is typically only partially supported. Prerequisites also fail to include diversity and cohesion intentionally or otherwise. Furthermore, it is clear RBSPs for cohesion do not crop up often throughout the LEED rating system overall, but where they do, they have been fully supported.

Table 3.1 Summary of correlations between credits and resilience properties

Credit	Diversity	Efficiency	Adaptability	Cohesion
IP Credit: Integrative Process		I, F		I, F
SS Credit: Light Pollution Reduction				
WE Prerequisite: Outdoor Water Use Reduction		I, F		
WE Prerequisite: Indoor Water Use Reduction		I, F		
WE Credit: Outdoor Water Use Reduction		I, F		
WE Credit: Indoor Water Use Reduction		I, F		
WE Credit: Cooling Tower and Process Water Use		I, F		
WE Credit: Water Metering			I, P	
EA Prerequisite: Fundamental Commissioning and Verification				
EA Prerequisite: Minimum Energy Performance		I, P		
EA Credit: Enhanced Commissioning			U, P	
EA Credit: Optimize Energy Performance		I, F		
EA Credit: Advanced Energy Metering			I, P	U, F
EA Credit: Grid Harmonization			U, P	
EA Credit: Renewable Energy			U, P	
EQ Prerequisite: Minimum Indoor Air Quality Performance			U, F	
EQ Credit: Enhanced Indoor Air Quality Strategies		U, P		
EQ Credit: Thermal Comfort	U, F			
EQ Credit: Interior Lighting	U, P			
EQ Credit: Daylight	I, F	I, F		
Pilot Credit: Assessment and Planning for Resilience	U, P		I, P	
Pilot Credit: Design for Enhanced Resilience	I, P	I, P	I, P	
Pilot Credit: Passive Survivability and Back-up Power During Disruptions	I, F			

As a group, the three pilot credits intentionally support diversity, efficiency, and adaptability, but do so in a partial manner. Diversity is supported under all three credits at least partially and is the only property to receive full support under one of these pilot credits.



(**a**) (**b**)

Figure 3.1 Summary of results: (a) Credit support for resilience properties (includes prerequisites); (b) Prerequisite only support for resilience properties.

3.2 RESULTS OF HUSKY UNION BUILDING EVALUATION

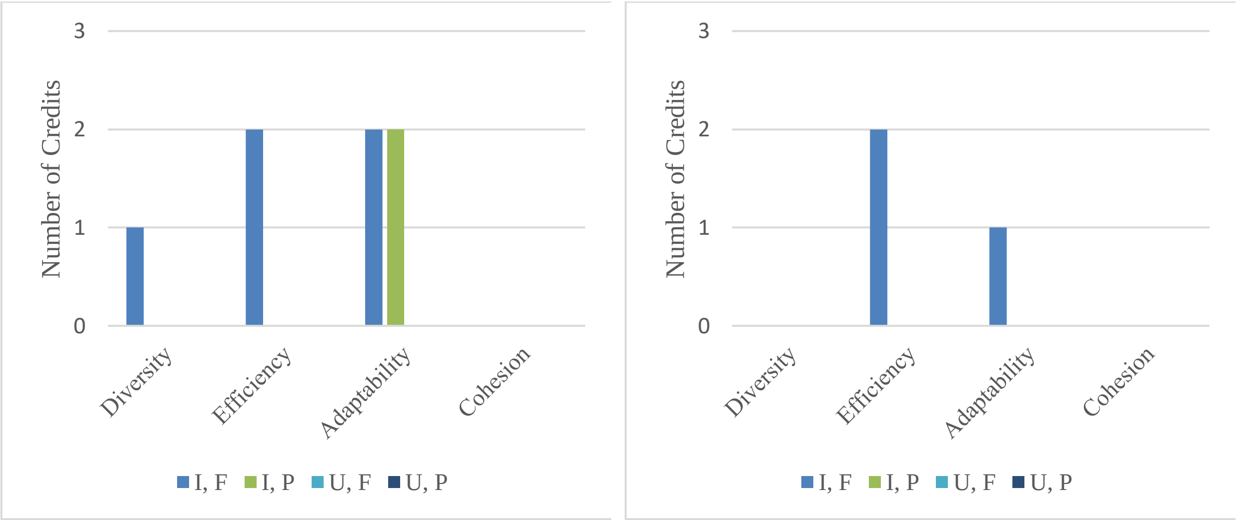
3.2.1 *Results of LEED 2009 NC Evaluation*

Interestingly, under the 2009 version of LEED, when the resilience properties were present under ventilation related credits, they were predominantly supported intentionally and fully. Table 3.2 and Figure 3.2(a) show this plainly. Nonetheless, a pattern similar to that seen in the evaluation of the latest version of the rating system (see section 3.1 above) emerged. Efficiency and adaptability were the most supported under the framework, with the latter facing partial support more frequently than the former. Efficiency was supported by the heaviest credit – worth up to 19 points on its own, while adaptability cumulatively was represented by a maximum of 13 points. Diversity was only present in one credit worth a single point. Once again, cohesion possessed the least support. In fact, cohesion was entirely absent from the Intent and Requirements of the ventilation credits.

This pattern where support for efficiency palpably prevailed above that for the other properties again carried through to the prerequisites. Here, efficiency was the only property supported under a required credit, this being an EQ prerequisite. The other three properties were present exclusively under voluntary credits.

Table 3.2 Summary of correlations between ventilation credits and resilience properties.

Credit	HUB Score	Diversity	Efficiency	Adaptability	Cohesion
EAp1: Fundamental Commissioning of Building Energy Systems	Req.				
EAp2: Minimum Energy Performance	Req.		I, F		
EAc1: Optimize Energy Performance	10/19		I, F		
EAc2: On-Site Renewable Energy	0/7			I, F	
EAc3: Enhanced Commissioning	0/2				
EAc5: Measurement and Verification	0/3			I, P	
IEQp1: Minimum IAQ Performance	Req.				
IEQc1: Outdoor Air Delivery Monitoring	1/1			I, F	
IEQc2: Increased Ventilation	1/1				
IEQc6.2: Controllability of Systems - Thermal Comfort	0/1	I, F			
IEQc7.1: Thermal Comfort - Design	0/1				
IEQc7.2: Thermal Comfort - Verification	0/1			I, P	



(**a**) (**b**)

Figure 3.2 Summary of results: (a) Credit support for ventilation resilience properties (includes prerequisites); (b) Resilience properties in credits earned by HUB.

Filtering this information through the lens of the HUB reveals much of the same. The HUB earned points on credits that supported efficiency and adaptability, but not on the one credit that supported diversity. Of course, since the LEED 2009 framework did not support cohesion under any of the relevant credits, the HUB did not earn points relating to this property either [27]. This can be seen in Figure 3.2(b).

3.2.2 *Analysis of the HUB's Ventilation System*

The As-built Drawings, Systems Manuals, Resource Conservation Audit Report, and the Commissioning Preliminary Report were the principal documents consulted. These documents describe the equipment, placement, and intended operations of the ventilation systems throughout the renovated HUB. Based on these documents, ventilation in the HUB represents all four of the properties of resilient systems in some way. Figure 3.3 below shows the various system features as they relate to the four properties in a Venn diagram.

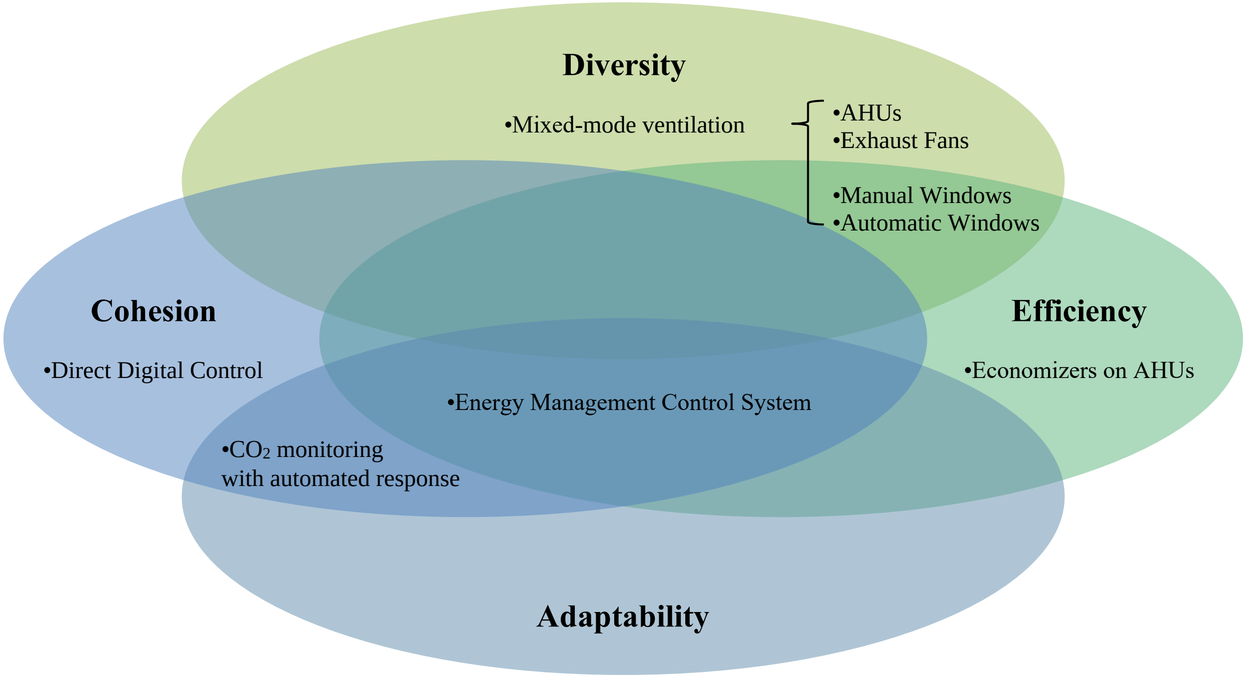


Figure 3.3 Alignment of ventilation systems in the HUB with the four properties.

The catalogue of various equipment employed throughout the building proves the presence of diversity of form. The HUB's ventilation is best described as mixed-mode. Both mechanical, natural, and mechanically assisted natural ventilation is incorporated in the building. Specifically, air handling units (AHUs) with heating coils make up the strictly mechanical equipment, while exhaust fans and automatic windows make up the mechanically assisted natural ventilation equipment. Manual windows of course are natural ventilation devices. Needless to say, the AHUs present diversity in behavior as well by offering the ability to heat, cool, and filter air. However not all zones in the HUB are served by the full range of equipment. Some areas only have natural ventilation devices, while the opposite is true for others.

For the most part mechanical cooling and air conditioning is not integrated into ventilation systems. However, this is present in a subset of zones. These are not the offices, but the largest populated areas. Namely, the bowling alley, the second floor ball room, the multi-purpose room, the bookstore, the kitchen offices, Scissors Edge, and the welcome area. Cooling elsewhere is incorporated into ventilation through the use of the natural ventilation equipment previously described and a nightly purge [28] [29].

Efficiency is addressed in two ways. Firstly, the diversity of form provided by mixed-mode ventilation inherently means that energy loads for cooling and ventilation can be reduced when outside conditions permit it by allowing natural ventilation equipment to be used instead of mechanical systems. Secondly, the energy consumption of mechanical systems is regulated by the Energy Management Control System (EMCS) and economizers which most AHUs are equipped with . The former works in tandem with the building management system, Direct Digital Control (DDC).

The EMCS and DDC work as the control center. They monitor and manage the building systems operations – not only for ventilation, but heating, and more. As such, this is the cohesive glue between the diverse range of equipment, controls, and environmental variables and allows the system to adapt accordingly. CO_2 monitoring sensors are installed within the most populated areas in the building and are tied to the DDC/EMCS as well. In this way, these zones are regulated for temperature and CO_2.

Student Legal Services, Room 306 is served by natural (and mechanically assisted natural) ventilation systems only. This is comprised of manual windows, automated windows, and exhaust fans. The Sequence of Operations (SOO) for this room dictates the behavior of the equipment through the EMCS based on the indoor and outdoor temperatures and CO_2 levels in relation to the respective set points. During the summer months when outdoor conditions and ventilation and cooling needs align, the EMCS will turn on the exhaust fan and open the automated windows. It will also notify occupants that it is permissible to open the manual windows by displaying a green light [30]. The indoor temperature and CO_2 levels are monitored through the sensors and equipment behavior is continuously adjusted. This can be seen in Figure 3.4 which depicts the system flow diagram during the Summer. Multiple feedback loops to indoor temperature and CO_2 can be seen here.

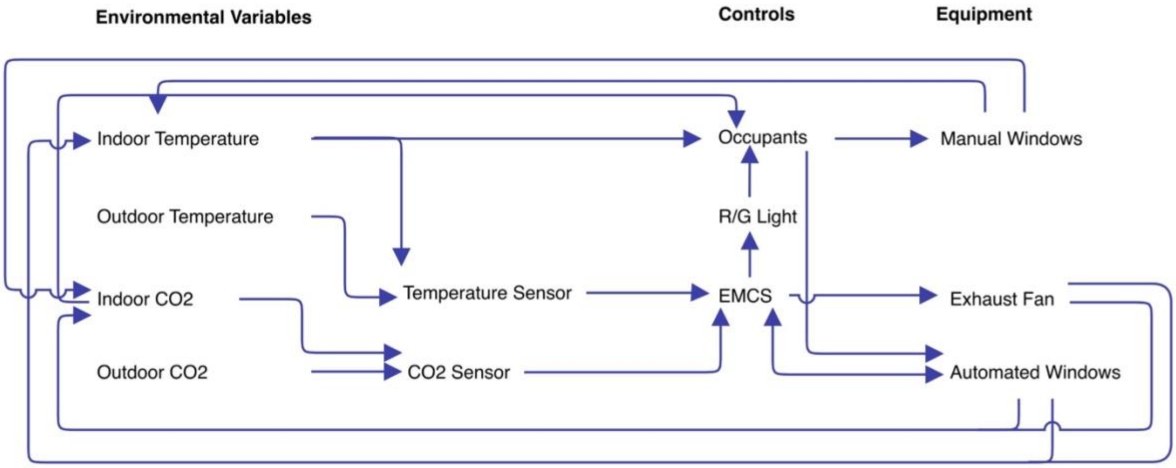


Figure 3.4 System flow diagram in Room 306 during Summer.

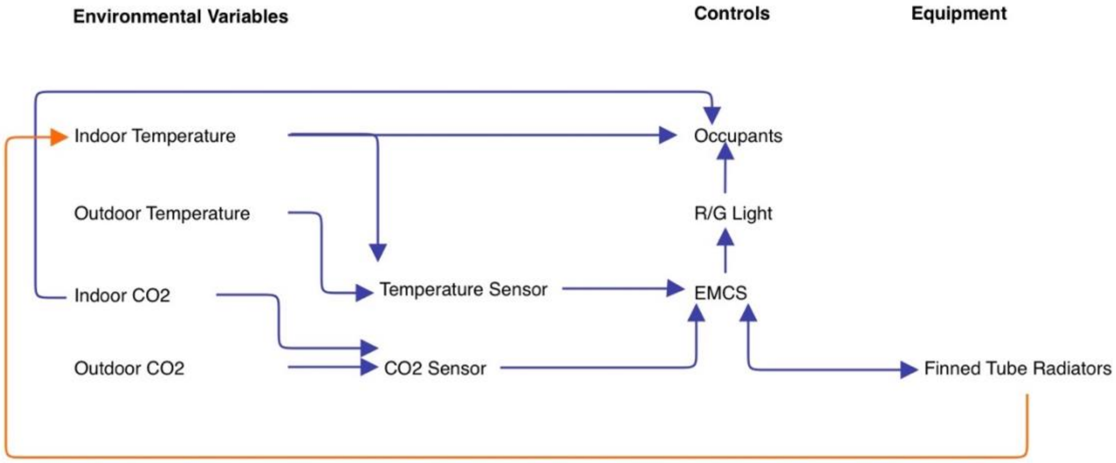


Figure 3.5 System flow diagram in Room 306 while heating.

Contrastingly, feedback loops to indoor CO_2 disappear when heating is engaged in colder months. Room 306 is not served by an AHU, rather heating is controlled by finned tube radiators. In this way the cohesive behavior between temperature and ventilation management that is seen during summer is severed. The SOO dictates that when the outdoor temperature drops below the set point and heating is required, the exhaust fan is turned off, the automated windows are shut, and a red light is displayed to occupants indicating that it is recommended to keep the manual windows closed [31]. Figure 3.5 reveals the system flow diagram under these conditions. It is important to note that the priority of temperature over CO_2 was written into the SOO after input from occupants. The original SOO activated ventilation during these colder months at the expense of heating and resulted in diminished thermal comfort. The SOO was updated accordingly.

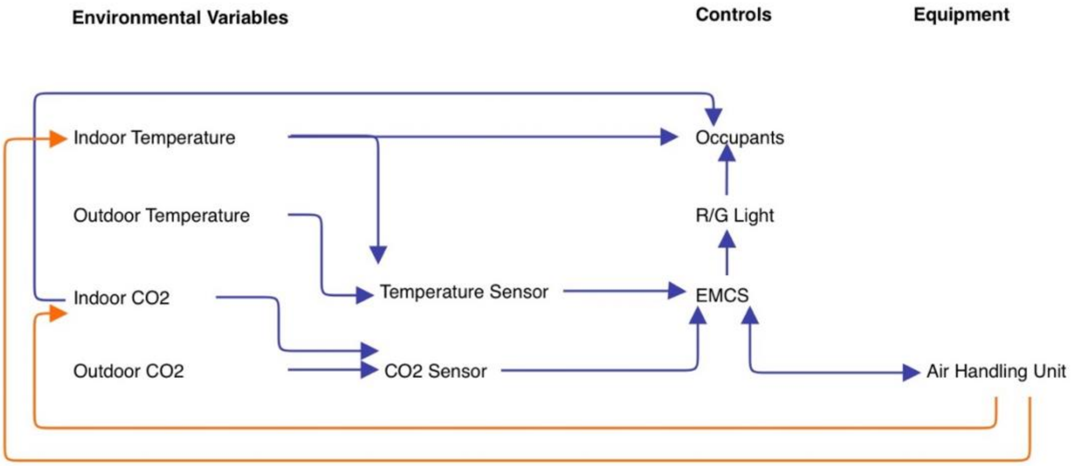


Figure 3.6 System flow diagram in HUB rooms with an AHU during heating.

Other rooms in the HUB do not face the same issue during heating. Rooms equipped with an AHU are capable of handling both ventilation and heating simultaneously. Under zones served by AHUs and natural ventilation, the EMCS dictates a similar approach when heating is required. Exhaust fans are deactivated, automatics windows are shut, and a red light will be displayed to occupants instructing them to keep manual windows closed. Then the heating equipment is activated. The inherent diversity in behavior afforded by the AHU maintains feedback loops to both temperature and CO_2.

Zones like Student Legal Services that are not served by an AHU rely on a nightly purge to handle ventilation. During operating hours, ventilation is not activated. As such the priorities currently reflected in the written SOOs place thermal comfort above indoor air quality while the building is occupied. Of course, the inherent conflicts between environmental factors will always persist, but the HUB's priorities can be adjusted in the existing system to alter behavior when needed.

3.2.3 *Analysis of Ventilation Performance*

The results from the Monte Carlo simulations showed that summer had a negligible probability of failure while both autumn and winter had concerningly large probabilities of failure, winter being the worse of the two. This was corroborated by the AFOSM results for winter quarter. The results for all methodologies are tabulated in Table 3.3.

Table 3.3 Room 306 Ventilation modeling results.

	Summer	**Autumn**	**Winter**	
	Monte Carlo	Monte Carlo	Monte Carlo	AFOSM
β	5.0451	1.2924	0.7592	0.7593
Probability of Failure	2.39e-05%	9.81%	22.4%	22.4%

For additional investigation, the Weibull distribution was also modeled using the Monte Carlo method for comparison on the autumn and winter quarters. The distribution was chosen based on visual inspection of the probability plots created in the MATLAB Distribution Fitter App. The resulting β and probability of failure values revealed a gloomier outlook for the HUB's ventilation. Probability of failure was found to be 11.5% and 26.4% for autumn and winter respectively under this distribution.

Chapter 4. DISCUSSION

As is readily seen in the results in Table 3.1, efficiency is supported for energy and water systems. Credits and prerequisites alike in the Water Efficiency (WE) and Energy and Atmosphere (EA) credit categories encourage project designers to reduce building demand for potable water and GHG-heavy energy or to seek alternative sources. In this way efficiency of water systems is readily encouraged, yet under energy systems, sustainability goals clash with those of resilience. Ultimately, energy credits focus on reducing carbon emissions from energy operations, and efficiency is merely one method of doing so. As a result, efficiency of energy systems is partially supported under the relevant EA credits.

Nonetheless, resilience of energy systems in LEED BD+C is not limited to efficiency and diversity RBSPs. EA Credit: Grid Harmonization, particularly Case 3 calls for flexibility in electricity loads of building operations. Requirements focus on shifting and reducing peak load, and thus naturally support adaptability in building systems from an energy perspective.

Although energy is often an integral commonality between building systems, their functions are wide-ranging and increasingly complex as technology develops. Varying disciplines and areas of expertise can apply to different building systems. As such, inter-system cohesion benefits from collaborative design and cross-disciplinary communication, which is explicitly supported by the Integrative Process (IP) credit category. Moreover, “synergies across disciplines and building systems,” [6] is specifically called for under the IP credit.

Inter- and intra-system cohesion is supported by monitoring requirements for energy. EA Credit: Advanced Energy Metering calls for remote sensors to be placed to measure building- and system-level electricity demand and consumption on a periodic basis. The data are to be collectively stored and remotely accessible to earn points towards the credit. This helps to unify system data and diagnostics thus explicitly supporting cohesion.

Carbon Dioxide (CO_2) monitoring for ventilation systems appears under the Indoor Environmental Quality (EQ) credit category within the Minimum Indoor Air Quality Performance prerequisite and Enhanced Indoor Air Quality Strategies credit for natural and mechanically ventilated systems respectively. CO_2 sensors must be equipped with an alarm or be capable of alerting a building automation system when levels exceed the set-point by 10%. This supports adaptability explicitly by requiring an alert to allow timely adjustment of system or occupant behavior.

Again, looking at the EQ credit category, diversity in lighting systems is well encouraged both in behavior and form. In behavior, diversity is supported via EQ Credit: Interior Lighting where control systems with at least three lighting levels are required within multi-occupant spaces. Diversity in form is seen under EQ Credit: Daylight which rewards projects for increasing access to sunlight inside the building.

Diversity of form is also seen in the pilot credit Passive Survivability and Back-up Power During Disruptions which, as its name suggests, encourages buildings to include energy system redundancies [32]. This and two related pilot credits, Assessment and Planning for Resilience and Design for Enhanced Resilience, can earn a project points towards the Innovation credit under the framework. While established credits such as WE Credit: Outdoor Water Use Reduction call for the use of historical regional and climate data, these two latter pilot credits require predictive modeling data to inform design decisions [33], [34]. This supports the spirit of adaptability in response to natural disasters by encouraging detailed forethought to climate hazards.

While support for resilience properties can be found within the framework and, existing supplements to the framework such as pilot credits reveal a promising direction for its development, a deeper consideration of the implications and structure of credit requirements reveals three key areas for improvement to better support diversity and adaptability of systems.

Firstly, explicit support for diverse systems is needed. The rating system indirectly supports the diversification of building energy sources by rewarding designs for the incorporation of renewable energy. LEED Zero, an add-on framework to LEED requirements which encourages projects to meet net-zero carbon and energy goals, does so as well [35]. However, it must be noted that this support is not inherent. In fact, because projects receive points based on GHG reductions, the framework does not distinguish between projects that manage to do so by reducing energy demand, transitioning to a single renewable energy source, or a diverse combination of energy sources. Making such a distinction by rewarding projects further for incorporating multiple renewable sources would prioritize diversity in the EA credit category. The same principle should be applied across the board.

In terms of behavior, mechanical heating, ventilation, and air conditioning (HVAC) systems have a rather well-established amount of diversity as they incorporate adjustable set points, and the ability to heat, cool, and filter air. EQ credits for indoor air quality however do not support mechanical ventilation over natural or mixed-mode systems. As such, both diversity of behavior and indeed diversity of systems are not supported here. Yet, these credits could easily be adjusted to prioritize mixed-mode ventilation designs.

Secondly, expansion of monitoring requirements is essential to supporting adaptability. Data collected via monitoring through sensors provides critical information that supports intelligent responses. EA Credit: Enhanced Commissioning specifies sensor placement that “assess[es] performance of energy- and water-consuming systems,” and requires the development of an action plan in response to errors [6], but only does so under Option 1, Path 2. Meanwhile, EA Credit: Advanced Energy Metering centralizes collected data, but falls short of requiring a system or plan that actively responds to this data. Expanding these requirements to include such a system or plan to be formalized would help encourage the closed-loop energy and water systems needed for adaptability.

On the other hand, CO_2 monitoring in the Minimum Indoor Air Quality Performance prerequisite and Enhanced Indoor Air Quality Strategies credit does address this more explicitly by requiring an alert when conditions exceed the threshold. However, under both the prerequisite and credit, CO_2 monitoring is just one of several listed strategies, only one of which must be met for a project to receive points, thus reducing the weight by which this strategy is encouraged by the rating system. As such, requiring the implementation of monitoring regardless of path or option chosen under these credits would more clearly support adaptability for ventilation systems.

It should be noted that more data-focused rating systems and platforms such as RESET and Arc have emerged and are quite often designed to complement LEED accreditation [36], [37]. These rating systems expand the scope of LEED monitoring requirements by tracking more resources and conditions, and more explicitly supporting adaptability and cohesion respectively. The former supports adaptability by necessitating response on the part of owners and both support cohesion by providing centralized data platforms. Furthermore, these data-rich platforms facilitate comparison and benchmarking between projects across the globe therefore facilitating intelligent adaption through cohesion on a much larger scale [36], [38]. While the USGBC, and LEED by extension, recognizes these rating systems and platforms, the current LEED manual does not specifically encourage their use. It would be easy to suggest doing so is ideal, however it would be naïve to ignore that a balance must be struck. Adding on supplementary rating systems or platforms increases the complexity of certification and can present additional paywalls for registration and maintenance. These are all important issues that deserve further deliberation as the framework evolves.

Lastly, in order for long-term adaptability to be better supported in the framework, consideration of natural disasters and climate change needs to be expanded. Sporadic circumstances arising from climate change are not yet well discussed in the manual but appear as a key concern addressed in three pilot credits in the online credit library. Unfortunately, the focus for two of these pilot credits lies solely on mitigating physical damage to structure and systems. Without question this is a very important concern, however consideration of system behavior particularly under multiple or overlapping stressors is also needed. The third pilot credit, Passive Survivability and Back-up Power During Disruptions is an excellent addition in this way by supporting system diversity in case of emergency. However, adaptability is not clearly encouraged here.

Unfortunately, as climate change increases the frequency of disruptions, our baseline operations will more closely resemble what is currently considered exceptional circumstances. In this way, additional stressors will require building systems to be adaptive under these strenuous conditions. Key to supporting adaptability to this end is integration of future climate conditions (rather than historical) for baseline calculations such as those conducted for the WE Credit: Outdoor Water Use Reduction. This is essential but should be done in a manner that respects the limitations of humans equipped with intelligence but not psychic abilities. Likewise, adaptive strategies such as modular design and foresight for expansion or remodeling of building systems could easily be supported by a devoted credit much like the healthcare-specific MR Credit: Design for Flexibility.

Taking a look into the relation between the four resilience properties in real life, we see the results of the modeling for the HUB's ventilation clearly show that for Room 306 ventilation is often unable to maintain CO_2 concentrations under the accepted maximum threshold of 1000 ppm. This is not an issue during warmer summer months when occupancy is low but is a persistent issue in the colder months of the autumn and winter quarters when students are on campus in high numbers. These modeling outcomes align with inspection of the raw data collected. Considering this threshold is the most lenient standard and more stringent thresholds exist for buildings aiming to earn recognition for sustainability and healthfulness, such as the HUB, this is concerning.

With the advent of COVID-19, the risks associated with improper ventilation have become all the more apparent. With this in mind, the findings suggest a need for the ventilation systems within the HUB to be re-evaluated and adapted so as to bolster performance. To ensure a more thorough and accurate understanding of the building's needs, further monitoring across the building may be needed to support this effort.

Considering however, that the ventilation system in Room 306 reflects each of the four properties of resilient systems, but *still* fails to adequately cope with expected loads enjoins a deeper consideration of the properties and the system itself. Have the properties been ill defined? Are they incomplete? The author argues that the former is the true culprit. One resilience property stands out amongst the four: cohesion. Fittingly, as its name suggests, cohesion seems to be the glue that holds together the other three properties of resilient systems. Cohesion is the feedback loops that make adaptability possible. The network that connects diversity… and crucially: deals with the tradeoffs between efficiency and performance. In other words, cohesion is where conflicting goals clash and priorities emerge victorious. This means that *priorities* define how cohesion is leveraged.

This brings us to Sequences of Operations, or SOOs. Room 306 clearly displays cohesion and adaptive practices in monitoring and build management systems. Management of IAQ according to SOO for Room 306 is executed via conditional statements based on indoor and outdoor temperatures, and indoor and outdoor CO_2 levels. Through these if- then- statements CO_2 management is placed below temperature management in priority. When heating, all ventilation is shut off, and a light displays to advise occupants not to open manual windows. As per standard practice, the SOO prioritizes energy efficiency over indoor air quality (IAQ). With the room's lack of an air handling unit, this easily explains the failure of ventilation seen in Autumn and Winter terms.

What this shows is that while one may achieve cohesion fundamentally, the manner of cohesion, and the priorities that govern it inevitably play a more critical role in determining the resilience in performance. If LEED, or indeed any rating system, desires to encourage resilience two things must be better addressed:

Firstly, a method whereby cohesion can be objectively described by characterizing the type and number of connections between key system components is necessary. An ideal solution might yield a quantitative value through which the level of cohesion could be understood as EUI does for efficiency. This would both help in the design of systems throughout project development, and provide a factor through which cohesion could be more explicitly encouraged in credit requirements. This alone poses a ripe topic for further research and will require a lot of work. It also cannot be ignored that like IEQ, such a factor would have limitations and could not be the only perspective through which cohesion is scrutinized.

Secondly, the role of SOO priorities must be addressed. Adaptability of SOO priority is necessary to react to negative performance results, as those that were processed here for the HUB. This especially is of import when considering that the priorities set upon initial occupation may change as disruptive events occur. Indeed, for the HUB, the failure of ventilation was not due to any disruptive event, and the very real intersection between COVID and wildfire smoke pushes air quality to the top of concerns.

Chapter 5. CONCLUSIONS

Diversity, efficiency, adaptability and cohesion are key properties that describe the resilience of systems. Under the LEED BD+C framework for New Construction, efficiency of building systems is intentionally and fully supported by the existing credits in LEED BD+C from a water perspective. From an energy perspective, credit goals are centered on reducing emissions rendering support for efficiency clearly intentional, but partial. Diversity, adaptability, and cohesion are sporadically present in the framework, but certainly require more attention and heartier endorsement. Adjustments that explicitly reward diversity of energy sources and system forms can easily be included to the betterment of existing credits. Likewise, the expansion of monitoring requirements to create closed-loop systems can be readily included. Finally, consideration of long-term adaptability through the integration of predictive climate data as opposed to historical data is needed. All in all, the LEED BD+C v4.1 rating system currently rewards resilient building systems but does not always actively encourage their development. Minor adjustments and additions that build off the existing goals and trajectory of the framework's development will better inspire resilience in LEED-standard building systems and effect major change. While these recommendations are specific to LEED, the gaps identified are concerning enough to inspire similar investigations into other rating systems internationally, as well as to express caution to communities looking to adopt them into policy or practice.

The case study conducted further identifies key areas for future research in building system resilience that will aid the development of such rating systems. Firstly, the role of SOOs on system performance is highly influential. Accordingly, a rating system that aims to incite resilience in actual system performance will need to encourage clarity and adaptability in SOOs. This of course, will be of particular importance in building typologies that handle large and automated systems. Consequently, research into how these aspects can be achieved and verified in an SOO and the priorities therein is needed.

Finally, and most importantly, a means of characterizing or quantifying the level of system cohesion is needed as well. The development of such a method would likely benefit from collaboration between multiple fields of study including but not limited to: mechanical engineering, systems engineering, and mathematics. The benefit of this however would not be narrowly limited to rating systems but be germane within the much broader realm of practice.

Architects and project engineers designing building systems would be better able to communicate and compare different system designs based on a perspective of resilience. The concept of resilience is multi-faceted. It is undoubtedly present in practice and in the path the field of sustainable buildings has set ahead, yet one property which holds great sway is seemingly overlooked. Cohesion holds the most pivotal function in governing the performance of systems. It is crucial that this property is awarded careful and comprehensive regard moving forward.

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APPENDIX A

HUB Summer

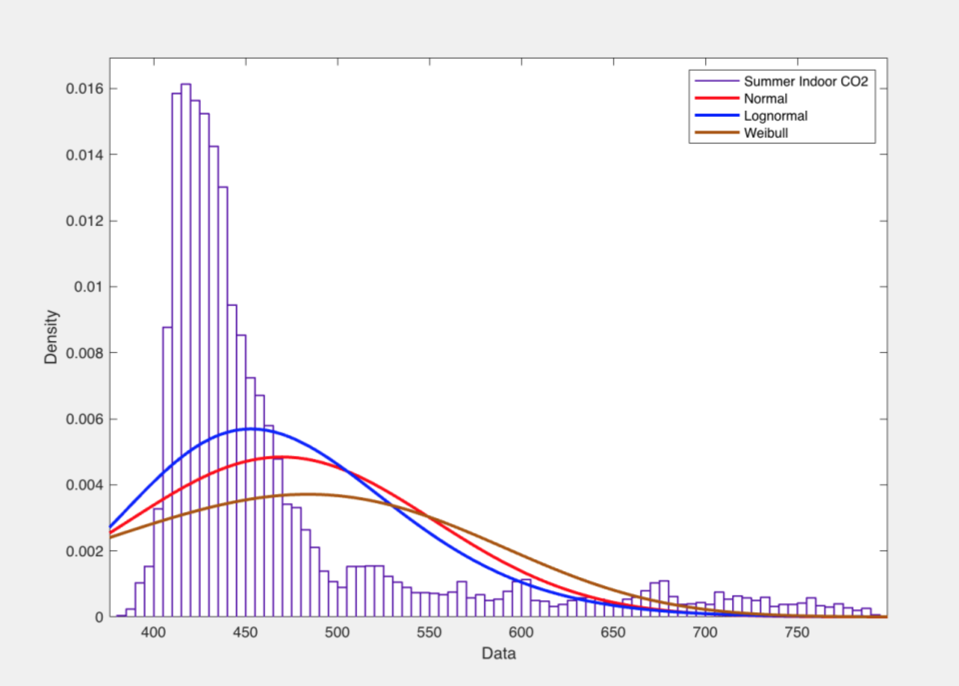


Figure A 1 Summer PDFs in Distribution Fitter App.

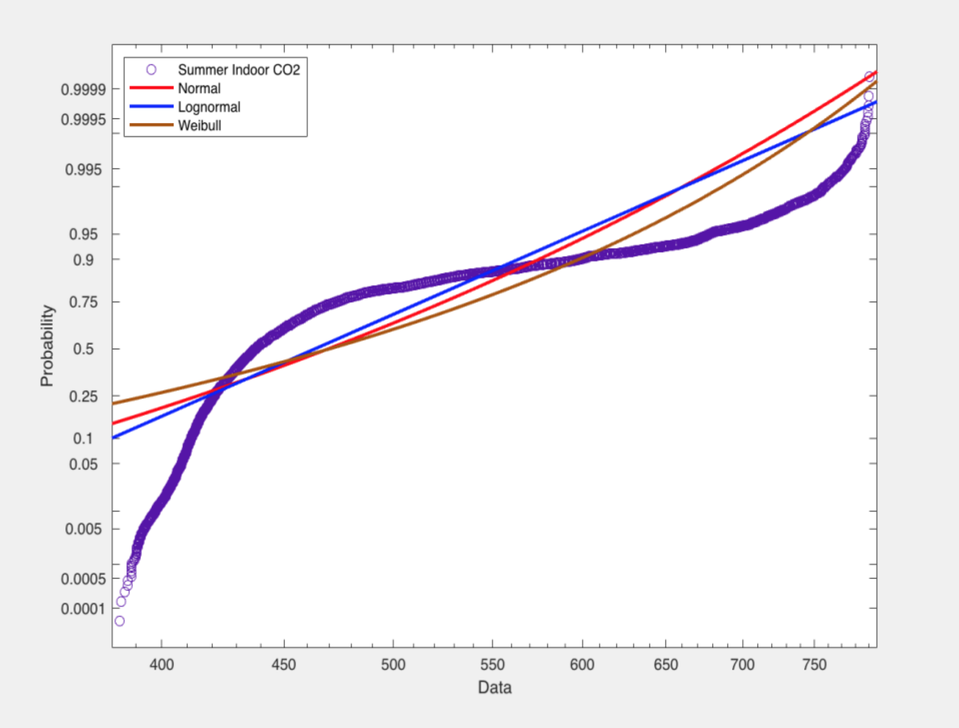


Figure A 2 Summer probability plot on normal paper.

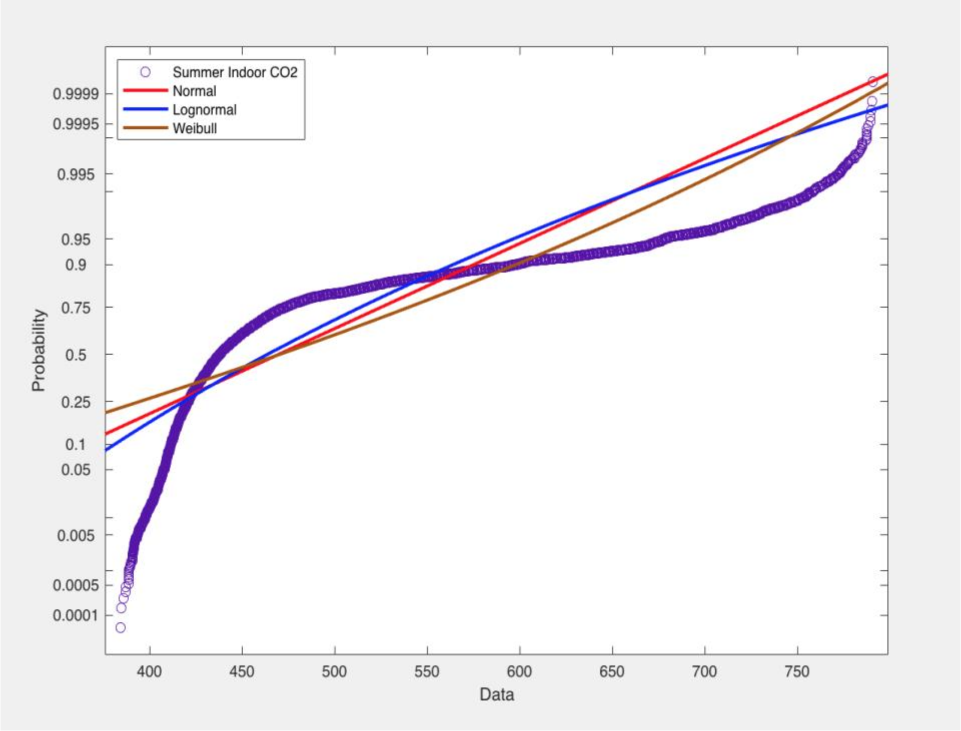


Figure A 3 Summer probability plot on lognormal paper.

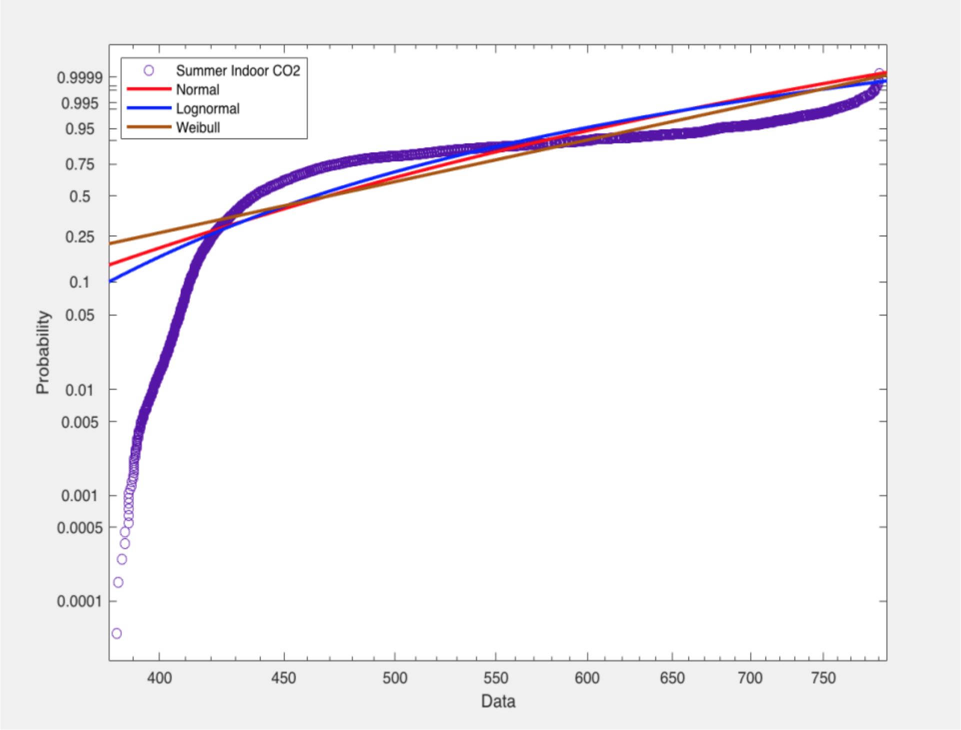
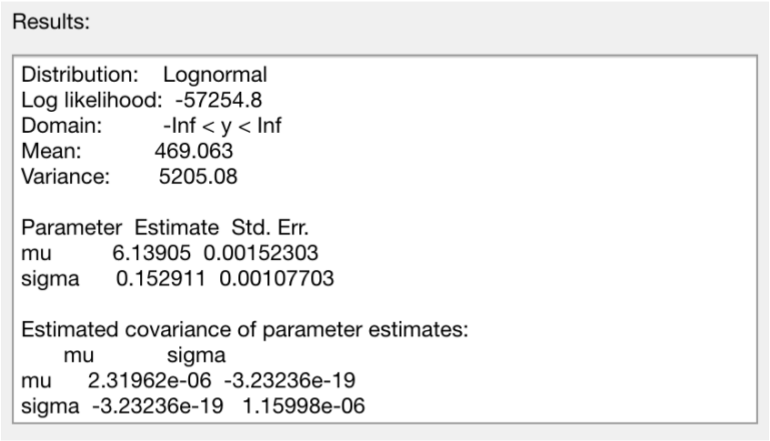
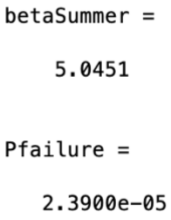


Figure A 4 Summer probability plot on Weibull paper.



```
Results:

Distribution:    Lognormal
Log likelihood:  -57254.8
Domain:          -Inf < y < Inf
Mean:            469.063
Variance:        5205.08

Parameter  Estimate  Std. Err.
mu         6.13905  0.00152303
sigma      0.152911  0.00107703

Estimated covariance of parameter estimates:
       mu           sigma
mu     2.31962e-06  -3.23236e-19
sigma  -3.23236e-19  1.15998e-06
```

Figure A 5 Summer lognormal distribution from Distribution Fitter.



```
betaSummer =

    5.0451


Pfailure =

   2.3900e-05
```

Figure A 6 Summer lognormal Monte Carlo results.

HUB Autumn

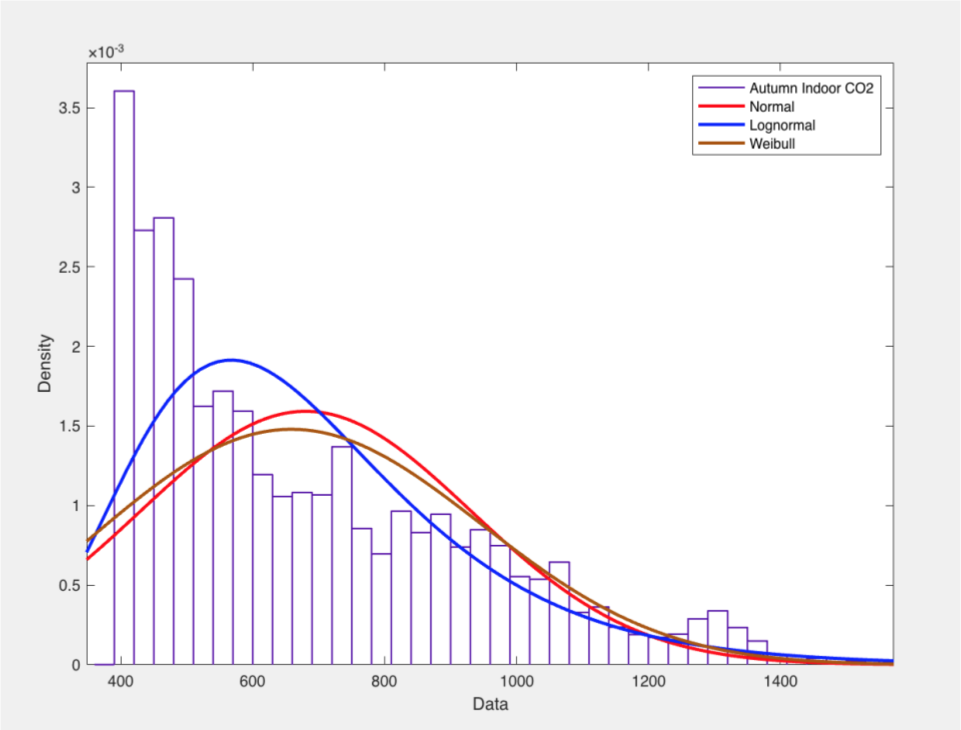


Figure A 7 Autumn PDFs in Distribution Fitter App.

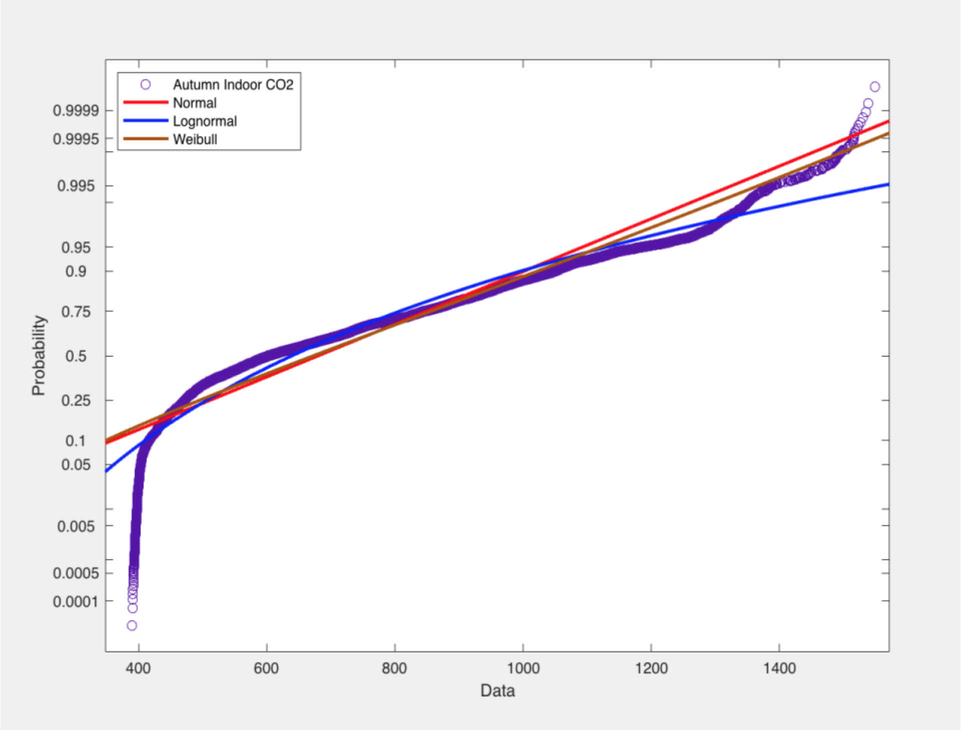


Figure A 8 Autumn probability plot on normal paper.

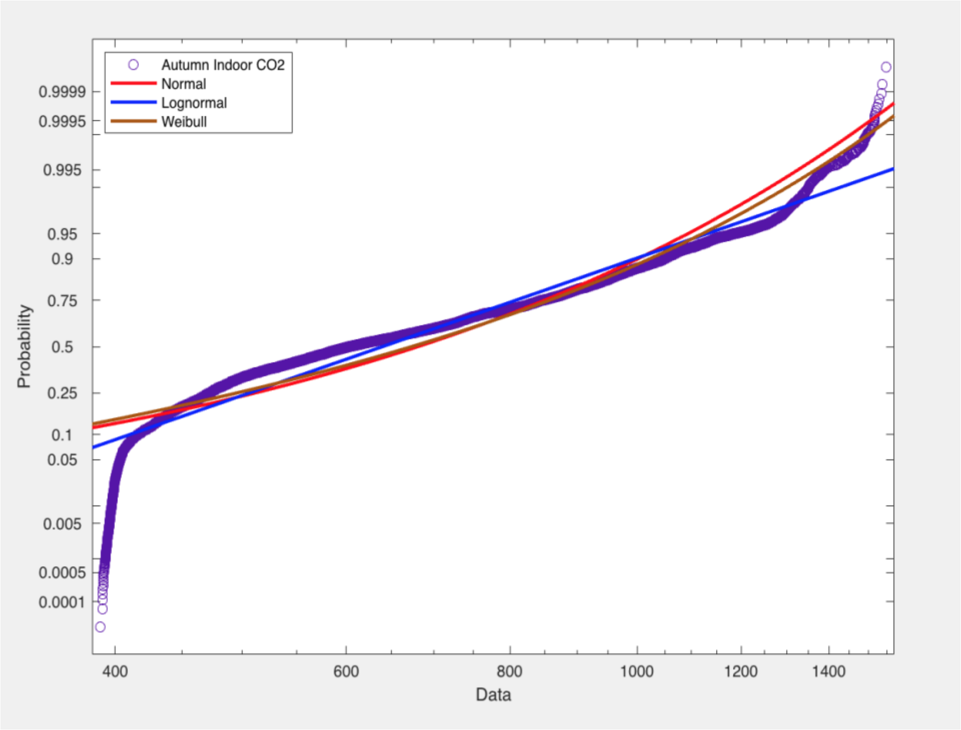


Figure A 9 Autumn probability plot on lognormal paper.

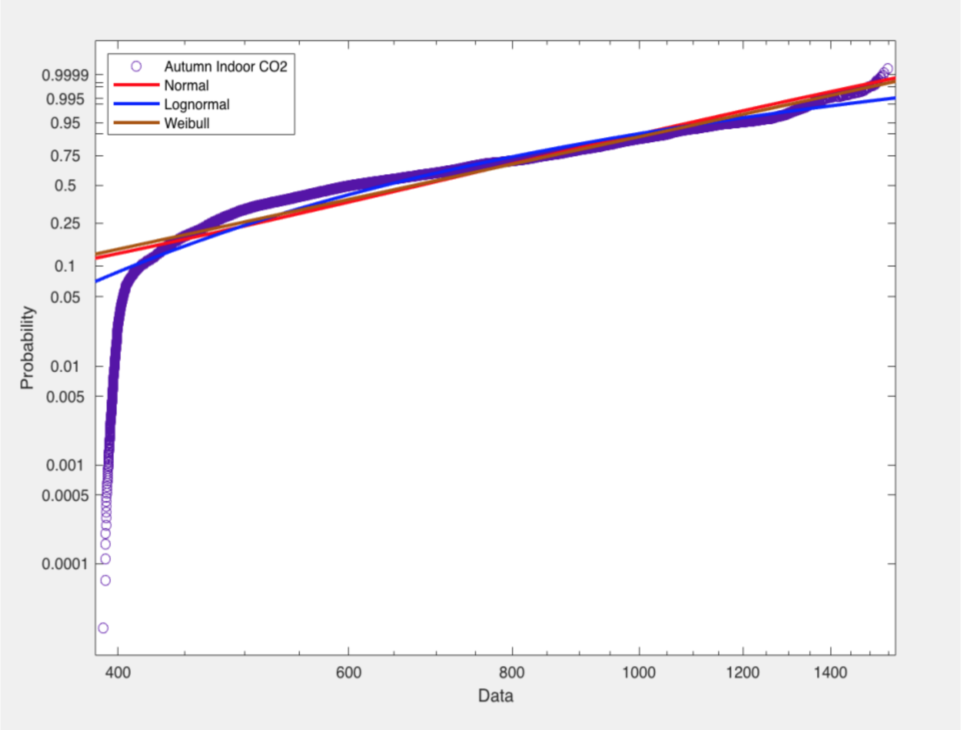
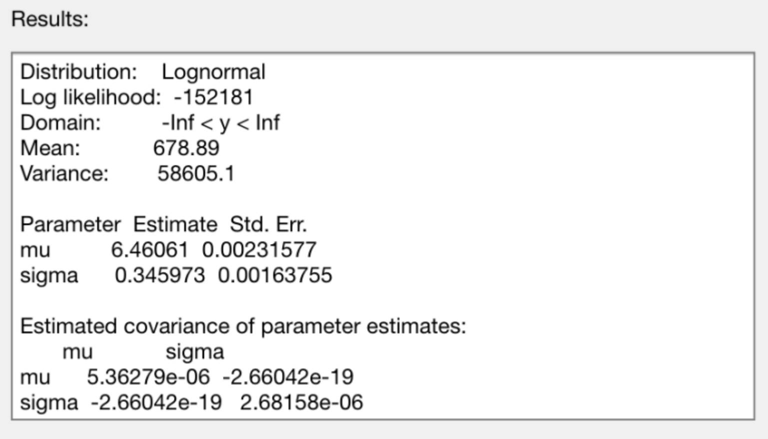
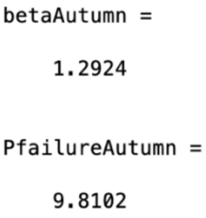


Figure A 10 Autumn probability plot on Weibull paper.



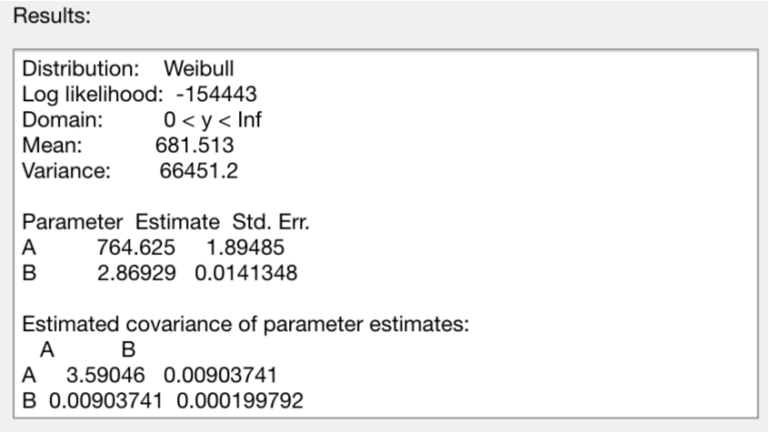
```
Results:

Distribution:    Lognormal
Log likelihood:  -152181
Domain:          -Inf < y < Inf
Mean:            678.89
Variance:        58605.1

Parameter  Estimate  Std. Err.
mu         6.46061  0.00231577
sigma      0.345973  0.00163755

Estimated covariance of parameter estimates:
       mu           sigma
mu     5.36279e-06  -2.66042e-19
sigma  -2.66042e-19  2.68158e-06
```

Figure A 11 Autumn lognormal distribution from Distribution Fitter.



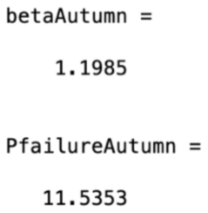
```
betaAutumn =

    1.2924


PfailureAutumn =

    9.8102
```

Figure A 12 Autumn lognormal Monte Carlo results.



```
Results:

Distribution:    Weibull
Log likelihood:  -154443
Domain:          0 < y < Inf
Mean:            681.513
Variance:        66451.2

Parameter  Estimate  Std. Err.
A          764.625    1.89485
B          2.86929   0.0141348

Estimated covariance of parameter estimates:
  A          B
A    3.59046   0.00903741
B 0.00903741  0.000199792
```

Figure A 13 Autumn Weibull distribution from Distribution Fitter.



```
betaAutumn =

    1.1985


PfailureAutumn =

   11.5353
```

Figure A 14 Autumn Weibull Monte Carlo results.

HUB Winter

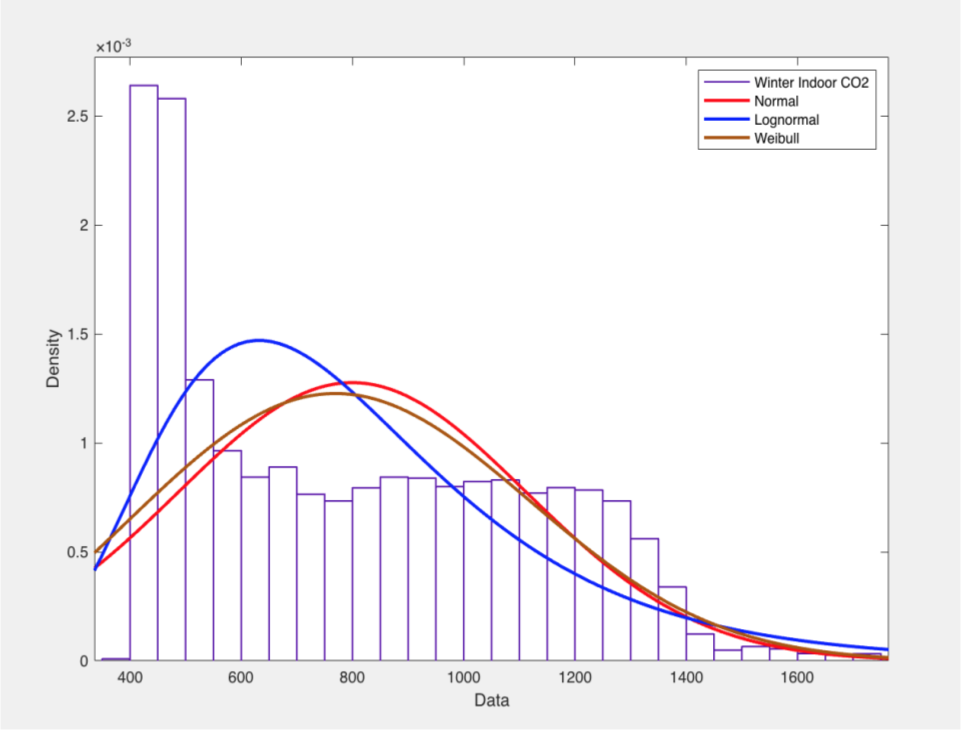


Figure A 15 Winter PDFs in Distribution Fitter App.

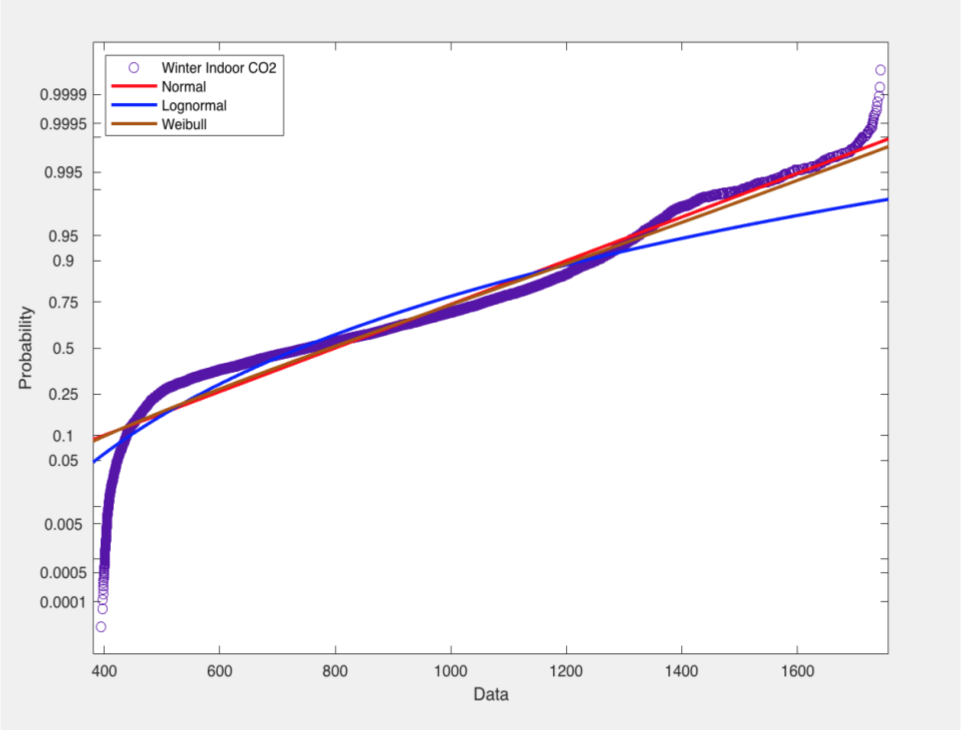


Figure A 16 Winter probability plot on normal paper.

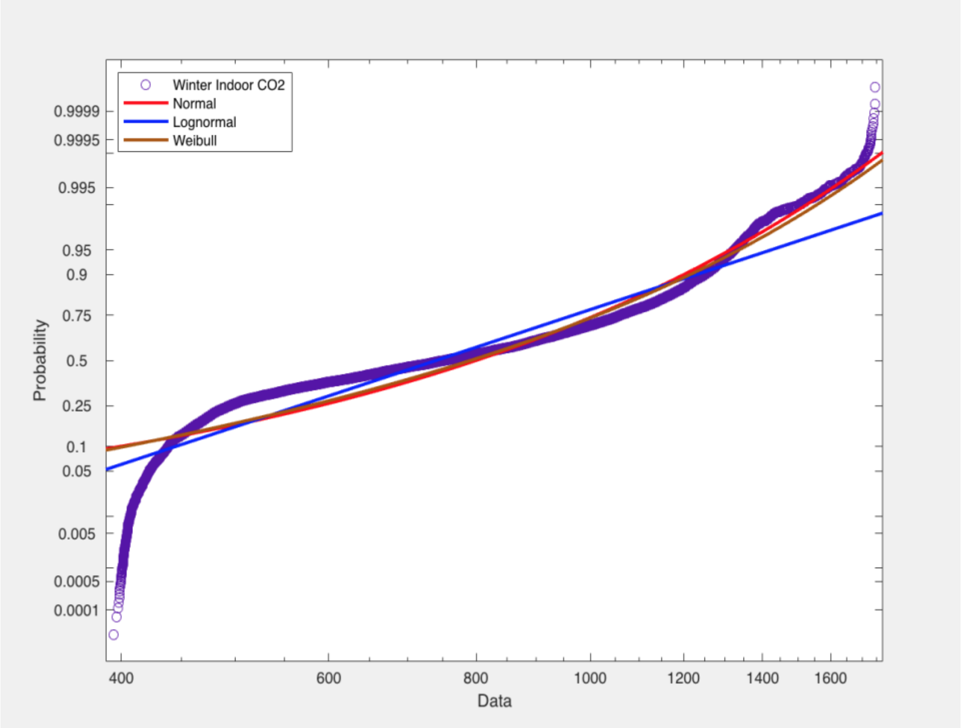


Figure A 17 Winter probability plot on lognormal paper.

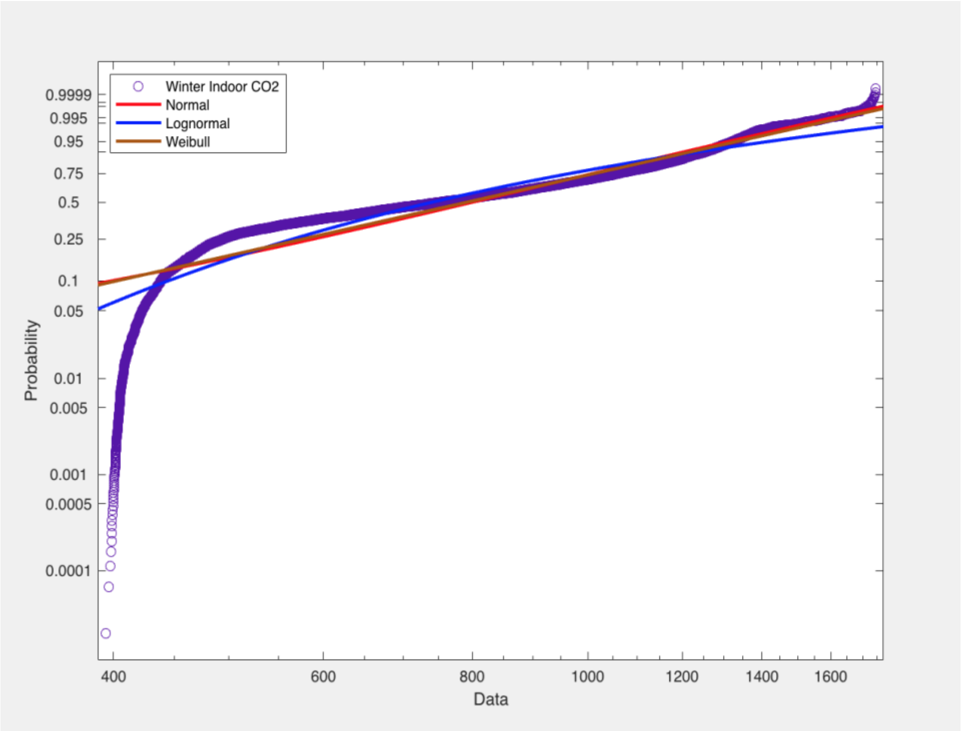
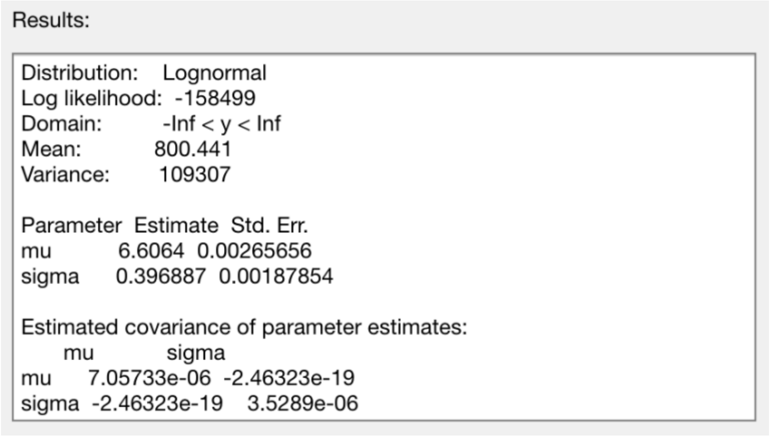
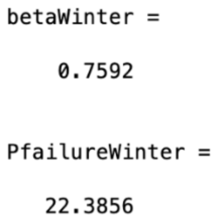


Figure A 18 Winter probability plot on Weibull paper.



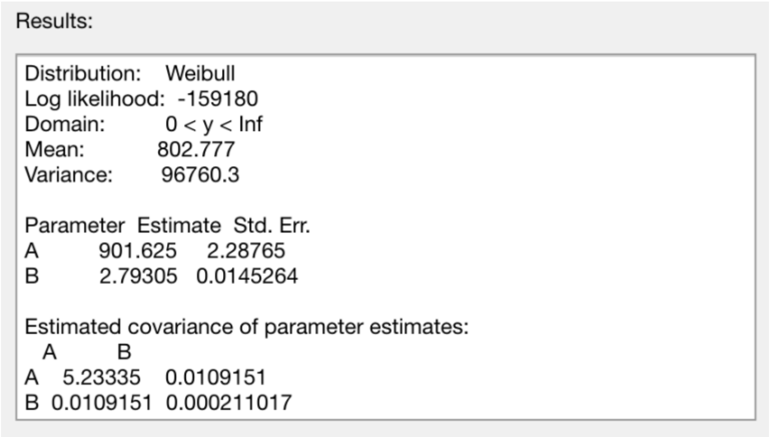
```
Results:

Distribution:    Lognormal
Log likelihood:  -158499
Domain:          -Inf < y < Inf
Mean:            800.441
Variance:        109307

Parameter  Estimate  Std. Err.
mu          6.6064  0.00265656
sigma      0.396887  0.00187854

Estimated covariance of parameter estimates:
       mu           sigma
mu      7.05733e-06  -2.46323e-19
sigma  -2.46323e-19   3.5289e-06
```

Figure A 19 Winter lognormal distribution from Distribution Fitter.



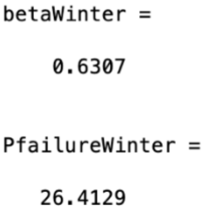
```
betaWinter =

    0.7592


PfailureWinter =

   22.3856
```

Figure A 20 Winter lognormal Monte Carlo results.



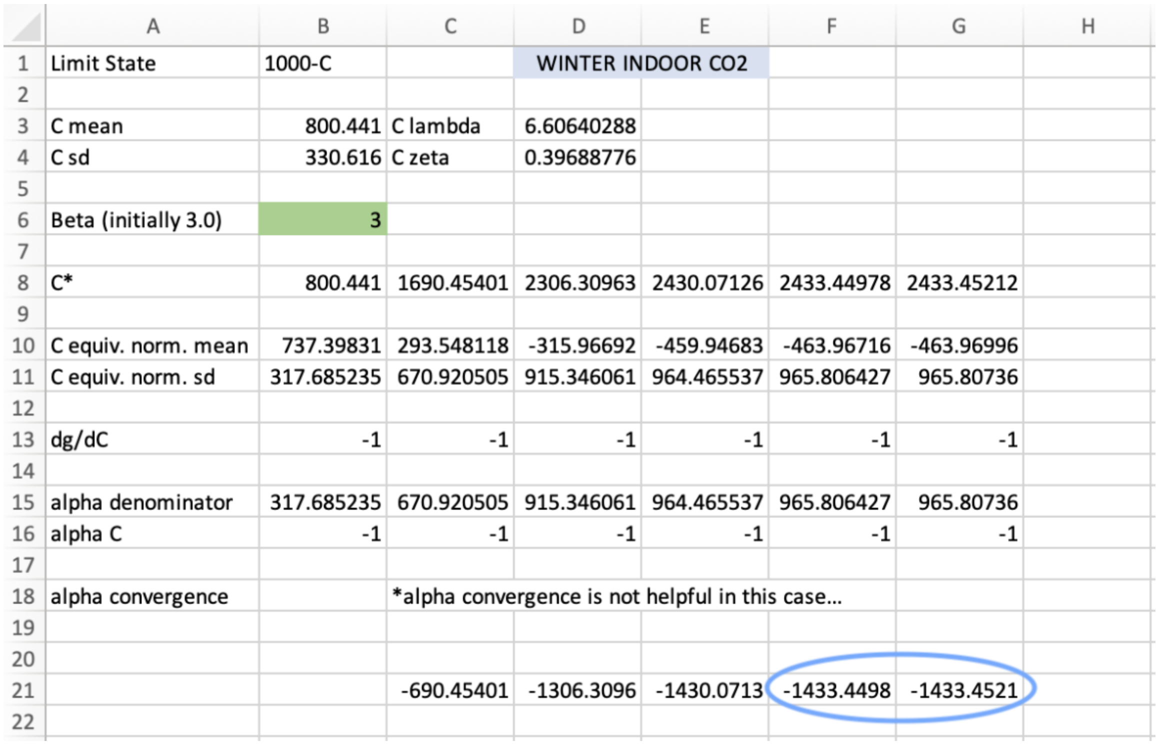
```
Results:

Distribution:    Weibull
Log likelihood:  -159180
Domain:          0 < y < Inf
Mean:            802.777
Variance:        96760.3

Parameter  Estimate  Std. Err.
A          901.625    2.28765
B          2.79305   0.0145264

Estimated covariance of parameter estimates:
   A          B
A  5.23335    0.0109151
B  0.0109151  0.000211017
```

Figure A 21 Winter Weibull distribution from Distribution Fitter.



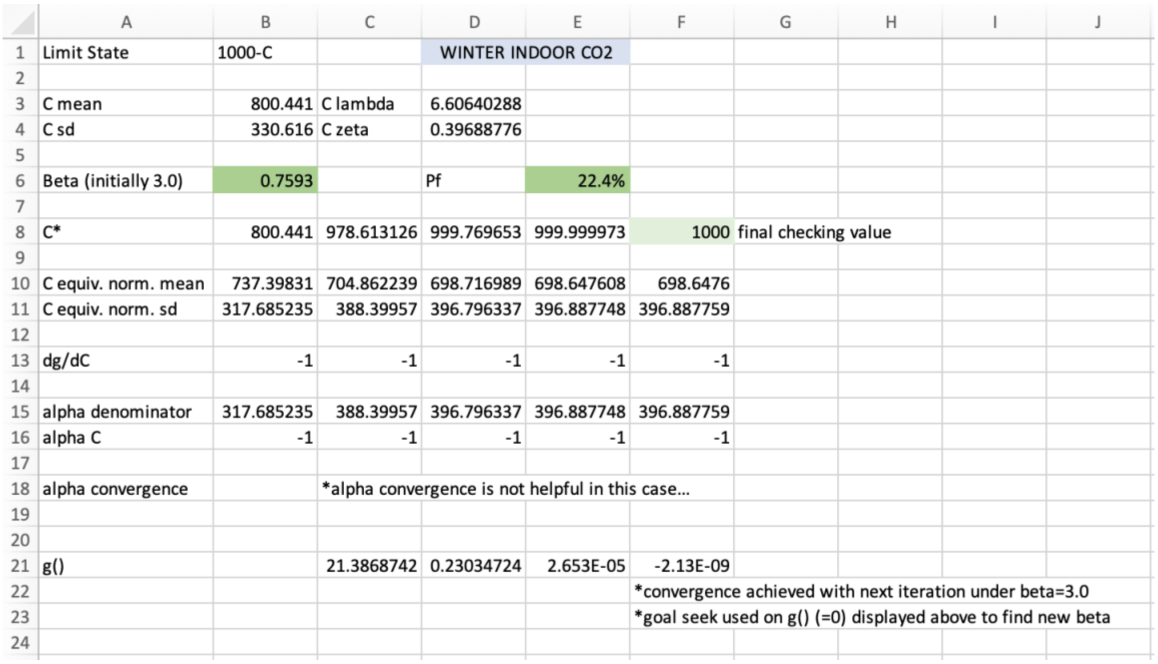
```
betaWinter =

    0.6307


PfailureWinter =

   26.4129
```

Figure A 22 Winter Weibull Monte Carlo results.



	A	B	C	D	E	F	G	H
1	Limit State	1000-C		WINTER INDOOR CO2				
2								
3	C mean	800.441	C lambda	6.60640288				
4	C sd	330.616	C zeta	0.39688776				
5								
6	Beta (initially 3.0)	3						
7								
8	C*	800.441	1690.45401	2306.30963	2430.07126	2433.44978	2433.45212	
9								
10	C equiv. norm. mean	737.39831	293.548118	-315.96692	-459.94683	-463.96716	-463.96996	
11	C equiv. norm. sd	317.685235	670.920505	915.346061	964.465537	965.806427	965.80736	
12								
13	dg/dC	-1	-1	-1	-1	-1	-1	
14								
15	alpha denominator	317.685235	670.920505	915.346061	964.465537	965.806427	965.80736	
16	alpha C	-1	-1	-1	-1	-1	-1	
17								
18	alpha convergence		*alpha convergence is not helpful in this case...					
19								
20								
21			-690.45401	-1306.3096	-1430.0713	-1433.4498	-1433.4521	
22								

Figure A 23 Winter AFOSM - convergence is reached.



	A	B	C	D	E	F	G	H	I	J
1	Limit State	1000-C		WINTER INDOOR CO2						
2										
3	C mean	800.441	C lambda	6.60640288						
4	C sd	330.616	C zeta	0.39688776						
5										
6	Beta (initially 3.0)	0.7593		Pf	22.4%					
7										
8	C*	800.441	978.613126	999.769653	999.999973	1000	final checking value			
9										
10	C equiv. norm. mean	737.39831	704.862239	698.716989	698.647608	698.6476				
11	C equiv. norm. sd	317.685235	388.39957	396.796337	396.887748	396.887759				
12										
13	dg/dC	-1	-1	-1	-1	-1				
14										
15	alpha denominator	317.685235	388.39957	396.796337	396.887748	396.887759				
16	alpha C	-1	-1	-1	-1	-1				
17										
18	alpha convergence		*alpha convergence is not helpful in this case...							
19										
20										
21	g()		21.3868742	0.23034724	2.653E-05	-2.13E-09				
22						*convergence achieved with next iteration under beta=3.0				
23						*goal seek used on g() (=0) displayed above to find new beta				
24										

Figure A 24 Winter AFOSM - final beta is calculated.

MATLAB Distribution Comparisons

The MATLAB script used to determine the appropriate distributions for Summer 2014, Winter 2014, and Spring 2015 is presented below.

```
%Project: Indoor CO2
%CESG 509
%Danielle De Castro

%Comparing Distributions
%% Summer
clear all
close all
clc

%Importing data from Excel:
opts = detectImportOptions("CESG 509 Indoor CO2 Matlab.xlsx");
opts.SelectedVariableNames = ["In_CO2_Summer"];
T = readtable("CESG 509 Indoor CO2 Matlab.xlsx",opts);

data = T.In_CO2_Summer;

% Comparing Normal, Lognormal, and Weibull

n = 10080; % rows counted in Excel
KSlim = 1.36/sqrt(n);

pdNorm = fitdist(data,'Normal')
[h,p,ksstat,cv] = kstest(data,'CDF',pdNorm);
KSNorm = ksstat
```

```
if KSNorm<KSlim
    Norm = "valid"
else
    Norm = "not valid"
end
k = 2; % Normal, Lognormal, and Weibull each have 2 parameters
nllNorm = negloglik(pdNorm);
aicNorm = 2*nllNorm+2*k+2*k*(k+1)/(n-k-1)

pdLognorm = fitdist(data,'Lognormal')
[h,p,ksstat,cv] = kstest(data,'CDF',pdLognorm);
KSLognorm = ksstat
if KSLognorm<KSlim
    Lognorm = "valid"
else
    Lognorm = "not valid"
end
nllLognorm = negloglik(pdLognorm);
aicLognorm = 2*nllLognorm+2*k+2*k*(k+1)/(n-k-1)

pdWeibull = fitdist(data,'Weibull')
[h,p,ksstat,cv] = kstest(data,'CDF',pdWeibull);
KSWeibull = ksstat
if KSWeibull<KSlim
    Weibull = "valid"
else
    Weibull = "not valid"
end
nllWeibull = negloglik(pdWeibull);
aicWeibull = 2*nllWeibull+2*k+2*k*(k+1)/(n-k-1)

%% Autumn
clear all
close all
clc

%Importing data from Excel:
opts = detectImportOptions("CESG 509 Indoor CO2 Matlab.xlsx");
opts.SelectedVariableNames = ["In_CO2_Autumn"];
T = readtable("CESG 509 Indoor CO2 Matlab.xlsx",opts);

data = T.In_CO2_Autumn;

% Comparing Normal, Lognormal, and Weibull

n = 22320; % rows counted in Excel
KSlim = 1.36/sqrt(n)

pdNorm = fitdist(data,'Normal')
[h,p,ksstat,cv] = kstest(data,'CDF',pdNorm);
KSNorm = ksstat
if KSNorm<KSlim
    Norm = "valid"
else
    Norm = "not valid"
```

```
end
k = 2; % Normal, Lognormal, and Weibull each have 2 parameters
nllNorm = negloglik(pdNorm);
aicNorm = 2*nllNorm+2*k+2*k*(k+1)/(n-k-1)

pdLognorm = fitdist(data,'Lognormal')
[h,p,ksstat,cv] = kstest(data,'CDF',pdLognorm);
KSLognorm = ksstat
if KSLognorm<KSlim
    Lognorm = "valid"
else
    Lognorm = "not valid"
end
nllLognorm = negloglik(pdLognorm);
aicLognorm = 2*nllLognorm+2*k+2*k*(k+1)/(n-k-1)

pdWeibull = fitdist(data,'Weibull')
[h,p,ksstat,cv] = kstest(data,'CDF',pdWeibull);
KSWeibull = ksstat
if KSWeibull<KSlim
    Weibull = "valid"
else
    Weibull = "not valid"
end
nllWeibull = negloglik(pdWeibull);
aicWeibull = 2*nllWeibull+2*k+2*k*(k+1)/(n-k-1)

%% Winter
clear all
close all
clc

%Importing data from Excel:
opts = detectImportOptions("CESG 509 Indoor CO2 Matlab.xlsx");
opts.SelectedVariableNames = ["In_CO2_Winter"];
T = readtable("CESG 509 Indoor CO2 Matlab.xlsx",opts);

data = T.In_CO2_Winter;

% Most likely distributions identified using Distribution Fitter

n = 22320; % rows counted in Excel
KSlim = 1.36/sqrt(n)

pdNorm = fitdist(data,'Normal')
[h,p,ksstat,cv] = kstest(data,'CDF',pdNorm);
KSNorm = ksstat
if KSNorm<KSlim
    Norm = "valid"
else
    Norm = "not valid"
end
k = 2; % Normal, Lognormal, and Weibull each have 2 parameters
nllNorm = negloglik(pdNorm);
aicNorm = 2*nllNorm+2*k+2*k*(k+1)/(n-k-1)
```

```
pdLognorm = fitdist(data,'Lognormal')
[h,p,ksstat,cv] = kstest(data,'CDF',pdLognorm);
KSLognorm = ksstat
if KSLognorm<KSlim
    Lognorm = "valid"
else
    Lognorm = "not valid"
end
nllLognorm = negloglik(pdLognorm);
aicLognorm = 2*nllLognorm+2*k+2*k*(k+1)/(n-k-1)

pdWeibull = fitdist(data,'Weibull')
[h,p,ksstat,cv] = kstest(data,'CDF',pdWeibull);
KSWeibull = ksstat
if KSWeibull<KSlim
    Weibull = "valid"
else
    Weibull = "not valid"
end
nllWeibull = negloglik(pdWeibull);
aicWeibull = 2*nllWeibull+2*k+2*k*(k+1)/(n-k-1)
```

MATLAB Monte Carlo Script

The MATLAB script used to determine the HUB's ventilation system's probability of failure for Summer 2014, Winter 2014, and Spring 2015 is presented below.

```
%Project: Indoor CO2
%Danielle De Castro

%Monte Carlo Simulations
%% Summer
close all
clear
clc

% Lognormal C (Indoor CO2 Concentration)
muC = 469.063; % given by Distribution Fitter App
varC = 5205.08; % given by Distribution Fitter App

zeta = sqrt(log(varC/muC^2+1));
lambda = log(muC)-0.5*zeta^2;
% values generated above agree w/ mu & sigma parameters from Dist Fitter.

Pfailure = zeros(1,100);% Preallocation (to save computation time)
beta = zeros(1,100);% Preallocation
for k = 1:100
% Creating Distribution
runs = 10000000;
C = lognrnd(lambda,zeta,[runs,1]);

gofx = 1000-C;
```

```
% Probability of Failure
sumpf = sum(gofx<=0);
pf=sumpf/runs;
Pfailure(k) = pf*100;

beta(k) = norminv(1-pf,0,1);
end
betaSummer = mean(beta(~isinf(beta)))
PfailureSummer = mean(Pfailure(~isinf(Pfailure)))

%% Autumn
close all
clear
clc

% Lognormal C (Indoor CO2 Concentration)
muC = 678.89; % given by Distribution Fitter App
varC = 58605.1; % given by Distribution Fitter App

zeta = sqrt(log(varC/muC^2+1));
lambda = log(muC)-0.5*zeta^2;
% values generated above agree w/ mu & sigma parameters from Dist Fitter.

Pfailure = zeros(1,100);
beta = zeros(1,100);
for k = 1:100
% Creating Distribution
runs = 10000000;
C = lognrnd(lambda,zeta,[runs,1]);
% C = wblrnd(764.625,2.86929,[runs,1]); % run for comparison

gofx = 1000-C;

% Probability of Failure
sumpf = sum(gofx<=0);
pf=sumpf/runs;
Pfailure(k) = pf*100;

beta(k) = norminv(1-pf,0,1);
end
betaAutumn = mean(beta(~isinf(beta)))
PfailureAutumn = mean(Pfailure(~isinf(Pfailure)))

%% Winter
close all
clear
clc

% Lognormal C (Indoor CO2 Concentration)
muC = 800.441; % given by Distribution Fitter App
varC = 109307; % given by Distribution Fitter App

zeta = sqrt(log(varC/muC^2+1));
```

```
lambda = log(muC)-0.5*zeta^2;
% values generated above agree w/ mu & sigma parameters from Dist Fitter.

Pfailure = zeros(1,100);
beta = zeros(1,100);
for k = 1:100
% Creating Distribution
runs = 10000000;
C = lognrnd(lambda,zeta,[runs,1]);
% C = wblrnd(902.625,2.79305,[runs,1]); % run for comparison

gofx = 1000-C;

% Probability of Failure
sumpf = sum(gofx<=0);
pf=sumpf/runs;
Pfailure(k) = pf*100;

beta(k) = norminv(1-pf,0,1);
end
betaWinter = mean(beta(~isinf(beta)))
PfailureWinter = mean(Pfailure(~isinf(Pfailure)))
```