MULTI-ASPECT ENERGY PERFORMANCE OF BUILDING FORM IN EIGHT U.S. CLIMATE ZONES

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by

TIANYU FENG

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MULTI-ASPECT ENERGY PERFORMANCE OF BUILDING FORM IN EIGHT U.S. CLIMATE ZONES

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To the people who challenge me to be courageous

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LIST OF SYMBOLS AND ABBREVIATIONS

A EUI: Energy Usage Intensity

B PI: Performance Index

C RC: Relative Compactness

D WFR: Window to floor Ratio

E AZ: Azimuth

F BF: Building Form

G SHGC: Solar Heat Gain Coefficient

H PSZ: Packaged Single Zone

I VAV: Variable Air Volume

J WSHP: Water Source Heat Pump

K FAR: Floor-Area-Ratio

L EPC: Energy Performance Coefficient

M DOE-2: Department of Energy 2

SUMMARY

This research examined how building massing and building form impacts on multiple levels of building energy usage and inspected their sensitivity against other components in a building energy simulation-based framework. Additionally, by comparing the results with the database of THE WEIDT GROUP, we concluded the actual energy saving potential by building forms in practice. A DOE-2 powered simulation programs with the facility to batch run simulation models developed by THE WEIDT GROUP and an ISO-13790 based quasi-steady state simulation model named Energy Performance Coefficient (EPC) calculator developed by Georgia Tech are used in the different stages of research to rationalize research deign and justify simulation results.

With the guidance of literature review, a concept called Relative Compactness (RC) is implemented throughout the research as one of the measures to evaluate and validate the energy performance impact of building massing and form. It was found that the decrease of Relative compactness shows clear correlation with the increase of building energy usage in comparison to a cubic form building massing in all major U.S. climate zones and major building type. From architectural design perspective, the RC (compactness) is coupled with window sizes, window distribution and orientation; they are collectively treated as building form. These architectural design elements are highly interactive in term of the energy performance and design practice. For instance, the building massing could impact on the distribution of the glazing design, which further impact on the R-value and solar transmittance of the building envelope. Hence, a combined rubric including all 4 architectural design elements including compactness,

window sizes, window distribution and orientation is explored to further test how these commonly understood architectural design elements are going to impact building energy usage in various climate conditions and different building types.

In the study of the building form, a comprehensive comparison of multiple energy saving measures is conducted to rank the energy saving potentials of various parameters, include HVAC system, cooling EER, heating COP, lighting power density, daylighting sensor, occupancy sensor, window U-value window and roof R-value, in a building energy simulation-based model for different building types and climates. In addition, the results are analyzed to understand the interactive effect of those measures to maximize the effect of the strategies.

The results reveal that building form impacts energy usage significantly up to 239% depending on the range of the parameters defined in this study, especially the window related properties including the unit U-value, window area and distribution methods. However, the potential to modify building form in an individual project is not always available, and it has to start from the early design phase. When the building forms are compared against other saving measures, it is found that the mechanical related strategies, such as the mechanical systems types, system efficiency and HRV implementation could provide a high and consistent saving potential across all building types and climate zones. Overall, the energy saving variation of all the evaluated strategies are highly interactive, and one inefficient component could affect the total energy consumption greatly. It is important to make sure each aspect of a project guarantees a proper efficiency level to maximize its effect.

CHAPTER 1. INTRODUCTION

1.1 Building energy simulation and conservation in current practice

The massive usage of energy by the building sector has been commonly noticed. Building energy conservation is drawing more attention in the past decades. With complex energy end use, building energy usage can be attributed to architectural design, building envelope assembly, building usage, mechanical system, lighting system, building automation systems, and other components. A series of policies, guidelines, rating systems, and protocols, such as increasingly stringent energy codes, LEED, Architecture 2030 and Living Building Challenge, have been initiated by governments or non-profit origination to reduce building energy use. Moreover, multiple financial incentives policies aim to encourage building energy reduction by utilities companies or governments.

Almost every profession involved in the building industry including architects, mechanical engineers, electrical engineers, urban designers, building managers and contractors has shown interest in contributing to building energy reduction with environmental, financial or branding considerations. Different professions are often drawn together by organizations such as USGBC to ensure energy performance of buildings. Building energy reduction device such as occupancy sensor/monitoring strategies are thriving in the consumer market to reduce energy use, such as smart senors, high efficiency appliances, complimented by a supplement of educational programs. In order to rationally and efficiently approach our goal in the building energy reduction, it is crucial to understand and quantify how the energy is consumed by building, and how much each energy conservation measures contribute.

The workflow on an AEC project could be regarded as a multi-criterion decision-making process around and enabled by a simulation-based performance assessment. From an energy conservation perspective, contributors include architectural designers, mechanical engineers, electrical engineers, contractors, building owners, building users and, potentially utility providers. Usually, multiple team members have different interests, which make the arriving at the final decision difficult. A comparative analysis is required to evaluate how each member of the design team could impact on the building energy usage under a multi-aspect framework.

1.2 Concept of the building energy usage and research sequence

Thermal loads are fundamental causes of the energy usage, which could further be categorized as 1> internal heat gain, 2> heat transmission through the envelope including conduction and radiation, 3> infiltration/ air leakage through the envelope, which doesn't include the outdoor air requirement by building code, 4> building thermal massing, 5> ventilation requirements. Thermal load doesn't mean the ultimate energy consumption, which is related to the system property such as the efficiencies of active systems like HVAC or lighting and losses in energy transport (Detlef Westphalen 1999).

Among these loads, the internal heat gain source includes equipment, people, and lighting, which at the same time consumes energy. The internal heat gain either alleviates or aggravates the loads by generating heat depending on the outdoor climate condition.

The rest of the elements of the thermal load could also be categorized as the envelope load. The building could be formed in any 3-dimensional shape to contain the interior space from purely geometric perspective.

To contain the same amount of the interior space, the area surface area, directly interacting with outdoor environment could change dramatically with different geometries. The heat transfer through the building envelope will consequently increase. This part of the load could also be reduced by improving its physical properties, such as the insulation level, or/and avoid unexpected thermal bridging caused by inappropriate construction methods, which will be introduced in depths in later sections. With the theory of thermal load being explained, architects and contractors are mostly responsible for minimizing the thermal load throughout design phase and during the later construction phase.

Buildings HVAC systems consume energy to offset the heating, cooling, and latent cooling load and maintain the indoor environment at setpoint conditions. Base on the data from National Grid, HVAC consumes between 25%-49% of total building energy usage (National Grid 2012). Besides HAVC, buildings have other energy consuming systems such as lighting system to operate normally. The energy usage by all systems in a building is regarded as site energy, which could be further tracked back to the energy (source) generation in the form of either electricity or direct usable natural gas. Both site and source energy is the ultimate metrics to evaluate building energy performance. The systems related to energy consumption are mostly relevant to mechanical and electrical engineers.

A framework for building energy consumption analysis is shown in Figure 1. The figure relates to a diverse group of participants in contributing reducing building energy consumption reduction, including architects, mechanical engineers, electrical engineers, building owners and general contractors. The climate and internal loads associated with specific building types are not changeable, so they are regarded as the object variables.

Besides the objective variables such as mechanical systems, electrical systems and building envelope properties, building form design by architects will largely determine the thermal load. The first half of the research is focused on building forms, and its components responsible for thermal load site EUI. A performance index will be used to evaluate the results in this phase. Different system types and construction are elements built on top of the architectural design and lead to site and source energy consumption. The second half of this research will focus on how the building form is compared to other strategies from multiple asepcts in impacting the building energy use.

A performance based approach is a key enabler of rational decision making across many prospects and based on a large set of performance criteria (Augenbroe 2011). It is vital to have building simulation specialist, conduct simulation and analysis in how each role contributes to energy usage or conservation compared to baselines. This model of practice has been applied for years and proved to be efficient in reducing building energy usage in multiple states under utilities based programs.

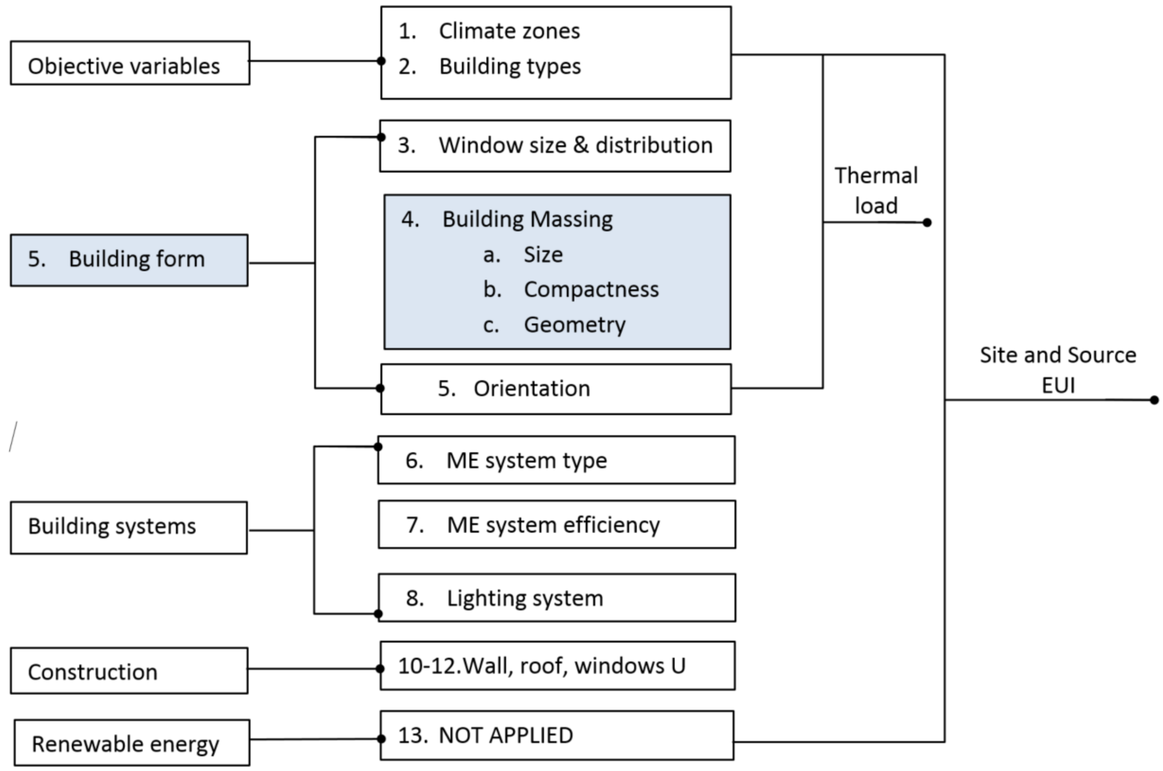


Figure 1- Building energy simulation flow and hierarchy

Each specialty in practice has potential to reduce the building energy consumption. The design of the building form could fundamentally and permanently impact on the thermal loads and energy usage in all climate zones and for building types. It is rational and critical to reduce the thermal load in the first place. With the load being minimized, the second is to design the systems to satisfy the load and maintain indoor thermal comfort. The subsequent design and choice of the mechanical system could significantly reduce the energy consumption. In addition, the energy source determines what systems are more advantageous especially on the heating side, as the heating system could use gas or electricity; whereas cooling system only use electricity regardless of direct expansion or heat pump.

Architectural design is a complex problem encompassing many more factors than just energy consumption, such as environmental, social, urban, spatial, structural and artistic expectation from different interests. In a design workflow, architects always start to consider the building form after studying and researching on the existing conditions. Building form joins urban fabric together, attracts visual attention from visitors, and also creates interior space with the unique user experience. From ancient architecture to current modern parametric-based design, the transitions of the building form are never justified simply by the functions, or energy usage. Furthermore, with the progress made in the building information modeling (BIM) system, materials and structured science, the constructability capacity keeps making improvements.

As described in Section 1.2, the building envelope load is the dominant cause of the thermal load in many building types, through heat transmission, infiltration/ air leakage, and thermal massing. When the amount of area of the surface to contain the same amount of the space is increasing, the heat transmission through the envelope will undoubtedly increase, which is also amplified by the trend of using more glazing on the surface. As Le Corbusier stated with his understanding of architectural modernism, architecture needs more glazing, as the windows create visual connections rather than ventilation or another functional purposes; those should be done by mechanical systems.

The complicated building envelope composition also brings in risk and uncertainty on the surface durability and tightness. Besides the glazing area, unique building form design could also cause potential thermal bridge or additional thermal loads. One example is the lawsuit by MIT over the Stata center leakage problem. Designed by Frank Gehry, the project used advanced digital algorithms to both tweak the complex curved forms of exterior surfaces and solve for a covering using standard sized rectangular pieces of metal. Three years after the building is occupied, the Stata center faced considerable masonry cracking with improper amount and spacing of control joints in the brick masonry (MIT 2007). As a result, most of the unique building creates additional surface area to form the space. It is commonly understood that one of the benefits of the enlarged surface is to utilize it as thermal massing to reduce heating or cooling load. However, it has been proven by Christian et al. from Oak Ridge Renewable National laboratory (ORNL) that thermal mass doesn't have consistently better performance results. It could actually consume more energy during the cooling season. The research team from ORNL developed a new matrix called dynamic benefit for the massive system (DBMS) to simulate and optimize the performance of the thermal massing, especially during the swing season (Christian 1996).

1.3 Introduction to comparative analysis

A simulation model includes many uncertain simulation inputs and variables. It is not practical to set up and simulate all possible scenarios to generate conclusive results. Even with multiple uncertain design elements now being "known" from research that has developed uncertainty estimates for generic energy model variables, there are still plenty of case variables causing simulation uncertainty that is hard to track. In order to avoid this dilemma, our comparative analysis methodology is based on a normative calculation that has been shown to be insensitive to uncertainties as it only compares across different parameter values, which can lead to comprehensive conclusions related to the relative effect of these parameters (Augenbroe 2011). Therefore, uncertainty is irrelevant in a normatively conducted comparative analysis.

In comparative analysis, it is crucial to clarify these concepts

1> Baseline- the model built with all standard inputs (normative inputs), and what the subsequent design cases are compared to

2> Comparable sample – what is being investigated with changing design variables, and other variables held constant.

3> Performance Index (PI) - the normalized results as a unit-less metric. Performance Index (PI) $= E_{design} / E_{baseline}$

4> Impact Index (ImI) - the normalized results to test how one variable impacts the performance on the other as a unit-less metric.

Impact Index (ImI) $= PI_{design} / PI_{baseline}$

5> Primary variables- the simulation variable that frames the comparative analysis. In this study, the primary variation factor is relative compactness (RC).

6> Secondary variables- the simulation variables dependent on the primary variables. In this case, the secondary variation factor includes WFR, window sizes, and orientation.

7> Variables intervals – upper and lower limit on the range of each variable

When calculating PIs to evaluate different alternatives, the PI equation will contain the primary variables and several secondary variables. In the baseline, the primary variable will be constant, but the secondary variable may or may not change depend on what variable are evaluating. In this model, the noise from other simulation variables on the targeted variation factor will be canceled out in PI calculation, as this noise exist in numerator and denominator.

1.4 Phase one- Performance measures for the building from and its components

With the concept of the thermal load being explained, the major impact on thermal load by architecture design came from the compactness of the building, window size, window distribution and orientation. A framework with the specified terminology of the thermal load is created to explain and further test the impact on energy usage.

1) Building massing – It indicates the compactness of the building and only relevant to the 3-dimensional geometry of the building. Relative Compactness (RC) doesn't indicate the window information or orientation information.
2) Building form – It indicates the building massing coupled with the window size, window distribution, and building orientation. It is a further description on building appearance built upon Relative Compactness (RC). Building form doesn't indicate any physical properties of the surface such as insulation.

As indicated in Figure 2, these 4 geometries are the same Relative Compactness (RC), but with different window size, distribution or orientation, they are 4 different building forms.

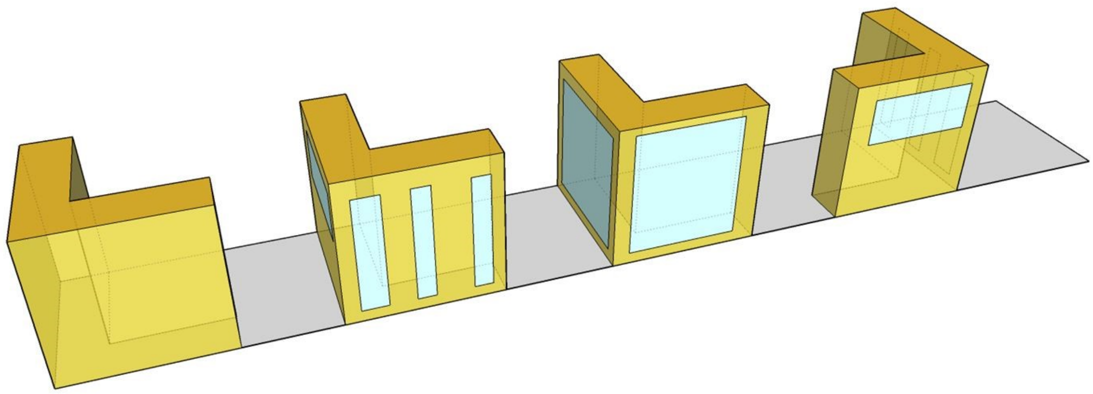


Figure 2- Difference between building form and massing

Initiated by Mahdavi et al. and tested by several academic papers ((Mahdavi and Gurtekin 2002) (Pessenlehner and Mahdavi 2003) (Vladimír Geletka & Anna Sedláková 2012) (AlAnzi, Seo and Krarti 2009), the Relative Compactness (RC) can be represented by the concept of RC, which is described as the equation below.

$$RC = \left(\frac{Volume}{Surface}\right) Baseline \;/\; \left(\frac{Volume}{Surface}\right) Testing$$

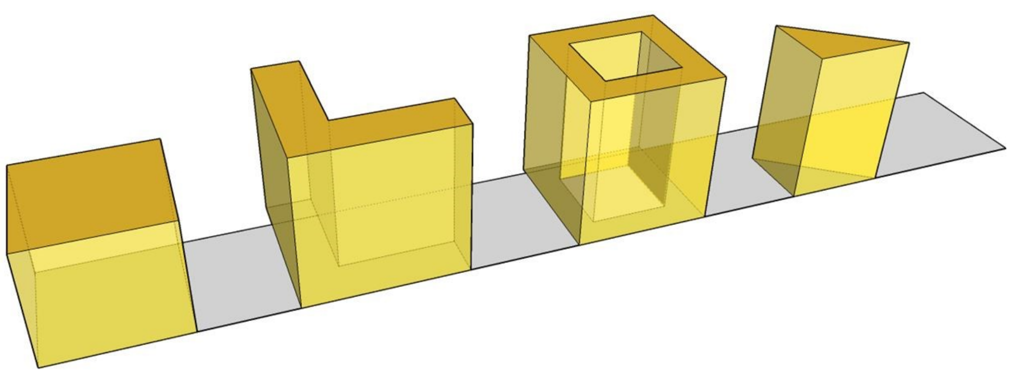


Figure 3- Building form and the baseline form

In the equation, the baseline massing is always a cube with same conditioned floor area and volume with the design massing. Essentially, RC is a ratio of two surface area with the volume canceled out in the equation. The surface includes all vertical, top and bottom opaque and transparent surface that enclose the space. Ideally, the RC could be higher than 1 when the Relative Compactness (RC) presents as a sphere or when the building has a common wall with an adjoining building. Most buildings have a RC less than 1. The lower RC is, the less compact of the Relative Compactness (RC) and higher thermal load theoretically. With this equation, the detailed design could be normalized and simplified as a shoe box model showing a high correlation with actual building geometry.

Stated in the previous section, the variable in phase one is the RC window sizes, window distribution, and orientation. Among these factors, RC, representing the Relative Compactness (RC), is the dominant parameter guiding through the analysis in the building form, as other variation factors are carried by Relative Compactness (RC). Therefore, the RC is the primary variables and rest three elements are secondary variables.

1.5 Phase two – Energy saving potential for multiple prospects in architecture practice

The Relative Compactness (RC) as a major architectural elements, impacts the building energy usage. The building energy sensitivity studies accomplished in the past do not present a fundamental treatment of building form as a whole against other building and system design parameters such as HVAC system or lighting system. However, it needs all these elements in composing building form since all other systems influence the performance of the building. Phase two of the research will take building form as one element to compare energy saving potential in relation to other building parameters. In this phase, the building form with the best, worst and medium performance will be used to conduct sensitivity analyses against other variables representing several major prospects (indicated as Figure 1) in building energy usage.

These elements include mechanical components, electrical components and envelope physical property components based on prototypical utility incentive based consulting process. In the process, multiple participants such as architects (building form and envelope property), mechanical engineers, electrical engineers and general contractor (envelope constraints) will hold a meeting to evaluate utility incentive-based energy conservation measures to determine what can contribute the most to energy and energy cost saving for a whole building simulation project. It helps the design team to capture the most accessible and cost effective saving strategies. It is crucial for the owner or design team lead to balance different prospects by considering budgeting and the integrated impact of all strategies, which could allow the team to maximize the financial benefit and minimize environmental impact. With a general guidance to initiate the process, it could greatly shorten the time and effort by going through a comprehensive strategies list as a pre-simulation energy use guideline.

With years of experience working with multiple projects in building industry, THE WEIDT GROUP has concluded most commonly applied strategies from each contributor in a design team, mainly including different 1a> mechanical systems, 1b> system efficiencies, 1c> energy recovery ventilator, 2a> lighting power density, 2b> lighting automation control, 2c> daylighting capture strategies, 3a> window U-value, 3b> window SHGC, 3c> roof R-value, 3d> wall R-value. These strategies will be simulated with all possible combinations, and the bundle compared against each other to explore the most energy costly components and be the most effective in prioritizing energy conservation methods under certain circumstance.

The results of phase two could also be utilized during the early schematic design phase to evaluate the building form design, especially for lower or net zero energy building design. Architects tend to spend much time to determine the architectural form without thinking about the energy conservation potential by the building form design, which is commonly understood as the major or fundamental energy saving method. With this in mind, the schematic design phase frequently goes beyond the parenthetic planned timeline and causes a compressed workflow for engineers and contractor to determine further energy saving methods. The phase two analysis is able to provide a framework to assist architects in determining the performance the building massing and co-operating better with engineers when they are able to understand the energy saving potential.

1.6 Objective and values of the research

With two consecutive phases in this research, the results reveal the performance of all elements in composing the building form in multiple levels. In phase one, the research reveals how each architecture design components in building form could impact on the building thermal load performance. In phase two, the research reveals the energy performance sensitivity of building form as a whole with all design elements against other elements determined by other systems. This approach systematically concludes how much architects could impact on in building energy reduction, and how a design could maximize energy saving potential.

RC as a simple rubric is effective in resolving the building massing in the early phase when architects still actively optimizing the building massing for various reasons. It is not wise to spend a lot of time modeling the detail in building massing with the risk of massing being changed before finishing modeling the older version. RC helps both energy modeler and architect to quickly grasp the ballpark effect of the building form performance and be able to compare with other elements to determine if any further modification makes sense in energy consumption perspective.

This research explores the building form and massing performance in multiple locations and typical building types. The database develop from this form the research will work as a powerful pre-simulation guideline for architects in future design by providing an estimated performance index of their target building type and climate zone during early schematic design phase when constant simulation update is not feasible. To a building energy consultant, the results of this research could also provide evidence on how they should advise architects and other team members in modifying the massing with high level answers in an early stage.

1.7 Relative Compactness extraction in current practice

Transiting from academic based simulation results to practice use is also challenging especially when dealing with continuous variation factors. Before an accurate result is settled in the research, it is always beneficial to derive data from a massive database of finished practice projects. With the support of THE WEIDT GROUP's database, the RC, window area, distribution and orientation of 1,375 finished projects ranging from a warehouse to hospital has been investigated. It provides evidence on what range of building massing compactness should be studied. The result also helps energy modelers and consultants to advise design teams to optimize the building energy performance starting from the early design phase. The following diagrams show how the RC of 1,375 projects is distributed. Some of the project shows a RC higher than 1, as they are adjacent to another building. Therefore, at least one surface of these projects has been neglected, as the shared-wall type of building is not included in this study. As it is shown in Figure 4, 92% of the buildings in the database have RC ranging from 0.3-1.

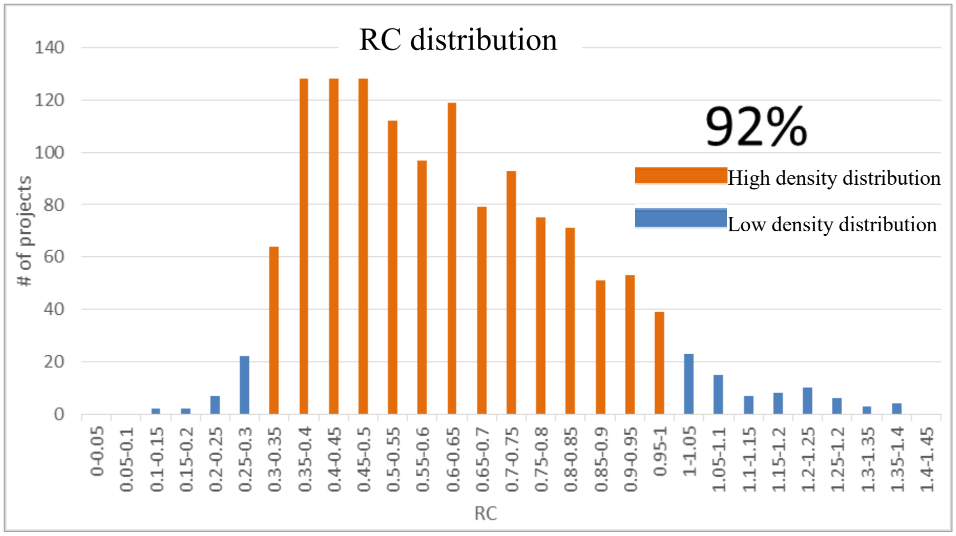
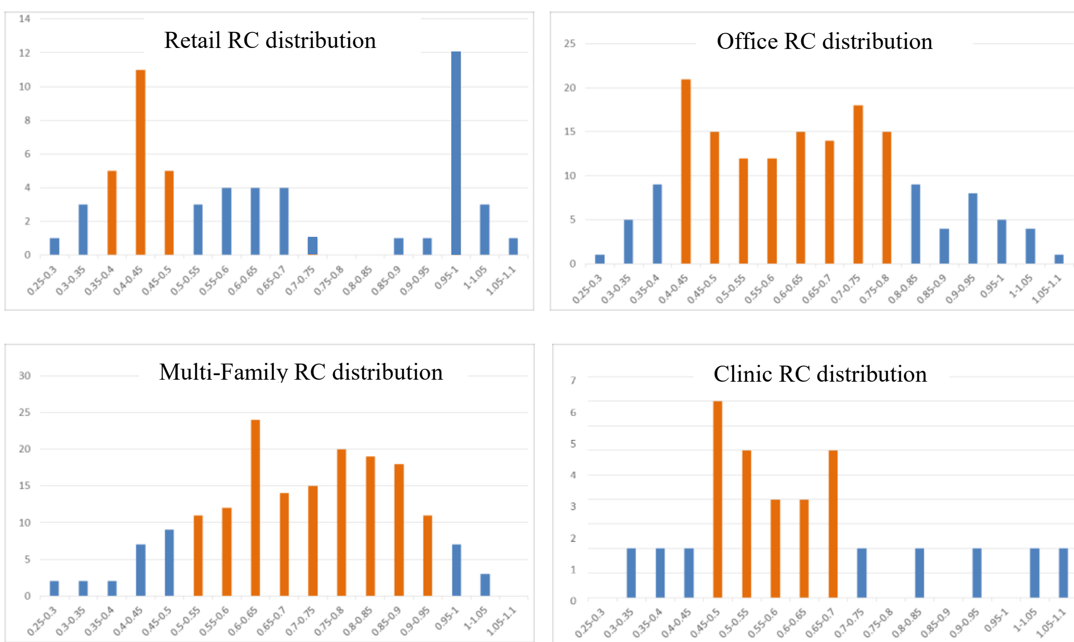


Figure 4- RC distribution of all finished projects from THE WEIDT GROUP database



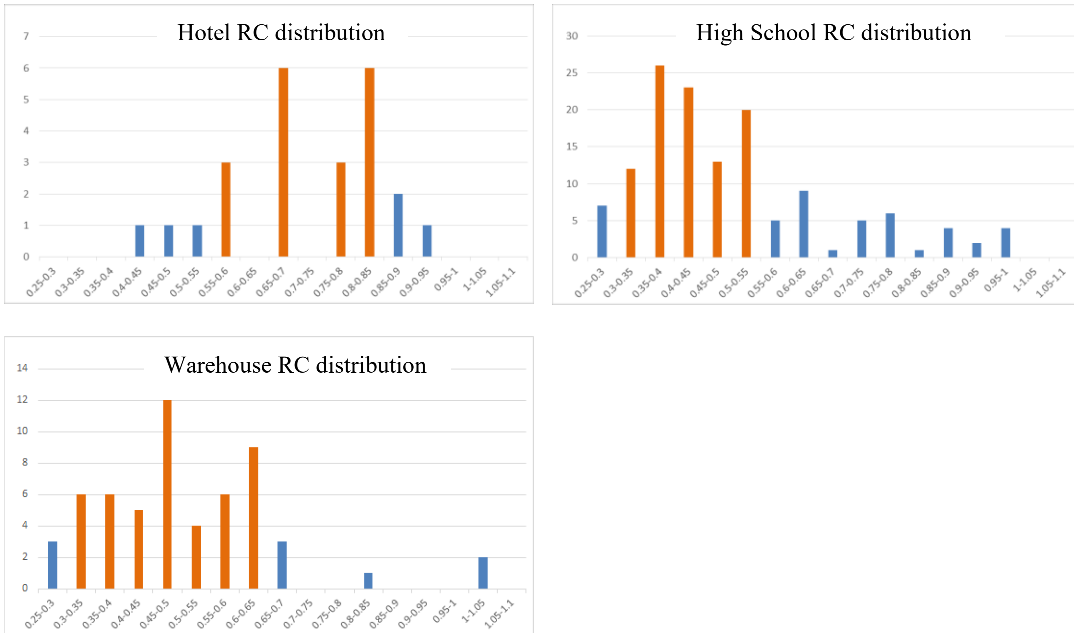


Figure 5- RC distribution by building types finished projects from THE WEIDT GROUP database

Table 1 - Typical RC range

Building Types	Typical RC Range
Retail	0.4-0.5
Office	0.4-0.8
Multi-family	0.5-1.0
Clinic	0.5-0.7
Hotel	0.5-0.9
High School	0.3-0.6
Warehouse	0.3-0.6
Overall	0.3-1.0

The RC distribution also varies with different building types and the total size of the building. Figure 5 reveals the RC distribution of major building types with building size from 10,000 sq. ft. to 50,000 sq. ft.

CHAPTER 2. LITERATURE REVIEW

2.1 Studies on weather file difference

The first step in the simulation is always determining which weather file to apply, which can be found in multiple versions. Among TRY, IWC, WAC, TMY and AMY weather file, we chose TMY (Typical Meteorological Year) throughout the study. It has been shown to be a reliable data source of the weather conditions if the hydrothermal analysis is not a concern (Crawley 1998). As TMY take the historical weather, there is couple issues related the TMY file, including missing extremes condition. As most weather stations are remote from urban settings, the weather data can’t represent site specific conditions such as surrounding building shading effect or urban heat island. However, the remoteness and inaccuracy of the weather file is irrelevant in comparative analysis as described in section 1.3, since the effect exists in both design and baseline simulation models.

2.2 Studies on comparative energy simulation analysis

Simulation involves the creation of a behavioral model of a building for a given stage of its development. The purpose of the simulation is to generate observable output states for analysis and their mapping to suitable quantification of performance indicators. Models are developed by reducing real world physical entities and phenomena to an idealized form at some level of abstraction (Malkawi and Augenbroe 2004). A reduced order comparative analysis method is more appropriate in this research. It has the similar logic with the EPC calculator developed by Augenbroe et al.,

$$\text{EPC} = \text{Energy calculated} / \text{Energy baseline}$$

EPC is an objective measure of the energy performance, normalized by proper definition of a reference value (Augenbore and Park 2005). The comparative outcome has been studied and applied widely to be proven as an accurate approach to indicate the performance of target simulation model. As the outcome of the comprative analysis, Performance Index is a quantifiable indicator that adequately represents a particular performance requirement.

2.3 Study on daylighting impact

Daylighting is a strategy that could replace artificial lighting and save a tremendous amount of energy. However, with LED technology being improved aggressively, the energy usage and cost to provide the same level of illuminance have been decreased compared to traditional artificial lighting. The energy usage reduction by applying advanced LED lighting is around 2-4 kBtu/sq. ft. depending on the window to wall ratio. As the window area is bigger, the energy usage by lighting tend to be stable, which means the energy usage reduction by utilizing natural daylighting remains on the same level when the space design is not specifically designed for utilizing daylighting. Therefore, enlarged window area won't be as preferable in terms of energy conservation. Overall, with advanced LED lighting, the energy consumption reduction by improving lighting efficiency can be controlled under 5% (The Weidt Group 2016). With additional lighting control such as occupancy sensor, the impact can be further reduced to 2-3% in whole building energy consumption. A study finished by THE WEIDT GROUP reveals the building with 15% WWR could maximize the building energy conservation from lighting sector (The Weidt Group 2016). Besides energy conservation, we can't ignore other positive effect brought with sufficient daylight. Architecturally, it will improve spatial quality, visual comfort level, and further improve the work environment.

2.4 Studies on relative compactness

Architectural schematic design happens in an early stage in new construction projects and usually has little changes in the later process. During this stage, the building massing always draws most attention from designers. With increasing attention on the building energy consumption issue, both engineers and architects have started to focus on how we can reduce energy usage from Relative Compactness (RC) design phase, which is also a key procedure of integrated design process under multiple green building evaluation standards such as LEED, BREEAM, iiSBE and etc. (Koch and Buhl 2013). Besides massing itself, a series of conditions influences the massing performance including climate zone, building asset types and floor areas in predesign phase, and wall to window ratio (WWR), surface to volume ratio (SVR) and orientation in later refining process (Hemsath 2013). These parameters are interdependent among variables which make it difficult to elicit meaningful design guidance. In the early design stage, it is not realistic to investigate specific aspect in architectural design, and a conclusive and simplified solution is essential to efficiently model and predict impact from a design aspect.

The study of building form and building was energy started by Philip Steadman in the early 1970s at the UCL Energy Institute's new Centre for Energy Epidemiology (UCL IRIS 2017). Steadman et. al. examines the wall area, volume and plan depth in relation to the building electricity and natural gas consumption (Steadman, Evans and Batty 2009). Later, the analysis is applied to the urban scale to study the correlation of energy usage and these architecture elements at the scale of the non-domestic building stock in London. Steadman et. al. concludes that the increase of building depth could results in the energy usage consumption. The major energy consumption increase are from lighting, core services in deeper, facade treatment, and ventilation control. (Steadman, Evans and Batty 2009) (Steadman, Hamilton and Evans 2014).

The architecture elements in building energy usage is further studied by Mahdavi et al. and firstly published in 2002 at 6th International conference: Design and decision support Systems in Architecture. Mahdavi et al. had analyzed the question in calculating RC by applying series irregular modular forms consists of smaller cubes units. (Mahdavi and Gurtekin 2002). The theory has been further tested by Mahadavi et al. with a similar approach on the geometry schemes with regular residential usage in Vienna, Austria. As the climate condition is heating dominant, the heating load is used to validate the accuracy of using relative compactness rather than actual details geometry in energy modeling. Through linear regression analysis, it is found that the detailed geometric forms could be simply represented as relative compactness, and the increase of relative compactness shows a high correlation with the decrease in heating load (Pessenlehner and Mahdavi 2003). The paper also studied the deviation caused by window sizes or window to floor ratio. From Figure 6, deviation of RC will be diminishing when the

WWR increase, but it overall stays within a relatively small range under the setting of this research.

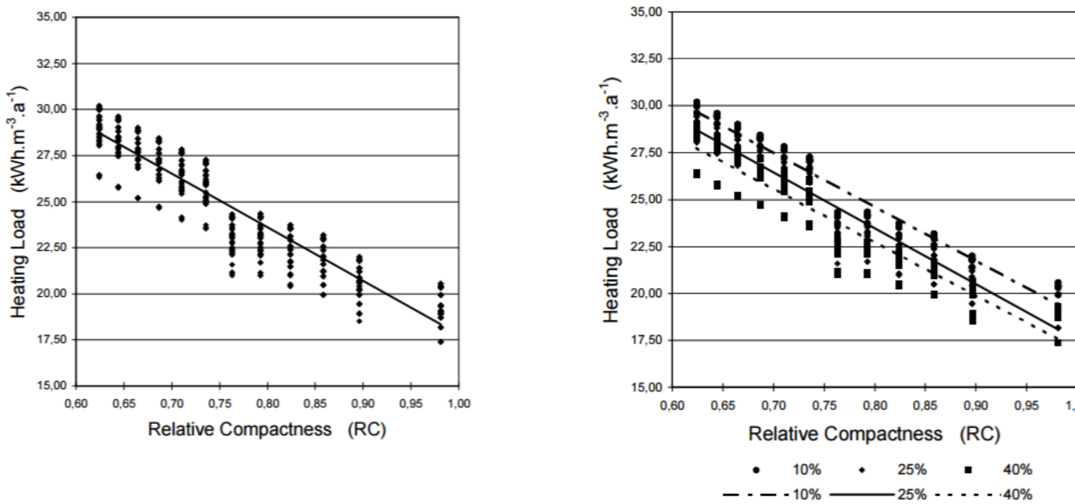


Figure 6- Simulation result of RC performance associated with WWR by Mahdavi et al. (Pessenlehner and Mahdavi 2003)

Carried on by another study located in a heating dominated region in Europe, the Geletka at el. (Vladimír Geletka & Anna Sedláková 2012) has considered more elaborate building shapes for a similar research purpose. However, the author has concluded that the difference in heating load between building shapes that building form could reduce the heating load, but it is questionable that the author directly stated it could save a considerable amount of energy. If the effect of different shapes is compared to building mechanical systems and if the cooling is also considered, the conclusion could be possibly different.

Similar research is also being conducted in the Middle East climate with only cooling energy usage as the measure. Alanzi et al. implemented 7 different Relative Compactness (RC), including alphabetical shape “L”, “U”, “I”, “H”, “T”, multiple rectangular, with RC from 0.05-1 to validate the concept of RC and also test the shelf shading effect on the cooling. (AlAnzi, Seo and Krarti 2009). The results show that with consideration of the self-shading effect on daylighting, the performance index of each shape along the RC change remains high identical. However, the result will deviate when the WWR increases. By simulating variable including relative compactness, WWR and SHGC, the author has concluded the research finding as an equation to multi- criterion decision making process in architectural design. However, from a design perspective, it is not appropriate to treat SHGC as part of the equation as it is not part of the architectural design decision. With author's logic, the roof and wall insulation should also be included in the question in able to make actual multi-criterion design decision making Oppositely, another two key design elements orientation and window distribution are not included throughout the research.

Parasonis et al. points out that it is not sufficient to only keep the same volume between baseline and design Relative Compactness (RC) (Pessenlehner and Mahdavi 2003). Other than the volume, the conditioned floor area should be used. However, no matter which parameter is implemented, they will cancel out in the final calculation. The author also stated when building becomes compact in Lithuania, it will be implemented with air conditioner and additional optional and energy usage will need to be considered (Parasonis, et al. 2012). This won't be an issue in most of the US based project since the majority of new buildings even in cold climate like Minneapolis are required to be mechanically cooled to maintain stricter thermal comfort standards.

2.5 Energy saving potential analysis of multiple prospects

In a multi-criterion decision making process in building energy conservation practice, building form is one criterion we evaluate to make an informed decision. Focusing on building form in an overall building simulation scheme, it is important to compare how much energy conservation potential building form has compared against other simulation variables. Rather than prescriptive analysis, the interactive simulation allows us to simulate the inter-effect in a model and conclude actual the role of each criterion play (Augenbroe 2011).

Dogan et al. (2015) have categorized the building floor plan, which consequently converts building forms to more detailed level and compare the ASHRAE prescribed zoning and its actual accuracy in measuring building energy performance. In addition, Augenbroe et al. (2013) has analyzed energy performance of uncoupling the building from HVAC system in a simulation model. It reveals uncertainty of the simulation when building form and HVAC system are decoupled in simulation analysis. From another perspective, the paper reveals relative energy usage comparison between building form and HVAC system.

From an architectural perspective, Samuelson et al. (2016) has demonstrated the energy performance changes of high-rise residential buildings with multiple variables including orientation, WWR and envelope property with vs. without urban context. In addition, the author addressed another issue in utilizing energy simulation result in the early design phase, when design teams lack either the budget or skills and/or because feedback from energy modeler often cannot keep up with the highly interactive design exploration in early design phase. With different simulation engines, the results could also vary when analyzing the exactly same project. The pre-simulation guideline with a consistent process of simulation and analysis could be a solution to reveal early stage building energy performance.

2.6 ASHRAE Code compliance in current building market

As of September 2016, the majority of the states have adopted a certain level of building energy code/standard in order to reduce energy usage and carbon emission (Department of Energy 2016). With the release of "ASHRAE 90-1 2016", more states are aiming to reach "ASHRAE 90.1-2013" standards within next several years. The demand-side management (DSM) programs regulated by utility companies typically use the prevailing state energy code as the baseline to evaluate the energy performance of buildings. At the same time, DSM programs must evolve to maintain cost-effectiveness and value for rate-payers (Elling, Reilly and Pappas 2012). To use the utility incentive program as one example, enrolled buildings will be evaluated by a series of strategies compared against "ASHRAE 90.1-2010". In order to receive energy saving incentives from the utility company, projects need to reach 5% energy savings by kWh, KW, and Therm with "ASHRAE 90.1-2010" as the baseline. It doesn't need to comply all requirements regulated by "ASHRAE 90.1"; therefore, it is crucial to understand what single or a group of strategies would contribute to energy saving the most.

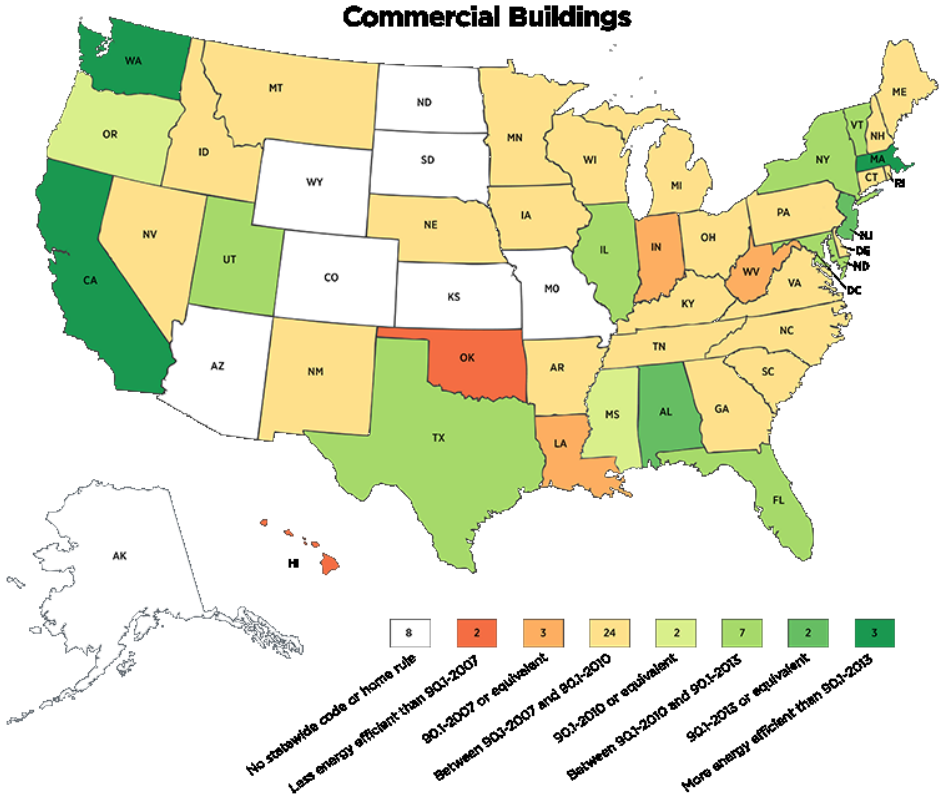


Figure 7 Commercial building energy usage standards by states

2.7 Remaining problems and solution outlines

With previously described research, we could conclude that numerous studies have been done in this field to analyze what type of building massing and architectural design elements could impact on building energy usage under varies of limitation.

Given the validity of the concept of relative compactness (RC), the current researches investigates the impact of building massing on building energy usage in several climate zones and limited building usage. The window area is also studied as it also impact building energy usage.

However, these segmented research conclusions all reveal the site EUI and building massing and through the completed literature review, the major limitations of finished study includes

1> the relative energy usage impact by several major architectural design elements;

2> uncertain energy saving comparison ranking among a wide range of strategies, including mechanical, architectural, electrical and building envelope aspects;

3> doesn't reveal the impact on various of building types;

4> doesn't include various of climate conditions;

In addition, this research discovered it is difficult to design a specific work flow to fit in the decision-making process in all cases. Further, in the early design phase, it is valuable to outline the high-level energy saving potentials of dominant applied energy saving strategies from different aspects that could be utilized in all projects. More specifically, the utility incentive based projects require a faster pace in decision making with the presence of all team members involved, therefore a non-project-specific guideline could further favor the work flow in this type of consulting process.

To respond to these questions and provide a high-level energy conservation guideline, this research is conducted in two phases to further understand the building energy usage and energy saving potentials.

In phase one, the research focuses on the architectural design related questions, regarding the energy performance impact of building massing, window area, window distribution, and building orientation. It is important to understand the individual energy performance of these elements, and then understand the interactive effect when these four design elements are combined together to represent major architectural design. Meanwhile, it would find out the relative energy impact potential among the design elements in prioritizing the focus in schematic design process.

In phase two, the study zooms out to a whole building resolution to understand how building form could impact on the energy usage is in comparison with other parameters such as the mechanical system and its efficiency, the lighting system and its automation system, and envelope properties. The holistic comparison among all different major building energy usage input was not found during the literature review. This study aims to reveal the performance of major relevant input under a consistent comparison platform. It is necessary to link different aspects together in a cooperative work environment.

The whole study is conducted under all 8 U.S. climate zones and typical building types to draw a more comprehensive understanding energy performance of a project when it is designed under a different environment. With a consistent simulation engine, input, and professional perspective from consulting industry, the research will analyze the energy usage from the comprehensive composition with consistent and comparative measures. The outcome of the research outlines pre-simulation building energy design principle in early design phase. The results of the research reveal the high level relative energy saving potential of the different participants in early design phase, and assist the team to make an informed decision with the acknowledgement of the energy saving from each participant in early stage.

CHAPTER 3. THE SIMULATION SET UP OF PHASE ONE

3.1 Simulation workflow

In phase one, the simulations and analysis focus on the relationship between four building form parameters including Relative Compactness (RC), window sizes, window distribution, and orientation. Building massing as a carrier of other 3 elements is treated as primary with a series of secondary factors for each element. Other simulation variables will be set as constant by "ASHRAE 90.1-2010" to form a complete building energy model. At this point, the cooling and heating load will be closely evaluated; the site EUI will be considered to understand how much impact the building form has on energy usage.

3.2 Choose the simulation variables

In Figure 1, the objects variables including location, climate condition, and building type represent a series of fixed existing variables that cannot be modified by the design, but they always set the tone of the energy performance and potentially influence the building energy usage.

ASHRAE has categorized the US into eight climate zones based on the humidity level and year-around temperature (PNNL 2011). The eight climate zones could be further categorized into 16 sub-zones. Located within a climate zone are functionally identical in terms of temperature, humidity and solar radiation. Therefore, all eight climate zones with one representative city, which dictates the TMY files are, will be chosen. These cities are listed as follows in Table 2.

Table 2 Climate zone and cities

Climate type	City
1A. Very hot - humid	Miami, Fl
2B. Hot - dry	Phoenix, AZ
3A. Warm - humid	Atlanta, GA
4C. Mixed - marine	Seattle, WA
5A. Cool - humid	Chicago, IL
6A. Cool - humid	Minneapolis, MN
7. Very cold	Duluth, MN
8. Subarctic	Fairbanks, AK

The heating and cooling degrees days of these cities, depicting the amount of the hours with heating or cooling need, also provide a high level of the quantification of different climate zone and suggest how the simulation result will look like. In Figure 8, the heating degree is decreasing consistently from climate zone 1 to climate 8, and the cooling degree day of Phoenix is higher than Miami even it is located in climate zone 2.

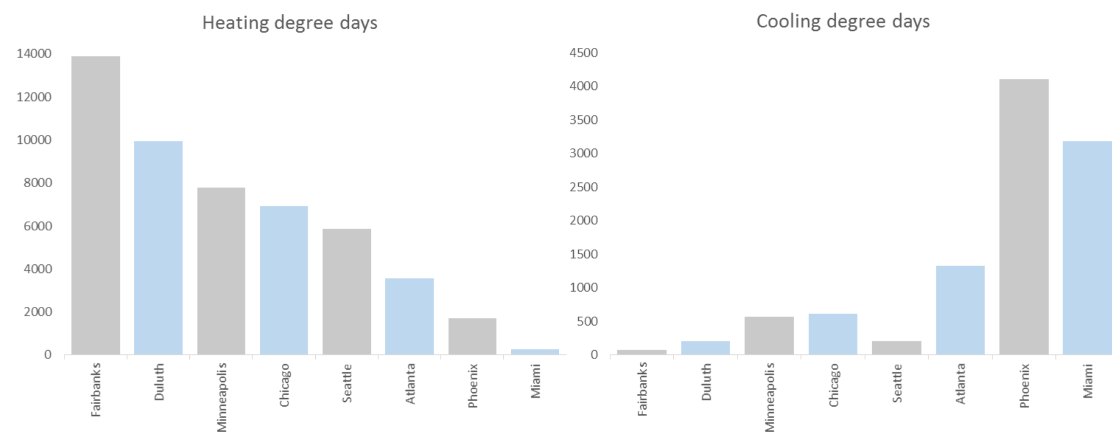


Figure 8- Heating and cooling degree days for chosen cities

The building type selection is also important to fully represent many possible variations, including residential vs. commercial, high occupancy load vs. low occupancy load, high internal heat gain vs. low internal heat gain, long operation schedule vs. short operations schedule, or complicated space types vs. single space type usage. The input of these conditions is determined by "ASHRAE 90.1-2010". With these conditions being considered, seven building types are chosen as follows. The detailed input parameters can be reviewed in the Appendix C. With different climate zone and building types being selected, there are 56 combinations in this research.

Table 3 Building types chosen in the simulation

Building types in simulation	
1. Hotel	5. multifamily
2. Office	6. Warehouse
3. Big box Retails	7.Healthcare-clinic
4. High school	

Table 4 General internal load conclusion of 7 building types

	Temp. Standard	People Density	OA demand	Plug load	Illu. level	Operation time
Retail	Medium	High	Medium	High	Medium	High
Clinic	High	Medium	High	High	High	Medium
High-school	Medium	High	Medium	High	Medium	Medium
Hotel	Medium	High	Low	Medium	Medium	High
Multi-family	Medium	High	Low	Low	Low	High
Office	Medium	High	Medium	Medium	Medium	Medium
Warehouse	Low	Low	Low	Low	Low	Low

The third step is to set up the first out of four interactive elements of the building from, building massing, which is represented by RC. With the validity of the RC shown in the previous literature review, the massing with different RC will be conceptualized as a series of shoeboxes with different proportions. Through a study by THE WEIDT GROUP, the building size doesn't have a strong correlation with the EUI. The gross floor area for all simulation runs is 16,000 sq. ft. for practicality of the simulation set up and eases of calculation. As the baseline and all the design cases are designed with the same floor area, and the performance index, which is a ratio of the EUI of design case to the EUI of baseline case, are used as the major rubric, the impact by the total floor area are avoided in the study.

Thus, there will be only 1 set of the baseline being generated for all test cases. Furthermore, the height of the all the geometries are set as around 63 ft, so the RC are essentially controlled by the width and length of geometries. In another word, the RC will be expressed by different length-width proportion of the floor plan. The range of the RC is derived from more than 1,300 finished projects by THE WEIDT GROUP. As the baseline massing is an RC of 1, the design massing consists of a series shoe boxes with RC ranging from 0.3-1 as described in Chapter 2. The RC essentially could be regarded as the ratio of the baseline surface area to the baseline massing surface area. The excessive load or energy usage of less compact building is mostly caused by the additional surface to form the same amount of the space. During heating and cooling season, the internal production (lighting, appliances, people) and solar through envelope (gain) or thermal transmission and ventilation through envelope (loss) (International Organization for Standardization 2008) fluctuates during the seasons or daily, which further impacts the energy consumption by HVAC system and needs to be quantified by the simulation process. For example, when the RC reaches 0.3, the area of the exterior surface is 3.33 times more than the cubic shape, and the heat transfer through the surface are also maximized in this study.

Table 5- RC design

RC	x	y	z	y/x
1.00	63.25	63.25	63.25	1.0
0.90	35.78	111.80	63.25	3.1
0.80	27.29	146.58	63.25	5.4
0.70	21.47	186.32	63.25	8.7
0.60	16.98	235.54	63.25	13.9
0.50	13.21	302.70	63.25	22.9
0.40	9.98	400.91	63.25	40.2
0.30	7.12	561.96	63.25	78.9

Besides Relative Compactness (RC), the composition of opaque and glazing surface is another important element in composing the building form. Although the physical properties of the glazing, such as U-values, SHGC, have been greatly improved, it still has a fundamental thermal difference compared to the opaque wall. The majority of the solar radiation and heat transfer is through the glazing, and even the best insulating glazing type such as triple-layer vacuumed glazing are much lower than code level wall R-value (Feng 2015). On the other hand, glazing is important as it introduces natural lighting to interior space and increases the aesthetic level of architectural design. In order to test the overall size, and distribution of the glazing, a methodology of glazing distribution by vertical surface has been applied to 15 scenarios. As all design simulations have the same conditioned floor area, this methodology takes the window to floor ratios to able to control the total glazing area and generate comparable results. It has 3 glazing sizes, 15%, 30%, and 60% of condition gross floor area. In other words, the window sizes are 2400, 4800 and 9600 sq. ft. Each size of the window has 5 different distribution methods on 4 vertical surfaces. The distribution methods are, evenly distributed on 4 vertical surfaces, then reduce glazing on one surface and re-distribute to rest 3 sides based on the proportion of the area of the vertical surfaces demonstrated as the diagrams below. Detailed window area distribution can be reviewed in Appendix A. In this way we make sure each of the surfaces could host the glazing area. With a total of 15 different glazing scenarios, we are able to compare the impact of the size and location of the glazing.

Table 6- Window area distribution logic

	Even distribution	S. glazing redist.	W. glazing redist.	N. glazing redist.	E. glazing redist.
15%	15%*16000*X/(2X+2Y)				
	15%*16000*Y/(2X+2Y)				
30%	30%*16000*X/(2X+2Y)	To remain 5% of the glazing on one side, and redistribute rest of 95% to rest of 3 surface (refer the following Figure 9)			
	30%*16000*Y/(2X+2Y)				
60%	60%*16000*X/(2X+2Y)				
	60%*16000*Y/(2X+2Y)				

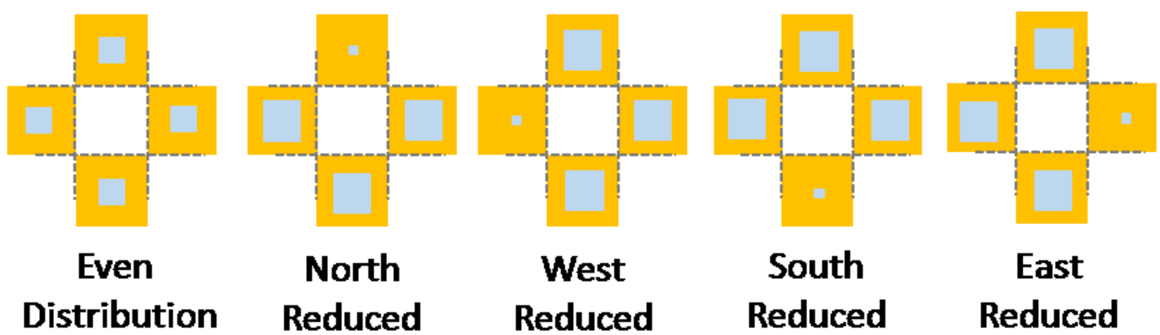


Figure 9 Window redistribution demonstration

The last element is the orientation of the massing. As the massing are represented by a set of shoe box models, they will be set as east-west axis and south-north axis. The orientation of the glazing and opaque surface will impact on the solar radiation of the building from. Regardless how the buildings are oriented the total surface area under the same RC remains the same, therefore, the heat transfer through the surface will be impacted minimally. The solar heat gain is impacted by the building orientation. In this research, the different orientation of the windows has been taken into consideration with 2 orientations. When the angle is 0°, the massing will present more South and North surface, which will consequently present more glazing areas on these 2 sides. When RC is 1, four sides will be in equal dimension; therefore, it is the only case with no orientation variations.

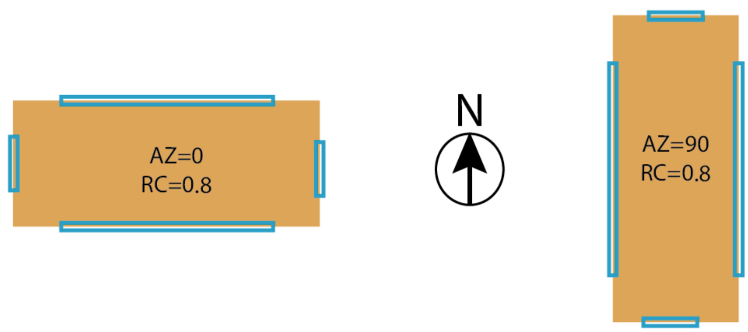


Figure 10- Building orientation demonstration

In a rigorous energy simulation model, it is important to keep other input consant. This study implements the minimum requirement by "ASHRAE90.1-2010". These variables includes, HVAC system type, system efficiency for both cooling and heating, indoor temperature set point, outdoor air requirement, operational schedule, occupancy density, envelope properties (R-value of the wall, roof and U-value of the glazing), infiltration, plug load, process load, hot water usage, lighting power density, illuminance level and lighting control. In conclusion, it will be 240 building forms under each building type and climate zone, which altogether generates 13,440 simulation models and results.

3.3 Simulation engines and introduction

Hourly simulation provides high accuracy result but also take tremendous of time to run a large volume of simulations. In the early stage of testing and validating the simulation logic and feasibility of the research, lower resolution simulation programs could provide sufficient accuracy with much short workload input. In this study, a simulation program EPC (Energy Performance Coefficient) calculator is used in the early stage simulation to provide quick results on individual manually adjusted simulation runs. Formerly known as Energy Performance Standard Calculation Toolkit, the simulation software is Excel based and developed by Georgia Tech using a quasi-steady state formulation of heat balance to simulate the thermal load and energy use by end-use in buildings. The EPC is based on ISO 13790-2008 developed by International Organization for Standardization (ISO) and European Committee for standardization (CEN). Strictly following the concept of the standards, the EPC calculator provides a normative statement about the functional building category to rule out the bias from modelers (Lee, Fei and Augenbroe 2011).

In order to run the large volume of the simulation at one time and reduce the set-up time, the simulation is shifted to batch run simulation models developed by THE WEIDT GROUP. This software has "ASHRAE 90.1" with different versions integrated and uses DOE-2.1e as the simulation engine. With 13,440 simulation runs, they are set in the backstage automated simulation framework WeidtSim®. This automated energy simulation allows modelers to input the architectural information by typing in glazing area, building massing dimensions and coordinates of several key points. The simulation software is also used in the consulting practice at THE WEIDT GROUP and has been validated by multiple utility companies and programs. With the shoe box massing to represent RC in this study, it also alleviates the amount of information input to the simulation and further shortens the simulation time per run to about 2 seconds.

It is necessary to selectively examine the simulation result and compared to THE WEIDT GROUP Quality Assurance database to assure accuracy before applying any analysis. Running with DOE-2 engines, it generates and breaks down the result in multiple categorization methods, which allow modelers to check and debug the building geometry, thermal load by month or by component, internal heat gain, and energy consumption. The following figure is visualization representation of graphic information generated by the simulation software. The glazing on each surface is evenly distributed on each floor, the center of the glazing overlap with the center point of the wall surface.

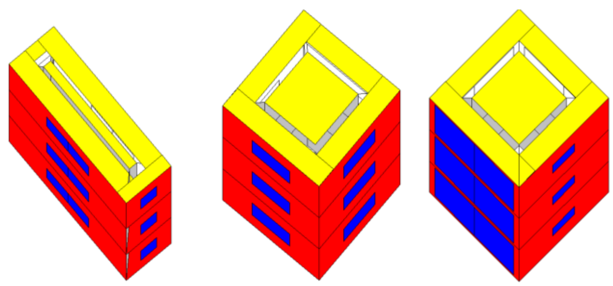


Figure 11- NEO model visual representation

CHAPTER 4. RESULTS ANALYSIS OF PHASE ONE

4.1 Analysis Logic and procedure

This chapter focuses on analyzing the result of the phase one simulation. To analyze the results, it is necessary to develop a rigorous flow and a multi-layer structure. As it has been studied and explained in the literature review, the RC is the major element impacting building form related performance; therefore it will be used to frame the analysis as the primary variable. PI will be used as the measurement of the performance; actual load, site and source EUI will be used only for reference to secure the comprehensiveness of the results. In the setup of this research, all the cases have the same conditioned floor area, and the actual EUI will probably change if the total floor area is different even with other variables held as the same, but the PI will stay the same.

In a comparative analysis, it is important to understand the PI reveals relative results relative to a baseline. The baseline is changing constantly when different design elements are evaluated. The baseline and design cases are always simulated under the same building types and climate zones. As the framework of the building form, the only variables in analyzing the building massing should be RC. As we test other elements of building form, the PI calculation will contain this secondary variable besides the RC to test its performance under the framework of RC, which will be explained more specifically in the later analysis section.

As it has been discussed in the previous chapter, there are four variables under building form, namely Relative Compactness (RC), window area, window distribution and building orientation. As the building massing is the carrier of other design elements and the change of the Relative Compactness (RC) could largely impact on the other three element of building form. Therefore, the research is set up to use RC as the primary variable and the remaining three elements as secondary variables. These 3 elements will be mainly compared along with the RC change. The performance index (PI) of evaluating the 1> building form should take the variation of all 4 design elements into consideration, 2> building massing should hold the rest of 3 design elements constant, 3> other secondary design variables should include the change of RC. The details are listed in Table 7 as follows.

Table 7- Variables Summary conclusion

	Primary variable	**Secondary variables**	**Constance**
PI for building form	RC	WFR, orientation, window distribution,	none
PI for Relative Compactness (RC)	RC	none	WFR, orientation, window distribution,
PI for WFR along RC	RC	WFR	orientation, window distribution,
PI for window distribution along RC	RC	window distribution	WFR, orientation,
PI for building orientation along RC	RC	orientation	WFR, window distribution,

Table 8- Baseline conclusion

Variables	Absolute Origins
RC	RC=1
WFR	15% WFR
window distribution	Evenly distribute on 4 surfaces
orientation	AZ = 0, elongated N-S axis

With 13,340 sets of simulation results, the analysis will be structured with three steps explained in Figure 12. The first step it to analyze the Relative Compactness (RC) under all different climate zones and building types; the results for each RC will be 30 PIs with all possible combination of WFR, window distribution, and orientation. Then the analysis will focus on WFR, window distribution, and building orientation from RC ranging from 0.3 to 1. The last step is to analyze the building form as a whole. As the analysis moves on with more restriction on what is being compared, the amount of the baseline reduces. In step 3, the building form only has one baseline in building type and climate zone.

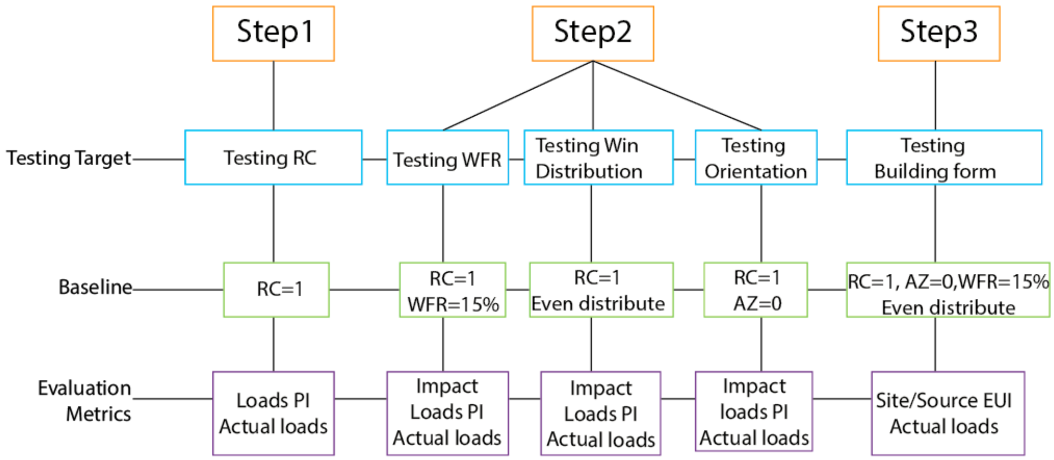


Figure 12- Analysis procedure in phase I

In this chapter, the simulation of climate zone 5 Chicago will be used to streamline and demonstrate specific analysis process in step 1 and 3, and office in Chicago in step 2. Compared among other climate zones, climate zone 5 is neither extremely hot nor cold. Other locations will be partially implemented to compare and assist in explaining the results. The results of all other locations and building types will be implemented in Appendix A.

4.2 Performance analysis of RC

The first step is to analyze how the performance of building massing compactness as an individual element by looking at cooling and heating load Performance Index (PI) and actual load. Therefore, all the cases with RC of 1 are baseline compared with different scenarios, and in total it will generate 30 baselines. In other words, it will have 30 different scenarios composed of all possible combinations of other 3 elements under each RC. Consequently, it will generate 30 PIs for each other RC, and the ultimate PI for each RC will be the average of these 30 results.

The performance Index (PI) calculation in this layer of analysis is:

$$PI = \frac{E\ design}{E\ baseline}$$

$$E\ design = f(\boldsymbol{RC} = \boldsymbol{x}; oreintation = a; WFR = b; win.dist. = c;)$$

$$E\ baseline = g(\boldsymbol{RC} = \boldsymbol{1}; reintation = a; WFR = b; win.dist. = c;)$$

$$a, b, c = constant$$

Example:

Design building form of RC=0.6, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with azimuth angle of 0,

Baseline building form of RC=1, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0.

In a Chicago office building, the cooling load of the design building form is 48 kBtu/sq. ft., and 49.34 kBtu/sq. ft. for the baseline building form. Applied in the equation, the cooling PI of this Relative Compactness (RC) is **1.03**.

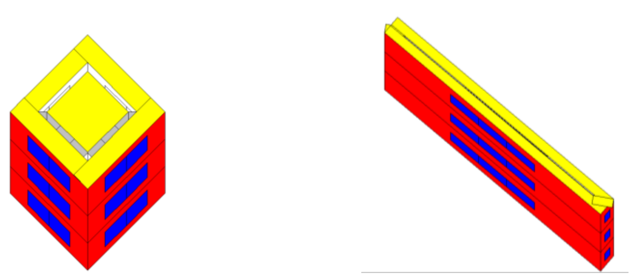


Figure 13- Baseline (left) vs. Design case (right)

4.2.1 Cooling load and performance index

In Figure 14-15, the results of Chicago present that the cooling load and its performance index doesn't increase monotonically in certain building types. While other building types with the small cooling load show linear increase, such as a warehouse, multifamily, and office. In Figure 14, the result shows the building types with the highest (warehouse) and lowest (retail) increase of the cooling load PI. The building types with a smaller overall change in PI typically has a high internal load, including internal heat gain, long operation hours or restricted temperature set point. Different building types could cause a larger difference on the lower case load within changing of RC, ranging from 9% in retail to 39% in the warehouse shown in Figure 14.

In some circumstances, a larger surface area helps to release internal heat gain to outdoor through conduction and convection. In heating dominant climate zones like Chicago, this effect is maximized when the outdoor temperature is lower than indoor but the heat transfer to outdoor in the baseline building massing is less than internal heat gain. Therefore, as the surface area increase, the internal heat gain will be transmitted to the outdoors faster, leading to the PI drops when RC is 0.9 or 0.8 in Chicago for a retail space. Contrarily, the drop of the cooling load PI when RC is 0.9 or 0.8 does not exist in climate zone 3A, Atlanta or hotter area. In the cooling dominant area, the net heat transmission from outdoor to indoor is much higher, and it is rare to reach a positive net heat transfer from indoor to outdoor during the cooling season. Therefore, it is not difficult to explain why these building types don't show a PI decline at any point of RC. The change of the cooling load PI presents a much bigger increase as the compact level reduces as the design case is located in hotter climate zone for all building types. In

Phoenix, the increase in the cooling load with RC ranges from 18% in the hotel to 104% in the warehouse.

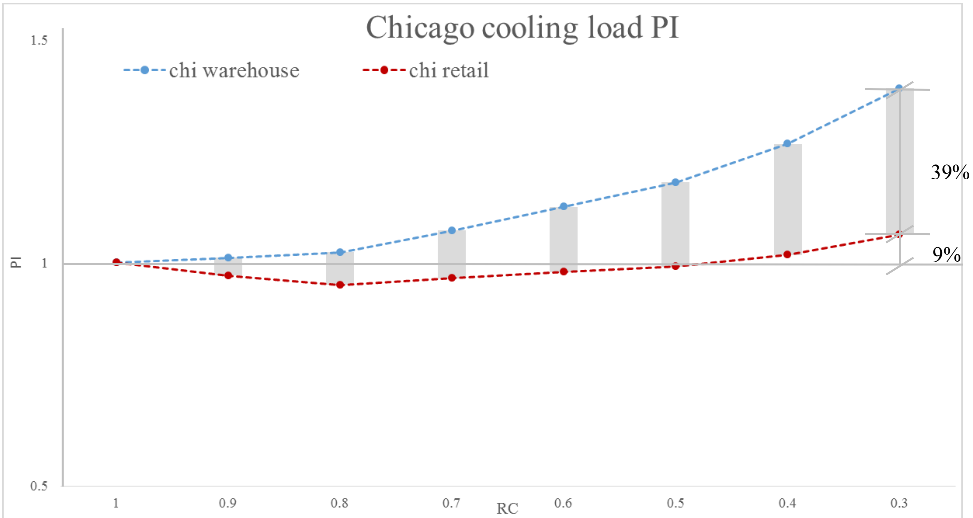


Figure 14- Chicago cooling load PI

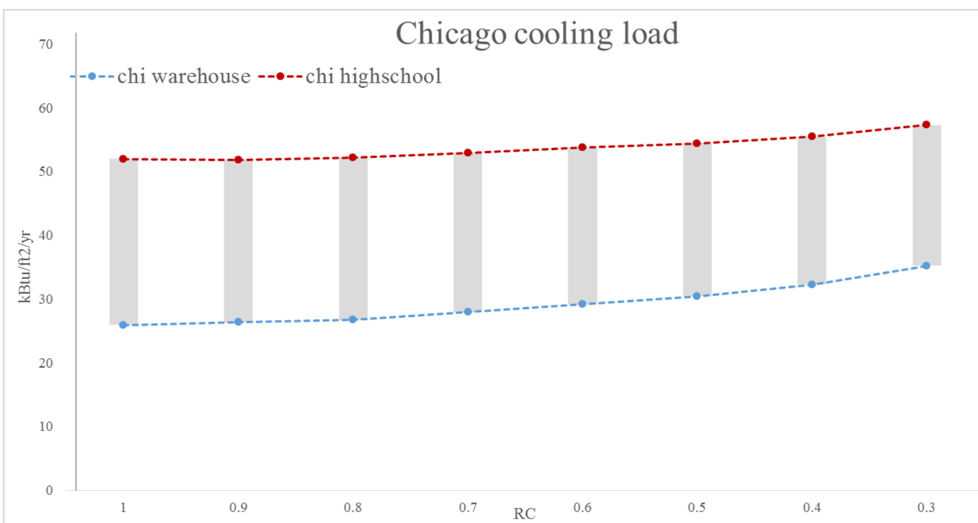


Figure 15- Chicago cooling load

The cooling load of different building types shows dramatically different ranking, but in general, the building types with lower cooling load PI shows higher cooling load. The effect of building massing is also consistent regardless of the building usage. As a result, when building cooling load is higher, the percentage that can be impacted by the building massing/surface area will decrease. PI shows the result of the comparative analysis; it doesn't present how much actual load is going to be impacted. With the highest PI change, the office shows 23% of the increase in the cooling load PI with actual 7.6 kBtu/sq. ft. in cooling load, whereas the multifamily show 24% of the increase in the cooling load PI with actual 6.4 kBtu/sq. ft. in cooling load. With this comparison, it is clear the PI is to express how sensitive the building form is impacting on the cooling load from its baseline.

In terms of cooling load, it appears different trends and rates in a different location when building types remain the same. From the Appendix A, it is found that the increase of cooling load PI is more drastic along the RC in Climate zone 2 Phoenix, where it is featured with highest cooling degree days. Generally speaking, the colder area with less heat gain from the outdoors shows a smaller cooling load PI change, and as the climate is becoming hotter the increase of cooling load PI becomes more dramatic.

Beyond viewing the results with a continuous change of RC, it is also crucial to compare with actual RC range by building type to tie the research back to reality. Figure 15 shows the range of cooling PI of all 30 cases under each RC all seven building types in Chicago. In each graph, the top black line represents the top quarter PI under each RC, the dark blue part shows the second highest quartile of the PI, the light blue bar shows the second lowest quartile of the PI and the lower black lines shows the bottom quartile of the PI. When RC is 1, the length of the bar is 0, because every case when RC is 1 is considered as the baseline explained previously in the equation. Therefore, the PI of RC equals to 1 is always 1. The light orange shading indicates the major RC distribution of the building type corresponding to Figure 5.

Relate back to Figure 15, the detailed cooling load PI distribution reveals that the PI fluctuation caused by WFR, window distribution, and orientation are actually bigger in these type of building with high PI or lower cooling load in Chicago. It is found that building form could cause a higher impact on the cooling load of the building type with the small internal load as the warehouse shown in Figure 14. For architecture designers, they should be more conscious on the compactness of the building when designing a building such as an office or warehouse.

Figure 16 shows the cooling load PI change along the RC. The vertical bar shows the quarterly distribution of PI under each RC. Moreover, each vertical bar demonstrates how much variation it has under the same compactness by the different WFR, window distribution, and orientation. The simulation results show the different result with what has been found in the literature review, these three elements could actually cause a much more significant impact on the cooling load PI in Chicago. Especially in the hotel, retail, high school, and clinic, the cooling load PI is far less than the combination of three other elements. Further analysis for the other three elements will be explored in next layer of the analysis in this chapter. Regardless, the impact by the building form on the cooling load can be large in Chicago, and this impact becomes more observable in hotter climate zones.

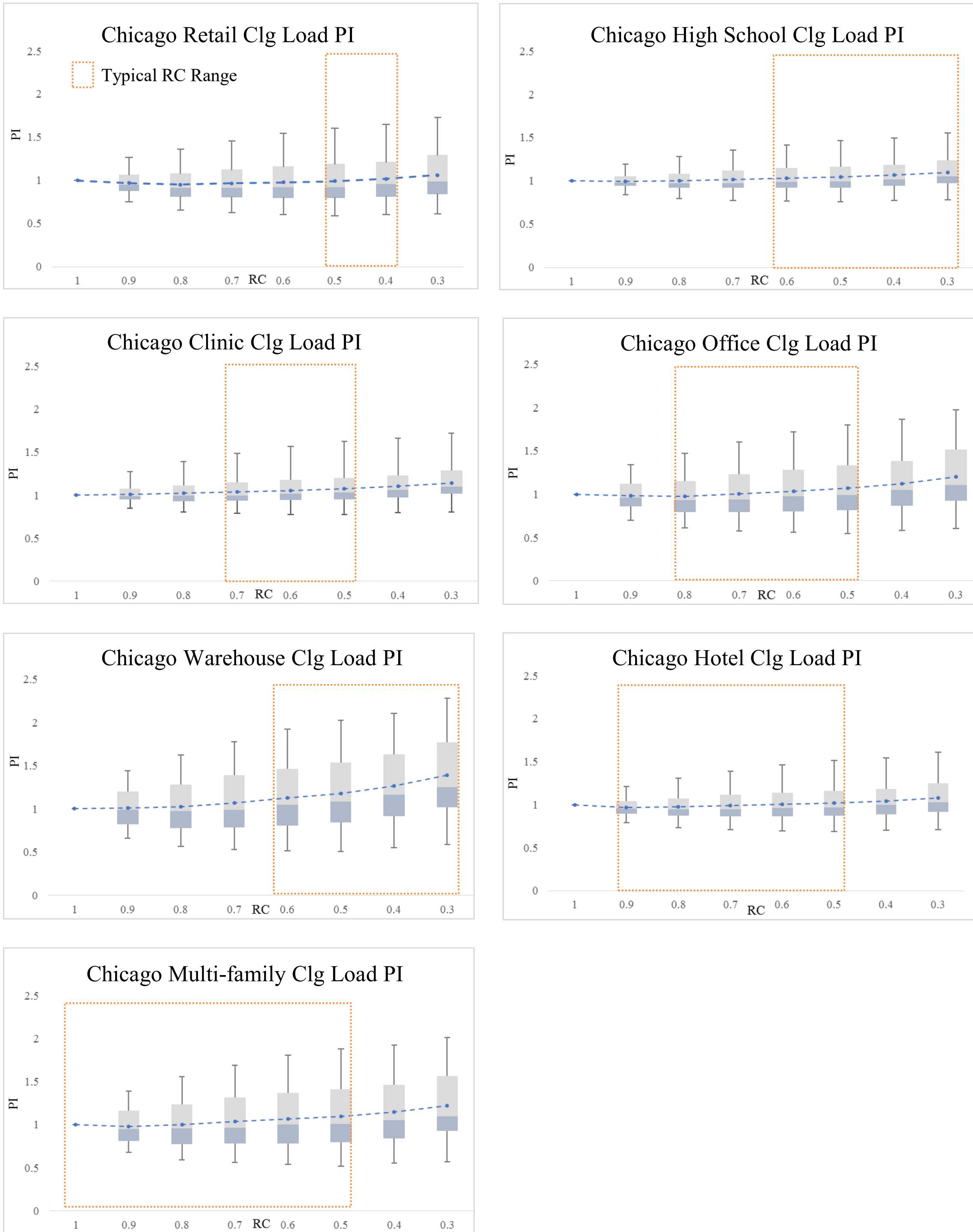


Figure 16- the detailed cooling load PI change along RC under 7 building types in Climate zone 5- Chicago

The warehouse currently is mostly in the range of 0.3-0.6, which is reasonable as most of these building types are spread out and with 1-2 stories for storage and circulation purposes. Also, in a certain site context, the building couldn’t reach an ideal compactness potentially due to the FAR (Floor area ratio) requirement by the city code or fire code. It is crucial to further explore how much load PI change actually is in the range of current RC design. It could also reveal another aspect of the building simulation, which is how much impact on the simulation results by input the building form information. As it is revealed in the literature review, the details building geometry wouldn’t impact the building energy simulation unless the geometry is specifically designed for certain passive strategies. Table 9 reveals the quantified result of ideal range and realistic range of RC change of Chicago, and the rest of the results can be found in Appendix A.

In Table 9, with an ideal range of RC from 0.3 to 1 the difference of the performance index ranges from 11% with the clinic to 48% warehouse. With the RC from THE WEIDT GROUP database as described in section 1.7, the clinic usually falls in a narrow range of RC. The warehouse has one additional condition of 15% WFR only in evaluating the realistic load change. Even so, the change of cooling load is still the highest among all building types. Overall, the impact on the cooling load by change the compactness of the building is not quite obvious when target range of RC is retained by the typical compactness of each building type. In Phoenix, and Constrained Cooling Load Change is typically 2-4 times higher than in Chicago, and the actual cooling load difference in phoenix caused by the building massing is 9-12 times higher than in Chicago depending on building types.

Table 9-Percentile change in cooling PI in Chicago

	Unconstrained Cooling Load Change by RC	Constrained Cooling Load Change by RC
Strip mall Retail	12%	3%
Clinic	15%	3%
High school	10%	7%
Hotel	11%	4%
Multifamily	24%	12%
Office	24%	15%
Warehouse(15%WFR only)	48%	15%

4.2.2 Heating load and performance index

Compared to Figure 17, the change on the heating PI along the RC shows more dramatic change than cooling load, and this pattern was found in all locations. The increase is monotonic without decrease when RC becomes smaller in cooler climate zones. In Chicago, the retail type shows the most sensitive change while the heating load of warehouse tends to be less sensitive to changing compactness, and this trend is opposite from the cooling load. However, it doesn't mean the warehouse has less potential in reducing the heating load by modifying the Relative Compactness (RC) compactness. The actual Heating Load Change in Figure 18 reveals another aspect of the impact by the Relative Compactness (RC) compactness. Warehouse with 130% increase on the PI, appear to have 38 kBtu/sq. ft. increases in heating load. It is worth pointing out that the percentage increase only indicates the energy usage in comparison to its own baseline, which has the same building types with the design case. Therefore, the percentage increase doesn't necessarily indicate a higher energy usage increase as the baseline energy usage could be drastically different depending on the building types. For design teams, the building type of a project is typically determined at the beginning of the process, so the percentage different would be sufficient in this context. Further detailed energy usage differences are found in Appendix A.

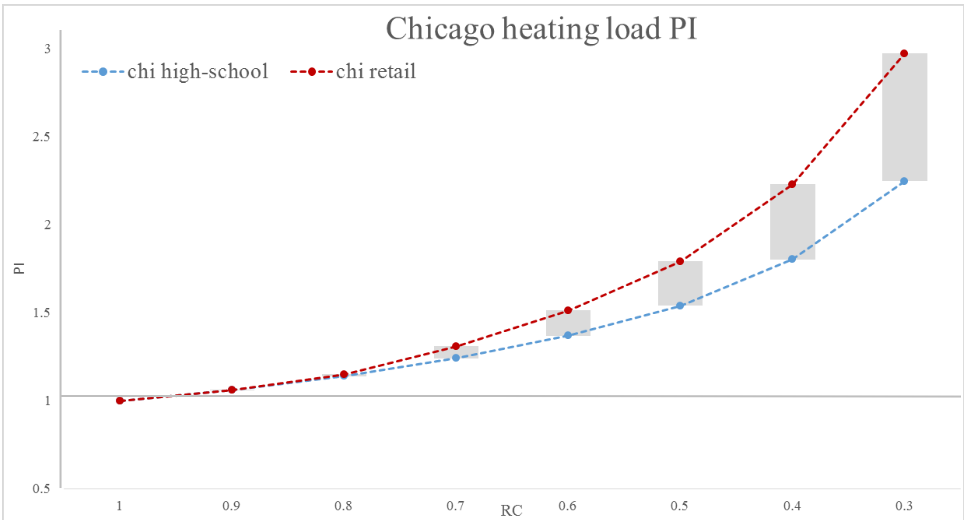


Figure 17- Chicago heating load PI

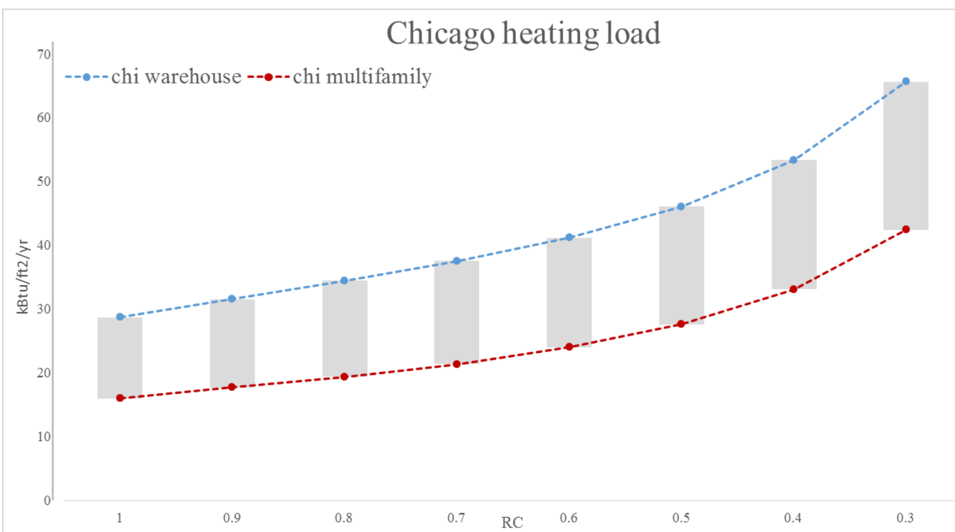


Figure 18- Chicago heating load

As the Relative Compactness (RC) become less compact, the impact on both cooling and heating load is more dramatic with all building types. Due to the function and other restrictions, certain building types typically only stay in lower compactness levels such as a warehouse or the strip mall. To these types of buildings, it is more crucial to control the RC and also other aspects in designing the building form as the heating load increase more dramatic in the lower range of RC. The heating load PI increase becomes sharper when the building is located in hotter climate. In Phoenix, where shows the highest cooling degree days in Figure 8, the increase of PI is most significant in retail, as the internal load is high, setpoint is lower and operational hour are longer demonstrated in Appendix C. The similar pattern appears in all building types with higher heating load PI.

In Chicago, where the HDD is higher than CDD, the heating load could actually be controlled under 25 Kbtu/sq. ft. in most of the design building types. In comparison, the cooling load in Chicago can be hardly reduced to below 30 Kbtu/sq. ft. except for warehouse. By only looking at the HDD and CDD, it is possible to misunderstand that the hot climate zone like Phoenix has a minimum heating load, but the simulation results find that when RC is smaller than 0.4. The level of sensitivity to change of RC on the heating load even in hot climate proved the significance of heating load in every climate zone, and architects could play an even bigger role in a hotter climate zone.

In Figure 19, the vertical length of each bar presents the impact by WFR, window distribution and building orientation on the Relative Compactness (RC). As it shown, the impact by other element is increasing when RC decreases. The building types with higher responsiveness to the change of RC in heating load, the impact by other elements of building forms to Relative Compactness (RC) are also higher. The sections 4.3-4.5 will discuss how and how much the rest of the building form elements can impact on the thermal load.

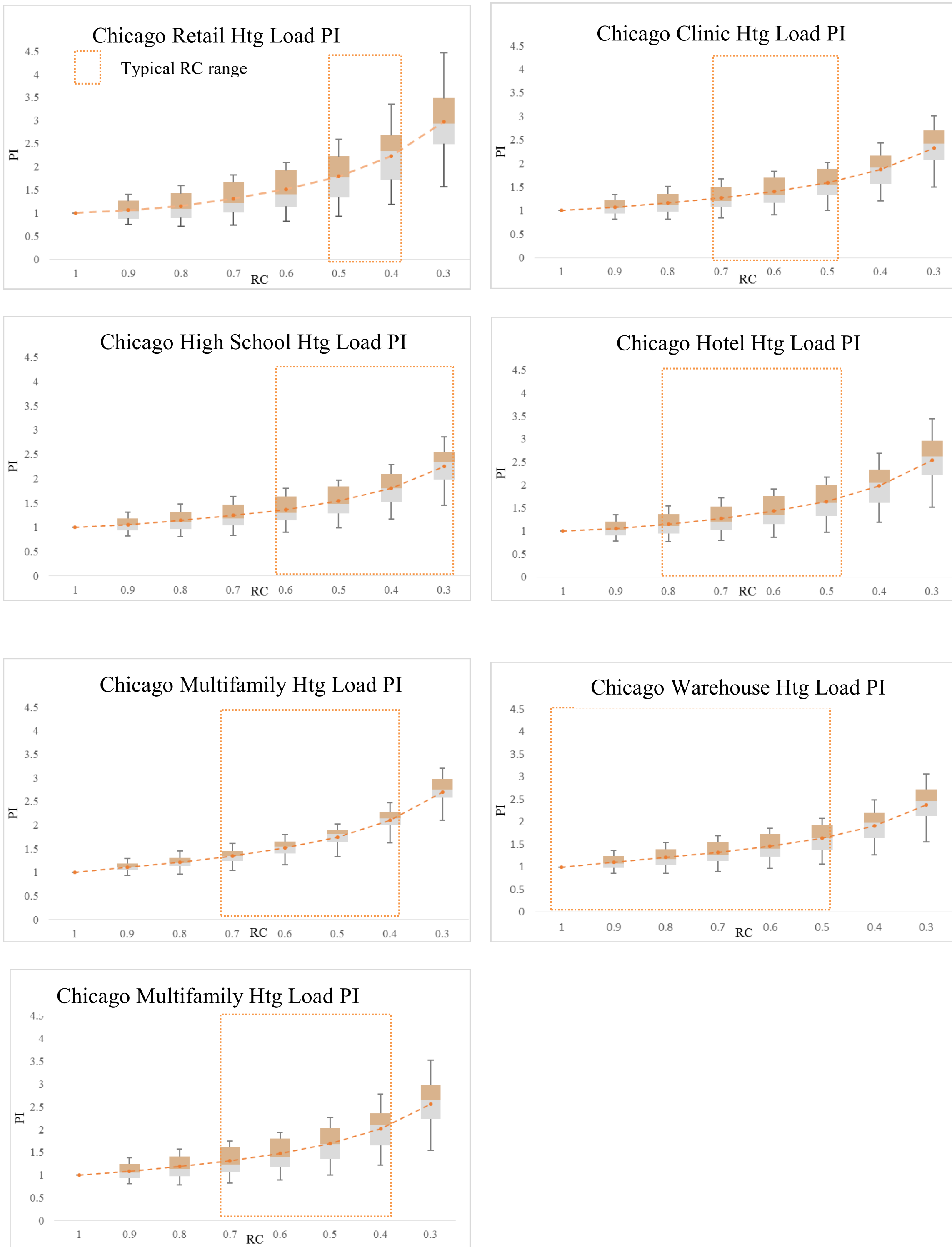


Figure 19- the detailed heating load PI change along RC under 7 building types in Climate zone 5- Chicago

When applying the RC of THE WEIDT GROUP database explained in section 1.7, the results shows the Heating Load Change has been significantly reduced by at least half of all the building types. Within the range of RC from the database, the change of heating load could be as high as 75% in multifamily or as low as 4% in retail (strip mall). In retail, the distribution of the RC concentrated in 2 ranges, and these are a strip mall with low compactness and department stores with higher compactness. If the analysis only focuses on the strip mall, the heating load will only change by 24%. By looking at the actual load difference with restriction of RC from the database, warehouse, retails and office with similar heating load difference is bigger than other building types. It is observed that retail buildings results are due to a higher change from its own baseline, and warehouse with lower sensitivity but has the high internal needs among all test building types. Office always stays in the median position among all seven building type, but in design practice, the range of RC is bigger due to complicated spatial and program requirement. It reveals that either building thermal properties (internal needs) or spatial design characteristic could impact on the building thermal load in practice.

Table 10-Percentile change in heating PI in Chicago

	Unconstrained Heating Load Change by RC	Constrained Heating Load Change by RC
Retail(strip mall)	198%	24%
Clinic	133%	25%
High school	125%	64%
Hotel	154%	36%
Multifamily	170%	75%
Office	150%	70%
Warehouse(15%WFR only)	175%	58%

Overall, the change of the heating load is higher than cooling load, and it is applied to all climate zones. At the same time, we could also evaluate the actual difference on both heating and cooling load as shown in Figure 19. In cold climate such as Fairbanks, heating load is surely predominant thermal load, even though it doesn't show as high PI change as in Phoenix. It should have a higher impact on the actual thermal load. The analysis revealing an actual change of thermal load will be carried the site and source EUI in section 4.6.

4.2.3 EUI analysis and performance index

When the performance of the RC is carried to the actual energy consumption level, the difference caused by the change of RC is not as drastic. Converting from site EUI to source EUI, the simulation has implemented nationwide conversion factors from EPA's Energy Star Portfolio manager: 3.14 for electricity and 1.05 for natural gas.

(Based on emissions data from 2011). It is found that the site EUI PI changed by the realistic range of RC, which is between 9% to 28%, and 7% to 18% in source EUI PI.

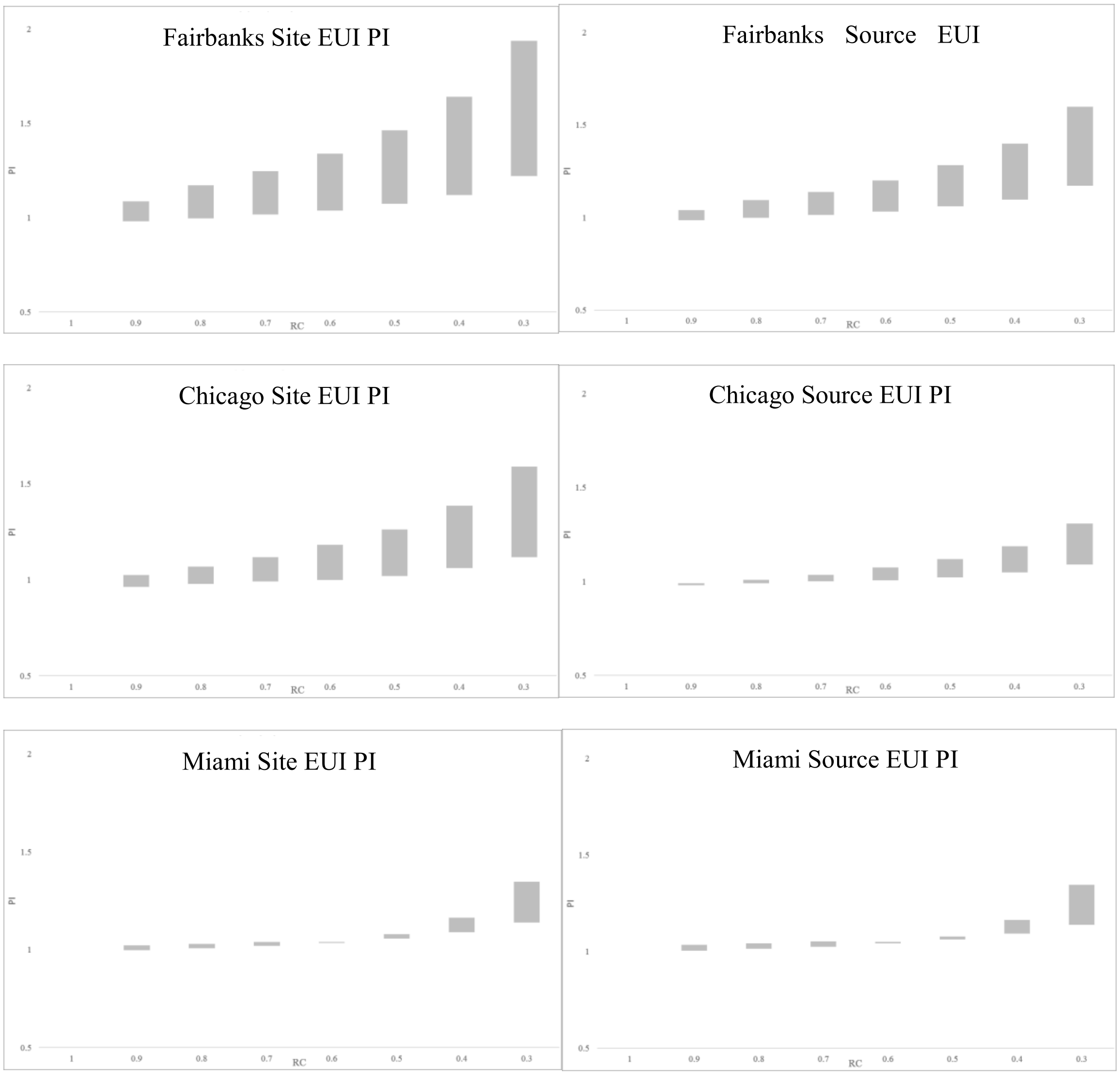


Figure 20- Site and Source EUI PI change in Fairbanks, Chicago, and Miami

The site EUI and its PI is used to analyze the Relative Compactness (RC) performance across 8 climate zones, as the cooling and heating cool profile is completely different and therefore difficult to compare. The intention to compare performance difference by climate zones is to understand how designers could optimize the building form in response to the objective condition changes. Figure 20 presents site and source EUI PI of 3 different climate conditions including Fairbanks, Chicago, and Miami. The grey vertical bars indicate the PI variation range of 7 different building types with uncertain certain RC and climate zone. It is clear that the both site and source EUI PI presents a clear increase along the RC in a colder climate. The increase of the site EUI PI in colder climate is faster, as the energy usage in colder climate are dominantly from heating. As already demonstrated in the Figures 14-15, the heating load PI increase is more sensitive to RC. Moreover, the cooling load is satisfied by the DX system based on "ASHRAE 90.1-2010", and with a default baseline COP higher than 1, the change of the site and source EUI PI in hotter climate will be even lower.

4.2.4 Monthly building form performance

The heating and cooling load by RC should also be evaluated monthly. As shown in Figures 21-22, the multifamily building in Chicago has less cooling load during heating seasons if the building is less compact. This pattern is more observable in colder climates especially in building types with low internal gains like multifamily, office, and warehouse. With well-considered passive design strategies and appropriate building forms, architects may be able to get rid of the mechanical cooling in these months. Thus the related installation, maintain operation cost and energy use will be gone, It may not be realistic in US setting where the indoor comfort zone is restricted to a very narrow range and a high standard. However in some regions such as China and Korea, it is feasible. In China, the public buildings indoor temperature can't be lower than 79 F degree during cooing season by the national code. In Figure 22, the heating load of a multi-family in Chicago increase only as the building mass become less compact, which explains the importance of improving the compactness level of building massing in colder climate.

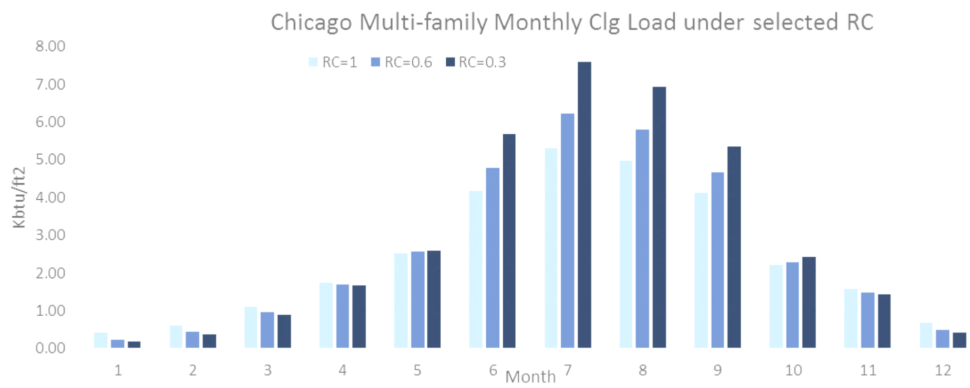


Figure 21- Monthly cooling load by RC

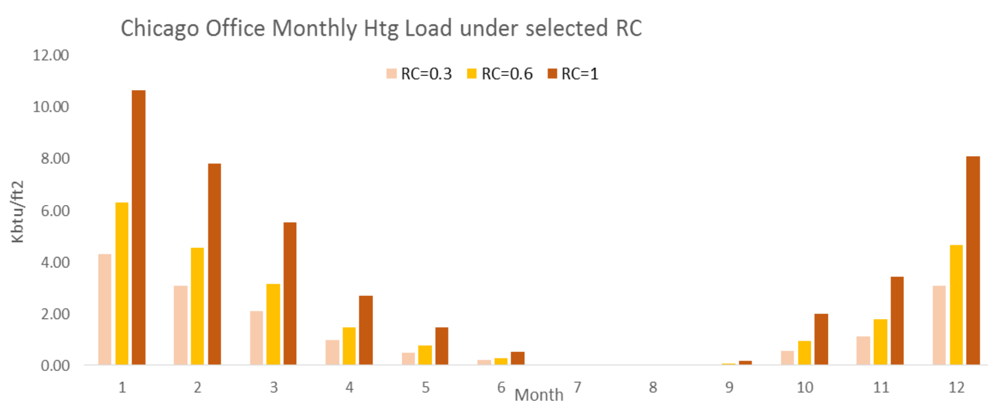


Figure 22- Monthly heating load by RC

4.3 Performance of Window Size (WFR)

The size of the glazing is another important element in a building form and architectural design. In modern architectural design, the glazing area is bigger, and a lot of building is basically designed as a glass box. As described in the analysis framework, the Relative Compactness (RC) is the primary variable in the analysis, and it is also the carrier of other elements of building form. All these variables are interacting and influence the performance of rest of the variables. To understand the role of secondary variables, step 2 will be further decomposed to three aspects, 1> the impact on the primary variables RC by the WFR, 2> the performance of individual WFR, and 3> its performance carried along with the primary variables. An office building in Chicago will be used as the example to demonstrate how the analysis is being processed.

4.3.1 WFR impact on Relative Compactness (RC) performance

The performance of the Relative Compactness (RC) changes along its compactness but also partially due to the other elements of the building forms. In this step, the calculation of impact will be the ratio of 2 PIs instead of the actual loads or EUI to examine the impact of WFR to the massing performance. The baseline should always have 15% WFR. Therefore, the comparison is set with the impact by the case with 15% of WFR and RC remains constant between baseline and design cases. When comparing the PIs, additional noise has been eliminated in the equation.

$$Impact = PI(design\ massing)/PI(reference\ massing)$$

$$PI\ design = f(RC = a; \boldsymbol{WFR} = \boldsymbol{x}; oreintation = b; win.dist. = c;)$$

$$PI\ reference = g(RC = a; \boldsymbol{WFR} = \mathbf{15}\%; oreintation = b; win.dist. = c;)$$

$$a, b, c = constant$$

Example:

Design building form of RC=0.3, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0. The heating load PI of this building massing is 2.48.

Baseline building form of RC= 0.3, with 2400 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0. As, baseline, the heating load PI of building massing is 3.05.

The impact of the design case is 2.48/3.05= 0.81

When the WFR is 15% is set as neutral or baseline, the impact from bigger WFR deviates more from the baseline of 1. In other words, the cooling load performance of the Relative Compactness (RC) will be impacted more when the windows area is bigger. Overall, the impact by the WFR on the cooling load performance is fairly smaller within ± 5%.

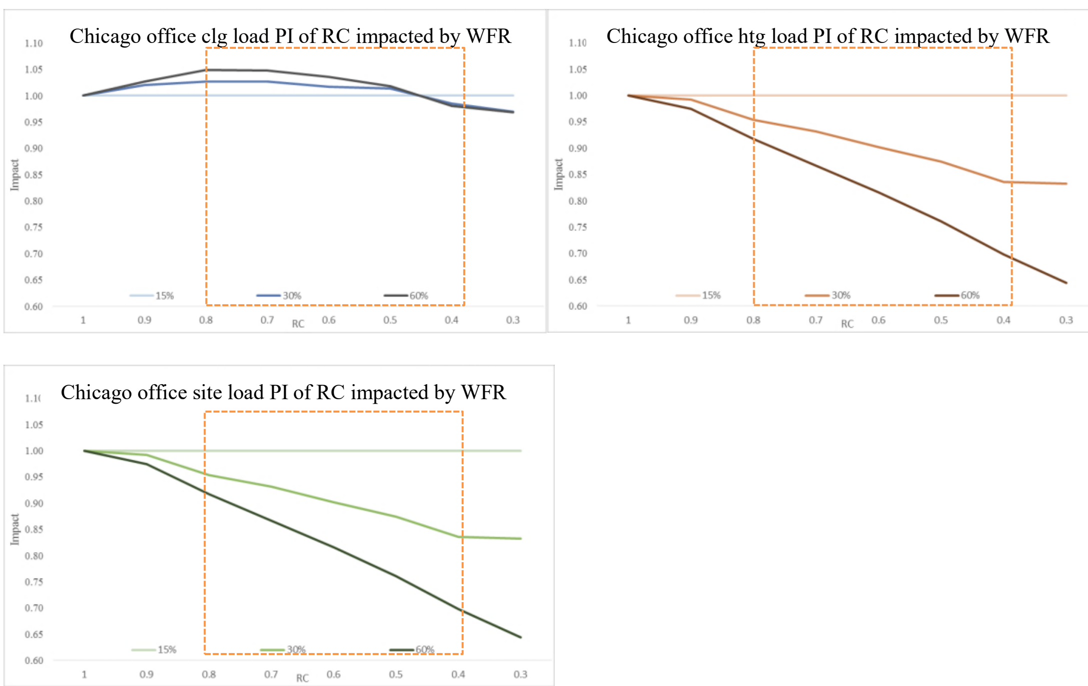


Figure 23-WFR impact on RC in cooling, heating load and site EUI PI

The impact on the RC by the WFR is becoming much bigger at heating load. Similar to cooling load, the impact with bigger WFR is also more dramatic. As the RC decreases, the impact by the WFR keeps increasing as it deviates more from 1 representing the neutral baseline, and this trend appears in all climate zones and building types. Compared to the cooling load side, the impact on RC by WFR reaches 35%, which is significantly lower than the impact on the heating load shown in Figure 23. This analysis doesn't reveal the actual impact on total thermal load by the window area. In order to further reveal the how much the window area could actually impact on the performance, the analysis is carried to study the performance index of window area. As a combined effect of heating, cooling load and other inputs, the site EUI also remains the same trend with heating load, and it is expected since the impact by cooling are minimum when comparing to the heating aspect in Chicago.

4.3.2 Performance evaluation of the individual WFR

When analyzing the impact of the WFR on the energy performance, the WFR should be the only variables in calculating the PI with the baseline as 15% WFR.

The performance Index (PI) calculation in this layer of analysis is:

$$PI = \frac{E\ design}{E\ baseline}$$

$$E\ design = f(RC = a; \boldsymbol{WFR} = \boldsymbol{x}; oreintation = b; win.dist. = c;)$$

$$E\ baseline = g(RC = a; \boldsymbol{WFR} = \mathbf{15}\%; oreintation = b; win.dist. = c;)$$

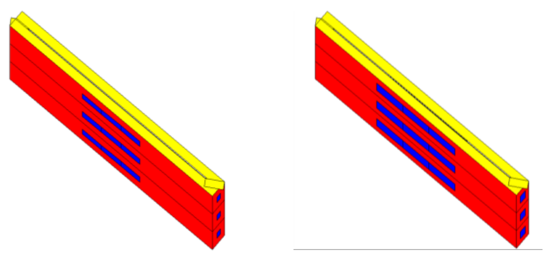
$$a, c = constant$$

Example:

Design building form of RC=0.6, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with azimuth angle of 0,

Baseline building form of RC=0.6, with 2400 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0.

Figure 24- Baseline (left) vs. design case (right)



It is commonly understood that the both heating and cooling load will increase with high WFR in design practice. Figure 25 pulls 3 individual RCs on heating load PI, cooling load PI and site EUI PI level to analyze the trend of the PI by WFR. In calculating the PI, the results come from average results under all 10 possible combinations of window distribution and building orientation under certain RC and WFR.

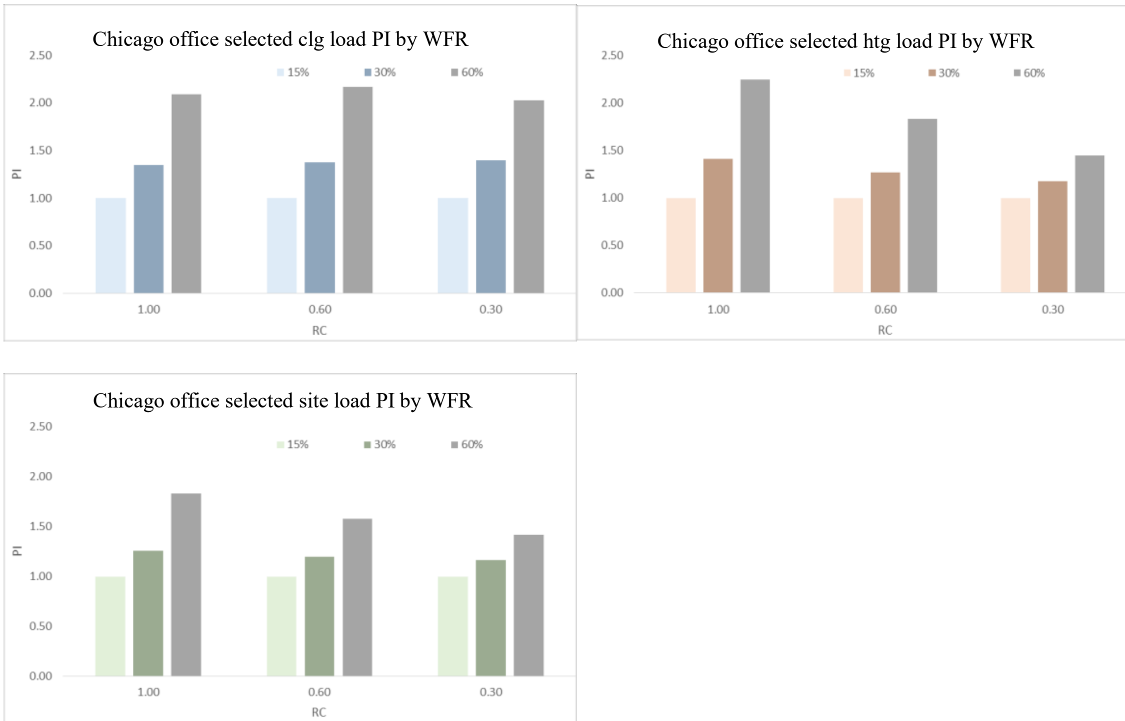


Figure 25- Selected RC analysis on cooling, heating load, and site EUI PI by WFR of office in Chicago

Figure 25 shows a similar analysis is conducted in the Site EUI. From the PIs of different WFRs in three selected RC, it can be found that the result is in between the cooling and heating load PI. It is also reasonable with Site EUI PI shows smaller digits as it includes other simulation variables.

As shown, when comparing the same Relative Compactness (RC), both heating and cooling load PI increases as WFR increases. In cooling load, the PI increase with three WFR remains relatively consistent in all three selected RC. In heating load, the difference under 3 WFRs is much bigger when the building is more compact. When the building is less compact, the WFR of the building increases tend to be slower. In general, both the heating and cooling load influenced by WFR remains consistent regardless of the building massing compactness level.

4.3.3 Performance evaluation of the WFR and RC

When the analysis is carried under the structure of the RC, the calculation of the PI will be changed in addition with the RC. In this step, the result will take the average results with all possible combination of orientation or window distribution, or a and c in the following equation. The major different in calculating the compare to 4.3.2 is with the fixed RC of 1 in the baseline.

The performance Index (PI) calculation in this layer of analysis is:

$$PI = \frac{E\ design}{E\ baseline}$$

$$E\ design = f(\boldsymbol{RC} = \boldsymbol{x}; \boldsymbol{WFR} = \boldsymbol{y}; oreintation = a; win.dist. = c;)$$

$$E\ baseline = g(\boldsymbol{RC} = \mathbf{1}; \boldsymbol{WFR} = \mathbf{15}\%; oreintation = a; win.dist. = c;)$$

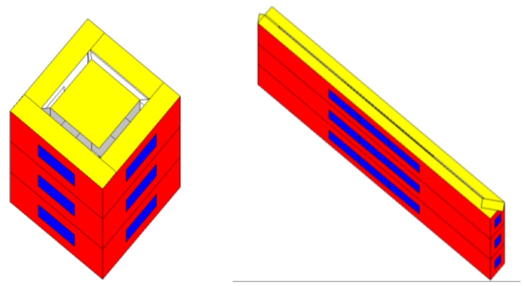
$$a, c = constant$$

Example:

Design building form of RC=0.6, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with azimuth angle of 0,

Baseline building form of RC=1, with 2400 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0.

Figure 26- Baseline (left) vs. design case (right)



In section 4.2.1, the cooling load PI of the Relative Compactness (RC) drops when RC is around 0.9 or 0.8 in most building types including an office in Chicago and other heating dominant climate zones. In Figure 27, the detailed analysis on RC reveals that smaller WFR as one of the cause. As the window area is smaller, the total surface area is more crucial in heat transmission, therefore the Cooling load PI drops when the RC is 0.9-0.8 as an expression of increased influence by the Relative compactness when WFR is smaller.

Along the change of the RC, Figure 27 shows that different WFR impact on the cooling load with the same trend with the almost identical increase rate of around 25% from RC of 1 to 0.3. Similarly, to the cooling load, the heating load PI is found to be influenced by different WFR with the same rate. With this trend, it is clear that the change of the WFR could bring a consistent impact on the energy usage, and the different level of the Relative compactness doesn't change how the WFR could influencing the building thermal load or energy saving potentially.

With the realistic range of the RC from THE WEIDT GROUP database, the cooling load increases from minimum (when RC is 0.8 with WFR of 15%) to maximum (when RC is 0.4 with WFR of 60%) with both effect of RC and WFR reaches 140% in office building in Chicago, where it is only 21% with the RC as the only variables. In heating side, this number is around 192%, which almost triples in comparison to 78% with RC as the only variables in heating load PI. The additional increase on PI and actual load is caused by WFR. In site EUI, the increase on the PI shows a similar pattern with the increase rate of around 25%. Full list of the heating load and cooing load impact by WFR of 7 simulated building types in Chicago is listed in table 11.

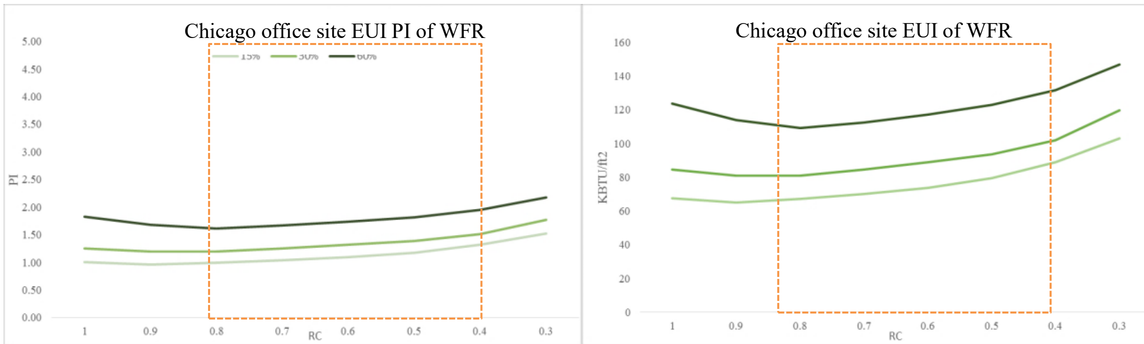


Figure 27- Cooling load, heating load, Site EUI PI by WFR and RC of office building in Chicago

Table 11- Percentile change of cooling and heating loads by WFR

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail (strip mall)	96%	86%	182%	95%
Clinic	48%	48%	100%	80%
High School	47%	47%	95%	73%
Hotels	60%	60%	123%	120%
Multifamily	149%	107%	49%	49%
Office	120%	120%	125%	107%
Warehouse(15% WFR only)	176%	0%	69%	0%

The building type represents different usage profile, including operational schedule, lighting requirement and thermal condition requirement. Besides, the climate type could also change the energy usage and thermal demand profile. The data provides solid evidence that the increase of the WFR leads to thermal load and energy intensity. However, the amount of increase and sensitivity of increase varies based on the building types and climate types.

Figure 28 present WFR performance in cold vs hot and low vs high internal load. The 6 figures present the biggest energy performance difference between 3 WFRs when it is in a different location and under builidng types. Regardless of the climate and building types, there are several features remain consistent, 1> the WFRs always have a bigger impact when the building form is compact; 2> the energy consumption always rises with the increase of the window area. Overall, the PI in a hotter and high internal load condition shows a minimum change as the WFR changes and maximum change in cold and low internal load conditions.

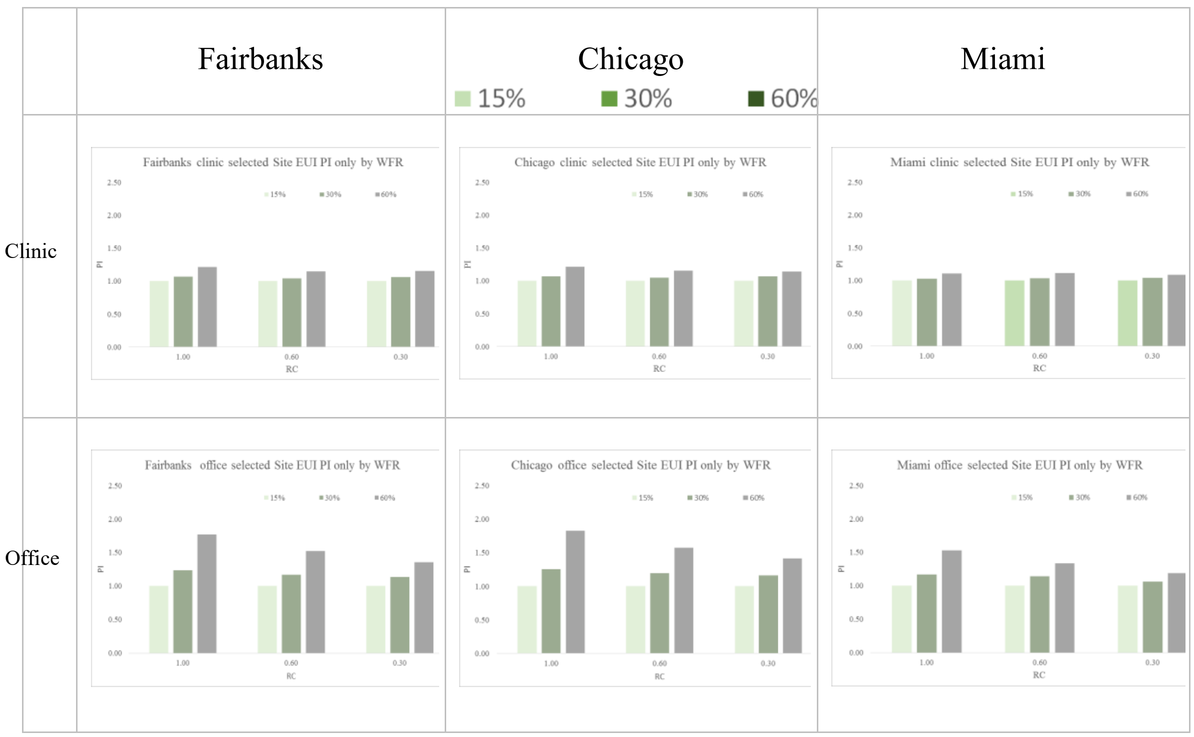


Figure 28 Site EUI PI comparison between 3 WFRs under different building type and climate zones

4.4 Performance of window distribution

Due to the setting of the simulation, the total glazing area remains the same, but the surface area to enclose a massing of each side is different. Therefore the window area on each surface could be bale to contain is also different. To make sure the analysis being rigorous, the analysis in this step will be still conducted in tree aspects, the impact on the building massing performance, and the window distribution performance by RC.

4.4.1 The impact on building massing performance

The performance of the Relative Compactness (RC) is also impacted by the window distribution. In this step, the calculation will be the ratio 2 PIs instead of the actual loads or EUI to examine the impact of window distribution to the massing performance. When comparing the PIs, additional noises have been eliminated while approaching the PI. To use the office building in Chicago as the example, the even distribution per surface area is treated as the baseline, and the orientation are normalized.

$$Impact = PI(design\ massing)/PI(baseline\ massing)$$

$$PI\ design = f(RC = a; WFR = b; oreintation = c; \boldsymbol{win.dist.} = \boldsymbol{x};)$$

$$PI\ baseline = g(RC = a; WFR = b; oreintation = c; \boldsymbol{win.dist.} = \boldsymbol{even};)$$

$$a, b, c = constant$$

Example:

Design building form of RC=0.3, with 2,400 sq. ft. window area with south side window redistributed to other three surfaces, with an azimuth angle of 0. The PI of this building massing is 2.95.

Baseline building form of RC= 0.3, with 2,400 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0. As, baseline, the PI of building massing is 3.05.

The impact will be the PI of the design case is 2.95/3.05 = 0.91

As the building massing is becoming less compact, the impact by the window distribution deviates from the baseline up to around 48%. The impact on building massing heating performance by window distribution starts to drop down when the RC is lower than 0.5. When the compactness decreases, the surface is increasing while the total window area remains the same, therefore, when the wall surface increase goes beyond a threshold the impact by window area will start decrease in comparison to the total heat transmission through a solid portion of the surface. Based on the analysis in section 4.2, the results here is expected as the heating load is always more sensitive in response to the change of the massing overall.

The redistribution of west side windows shows the highest impact on the heating and cooling load performance of the building massing. In the chapter 4.4.1, none of the results indicates the actual performance of the window distribution rather its impact on the performance of the building masing (RC).

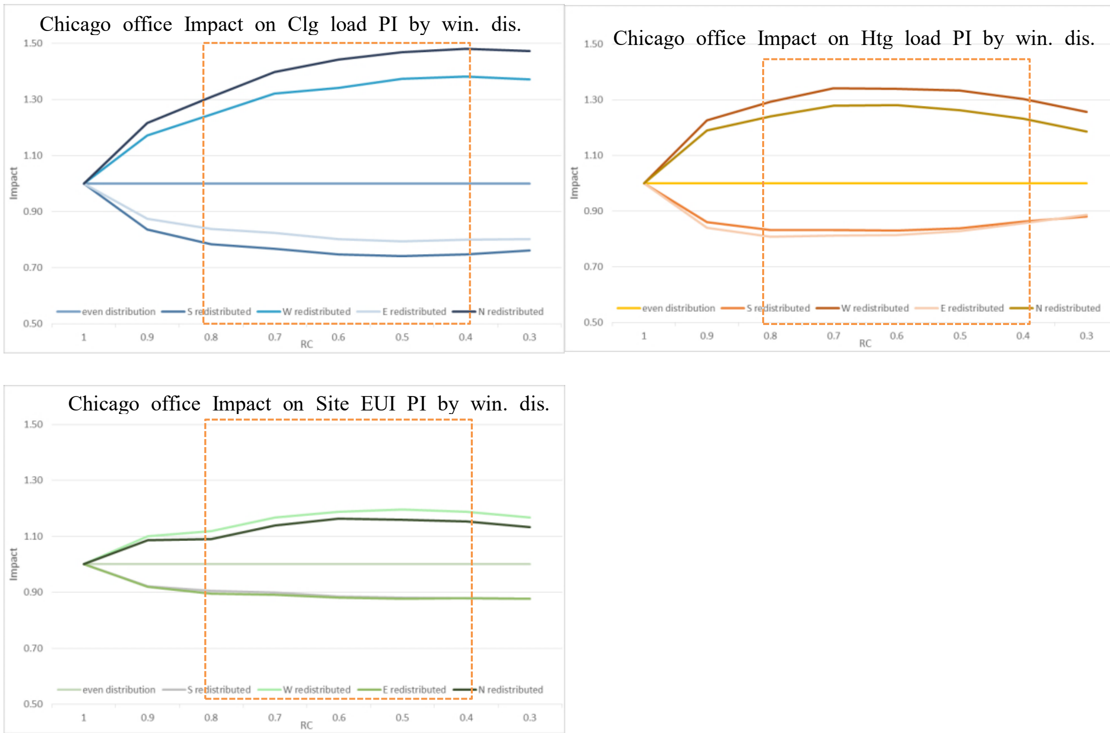


Figure 29- Orientation impact on RC in cooling and heating load and site EUI PI

The impact on the Site EUI PI of RC by window distribution follows the similar trend as heating and cooling load PI with a smaller quantity. The impact caused by south and east window re-distribution is almost identical. When zoomed into the RC range from THE WEIDT GROUP database, the impact on the certain side of redistribution remains fairly stable.

4.4.2 Performance evaluation of window distributions

When designing the performance of different window distribution methods, the only fixed value in the baseline is evenly distributed windows.

The performance Index (PI) calculation in this layer of analysis is:

$$PI = \frac{E\ design}{E\ baseline}$$

$$E\ design = f(RC = a; WFR = b; oreintation = c; \boldsymbol{win.dist. = x};)$$

$$E\ baseline = g(RC = a; WFR = b; oreintation = c; \boldsymbol{win.dist. = even};)$$

$$a, b, c = constant$$

Example:

Design building form of RC=0.6, with 4800 sq. ft. window area with south side window redistributed around four vertical surfaces, with an azimuth angle of 0,

Baseline building form of RC=0.6, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0

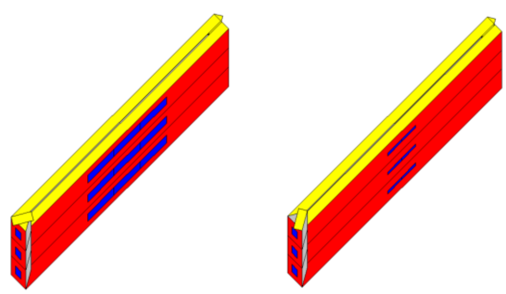
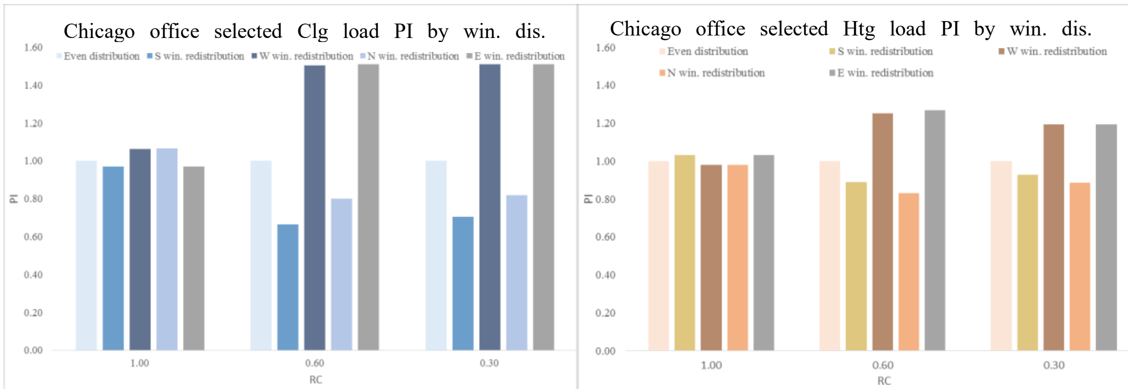


Figure 30- Baseline (left) vs. design case (right)

The graphs show that with smaller south or north windows, it could mitigate both cooling and heating of office buildings in Chicago. With small south side window, it could be in cooling load performance with 26% reduction when the RC is 0.3, while the redistribution of the north window could only reduce the cooling load PI by 17% when the RC is 0.3. Meanwhile, in heating load PI, the redistribution of South window reduces the PI by 10%, and the redistribution of the North window show 13% reduction. As building becomes less compact, the influence in cooling and heating load PI change by the window distribution increases, as the exposed surface area and the associated heat transfer brings a higher impact on the building energy usage.



Chicago office Impact on Site EUI PI by wind dis.

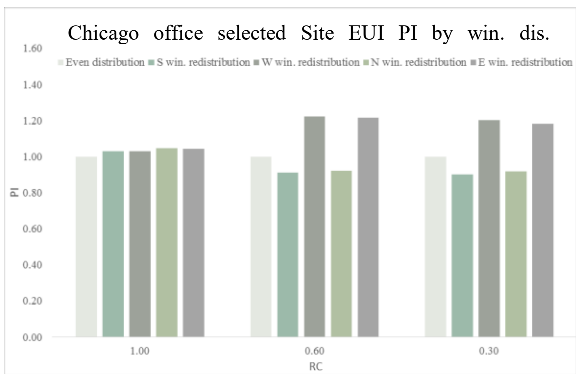


Figure 31- Selected analysis on cooling and heating load and site EUI PI by window distribution of office in Chicago

4.4.3 Performance evaluation of the window distribution and RC

When comparing the performance of building orientation along RC, the baseline should have RC as 1 besides evenly distribute the window area as part of the baseline.

The performance Index (PI) calculation in this layer of analysis is:

$$PI = \frac{E\ design}{E\ baseline}$$

$$E\ design = f(\boldsymbol{RC} = \boldsymbol{x}; WFR = a; oreintation = c; \boldsymbol{win.dist.} = \boldsymbol{x};)$$

$$E\ baseline = g(\boldsymbol{RC} = \boldsymbol{1}; WFR = a; oreintation = c; \boldsymbol{win.dist.} = \boldsymbol{even};)$$

$$a, c = constant$$

Example:

Design building form of RC=0.6, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0,

Baseline building form of RC=1, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0.

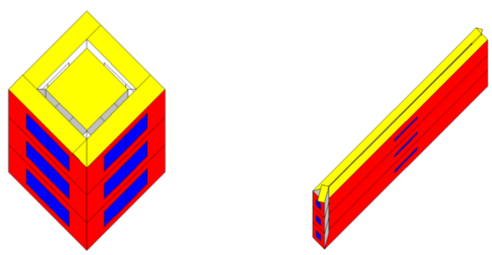


Figure 32- Baseline (left) vs. design case (right)

Comparing cooling and heating load PI, the window distribution plays a bigger role in changing the cooling load up to 42% from the baseline. Along the range of RC, the loads keeps increasing when building massing become less compact. This pattern is broken when zooming in a certain combination of window distribution and RC. Demonstrated in the future, when RC is 0.8 with north window redistribution (small north window), the cooling load PI and load is higher than the case with RC is 0.7 with south window redistribution (small south window). Therefore the amount of excessive load by less compact building massing could be mitigated by well-designed window distribution.

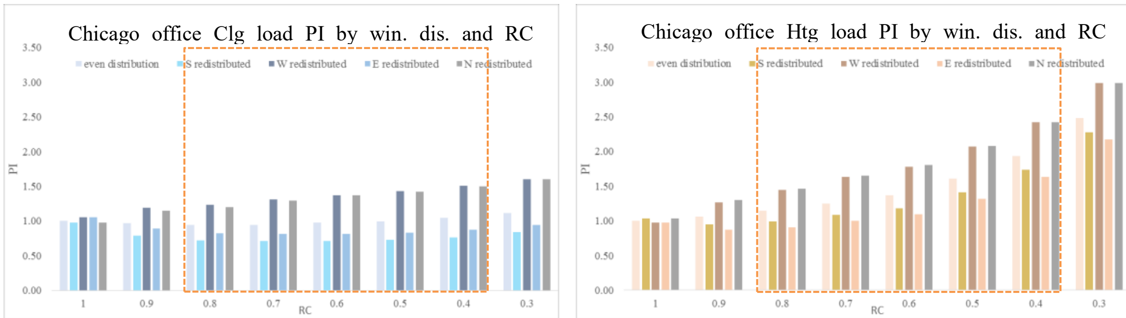


Figure 33- Cooling and heating load and PI by window distribution and RC of office building in Chicago

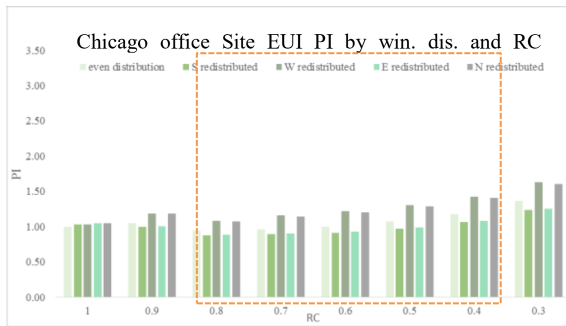


Figure 34- Site EUI and PI by window distribution and RC of office building in Chicago

By evaluating Figure 33-34, it is found the relationship between 5 window distribution methods remains consistent under each RC. The best to worst performance is ranked with a smaller south window, smaller north window, evenly distributed, smaller Easter winter and smaller west window, which reveals the hierarchy of locating windows in early design process.

To further validate the results, the research is carried to check Peak loads extracted from DOE-2 SIM files. Peak load can be important in impacting the sizing of the system and further impact on the system efficiency or relate costs. Figure 35 reveals the peak load trend between 5 window distribution methods remains the same with loads.

It further secures the design hierarchy of the window distribution can be concluded from Figure 34 site EUI performance index.

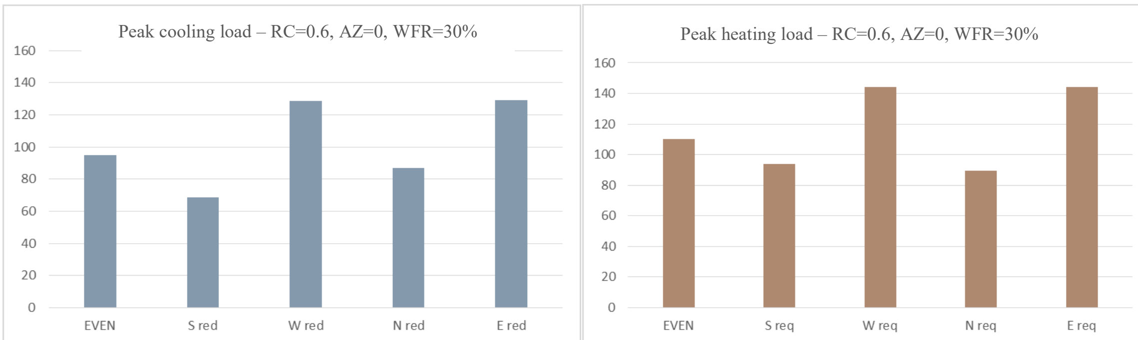


Figure 35- Heating and cooling peak load by window distribution when RC is 0.6 with elongated S-W axis and 30% of WWR

In an office building in hotter climate, the performance difference between 5 window distributions is significantly bigger in comparison to the results in colder area. In phoenix, When RC is 0.3, the east or west window redistribution could cause 50% increase on the site EUI, and the south and north window redistribution with smaller impact could also increase lower the site EUI by 25%.

Table 12- Percentile change of cooling and heating loads change by window distribution

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail	79%	78%	89%	79%
Clinic	43%	41%	59%	58%
High School	42%	42%	58%	58%
Hotels	54%	49%	68%	68%
Multifamily	116%	108%	29%	29%
Office	99%	92%	67%	67%

Table 12 continued

Warehouse	132%	9%	195%	4%

Window distribution directly impacted on the solar radiation, which is also associated with the climate. It is shown in Appendix D, and the window distribution is more influential in a colder climate and low internal load building types. The overall difference among 5 different distribution methods remains the similar pattern regardless of climate zones and building types.

Figure 36 - Site EUI PI comparison between 5 window distributions under different building type and climate zones

4.5 Performance of Building orientation

As it is explained, these building orientation variables have 2 intervals, when Azimuth is 0 with N-S elongated axis, and azimuth is 90 with W-E elongated axis. The geometric dimension is described in Table 4, and the roof surface remains unchanged in both cases. This variable will explore when the total wall surface is certain, should architect maximize North and South or East and west wall. How much of building orientation could impact on then energy performance on multiple levels. As another secondary variable, the building orientation could also be analyzed from three aspects the impact on the RC, individual performance and the performance along with its carrier RC.

4.5.1 Building orientation impact on Relative Compactness (RC) performance

This section tests how the Relative Compactness (RC) performs will be impacted by different orientation, and it doesn't include actual orientation performance.

Similar to the WFR, the Impact is a ratio of two PIs. When comparing the PIs, additional noises have been normalized while approaching the PI.

$$Impact = PI(testing\ massing)/PI(baseline\ massing)$$

$$PI\ testing = f(RC = a; WFR = b; \boldsymbol{oreintation(az) = 0}; win.dist. = c;)$$

$$PI\ baseline = g(RC = a; WFR = b; \boldsymbol{oreintation(az) = x}; win.dist. = c;)$$

$$a, b, c = constant$$

Example:

Design building form of RC=0.6, with 2400 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 90. The PI of this building massing is 3.07.

Baseline building form of RC= 0.3, with 2400 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0. As, baseline, the PI of building massing is 3.05.

The impact will be the PI of the design case is 3.07/3.05= 1.01

In Figure 37, the result reveals that the cases with AZ=90, or elongated west and the east surface shows a higher impact on the building massing performance in cooling load, heating load, and Site EUI. Comparing the impact on cooling and heating load PI of RC, it is found the building orientation will cause higher impact in cooling load performance of the building massing. In heating load side, the building orientation almost shows no impact on the performance of the building massing compactness level. In hotter climate, such as Phoenix, the impact on the cooling load performance remains the similar trend, but heating load performance shows the opposite results, which the massing with AZ of 90 shows the impact on the building massing performance lower than 1.

In comparison to 17% of deviation from the baseline in the cooling load PI impact, the design cases only present less than 4% on the heating side. The overall trend of the heating and cooling remains the same. The overall impact by orientation on the massing performance index is quite small compared to WFR with less than 7%.

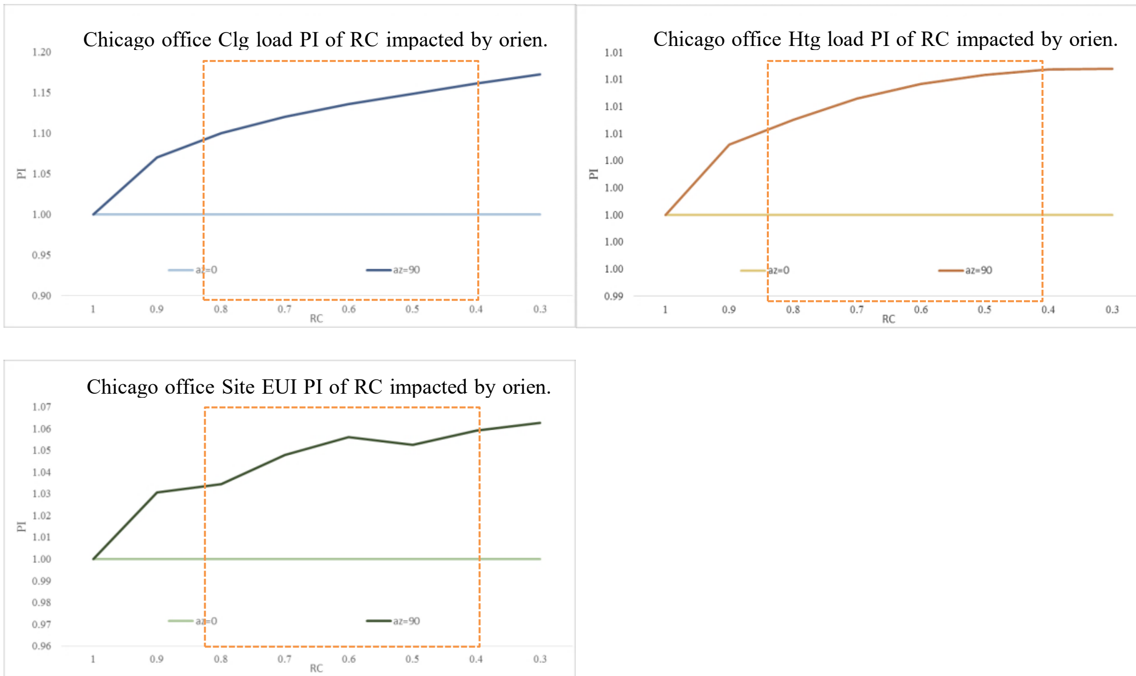


Figure 37-- Orientation impact on RC in cooling and heating load and site EUI PI

4.5.2 Performance evaluation of the orientation

When analyzing the performance of just WFR, the RC is held the same so the results of two orientations could be comparable. Similar to the analysis to WFR, the RC is a constant number in analyzing the individual performance index of the building orientation. When RC equals to 1, the design case are orientation neutral.

The performance Index (PI) calculation in this layer of analysis is:

$$PI = \frac{E\ design}{E\ baseline}$$

$$E\ design = f(RC = a; WFR = b; \boldsymbol{oreintation} = \boldsymbol{x}; win.dist. = c;)$$

$$E\ baseline = g(RC = a; WFR = b; \boldsymbol{oreintation} = \boldsymbol{0}; win.dist. = c;)$$

$$a, b, c = constant$$

Example:

Design building form of RC=0.6, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with azimuth angle of 0,

Baseline building form of RC=0.6, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with azimuth angle of 0.

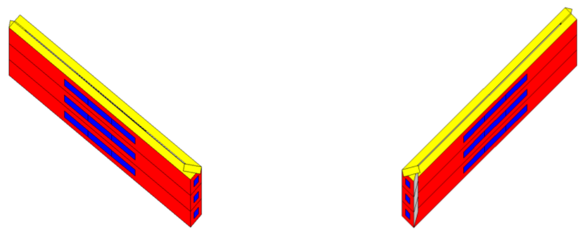


Figure 38- Baseline (left) vs. design case (right)

When RC drops, the PI of AZ = 90 with elongated west and east façade always shows a higher performance index against the AZ of 0 with elongated south and north facade. The difference between these two orientations becomes bigger when the compactness is smaller, but the difference is always within 25% as shown in Figure 39. It doesn't include the effect of the RC, as the comparison between the design case and baseline is always controlled to have the same RC.

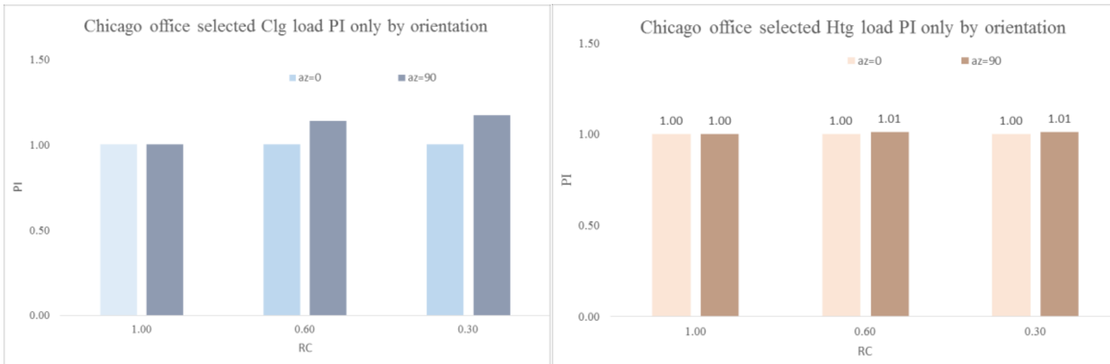


Figure 39 -Selected RC analysis on cooling and heating load PI by orientation of office building in Chicago

In heating load PI, when AZ changes from 0 to 90, the result are almost identical, with a slight difference with actual digits marked in Figure 39. The major reason for this result is the heating transmission during winter is mostly through conduction, and the solar radiation could alleviate the heating load minimally. In Chicago, the solar intensity during winter is not as intensive, therefore and the solar radiation plays a smaller role in determining the thermal load. While in hotter climate zone like Phoenix, the heating load in office building actually shows decreases when the building has elongated west and east façade. During cooling season, the elongated west and east façade shows worse performance in Phoenix similar to Chicago. In Phoenix where the heating load is significantly smaller, the heating load can be mitigated through the radiation especially during swing season, and this effect will be more observable in Chicago office building where the heating load is high enough to neglect this effect. The elongated West-East axis building massing shows worst performance in both heating and cooling season in Chicago.

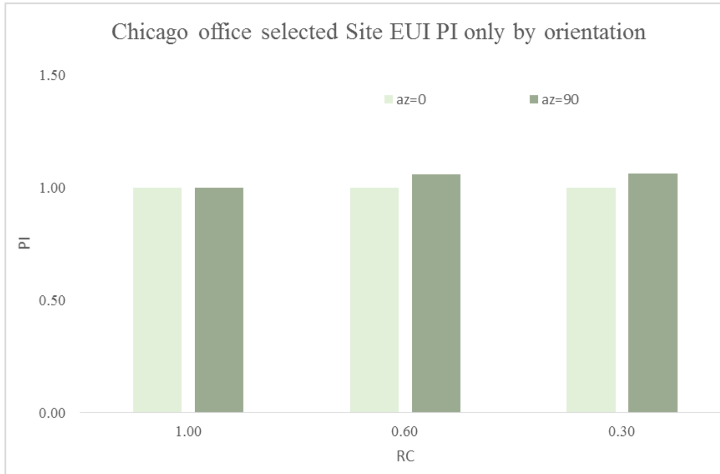


Figure 40- Selected RC analysis on site EUI PI by orientation of office in Chicago

In site EUI of office buildings in Chicago, the impact by the building orientation has been levelized by cooling and heating load PI. In the PI (left) side, the comparison doesn't relate to RC, therefore the PI of AZ=0 is also 1. From the actual EUI (right side), it can found that the change between two orientations is becoming bigger as the massing becomes less compact. It reveals that the orientation impact on the Site EUI PI more when the building is less compact.

4.5.3 Performance evaluation of the building orientation and RC

The performance Index (PI) calculation in this layer of analysis is:

$$PI = \frac{E\ design}{E\ baseline}$$

$$E\ design = f(\boldsymbol{RC} = \boldsymbol{x}; WFR = a; \boldsymbol{oreintation} = \boldsymbol{y}; win.dist. = c;)$$

$$E\ baseline = g(\boldsymbol{RC} = \boldsymbol{1}; WFR = a; \boldsymbol{oreintation}(\boldsymbol{AZ}) = \boldsymbol{0}; win.dist. = c;)$$

$$a, c = constant$$

Example:

Design building form of RC=0.6, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 00,

Baseline building form of RC=1, with 4800 sq. ft. window area and evenly distribute around four vertical surfaces, with an azimuth angle of 0.

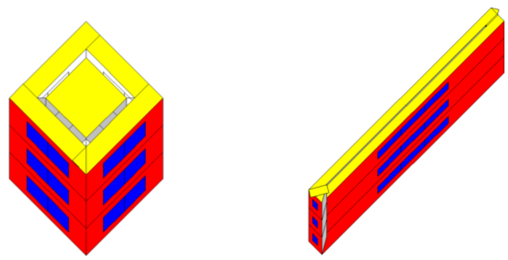


Figure 41- Baseline (left) vs. design case (right)

When anayzling the PI for the building orientation along the RC, we can tell that the cooling PI of office buildings in Chicago along RC from 1 to 0.3, has only rise by 30% in cooling load PI. Heating load PI on the other hand, rise around 160% under unconstrained condition. With RC decreasing with more surface area, the difference in both heating and cooling load and PIs by re-orientating the building massing is becoming more obvious. The fundamental difference between 2 orientations is the amount of the radiation the surface could receive.

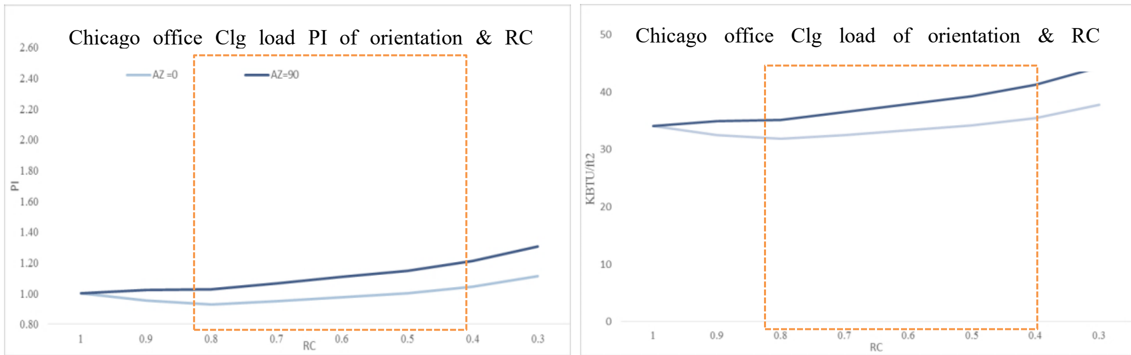


Figure 42- Cooling load and PI by orientation and RC of office building in Chicago

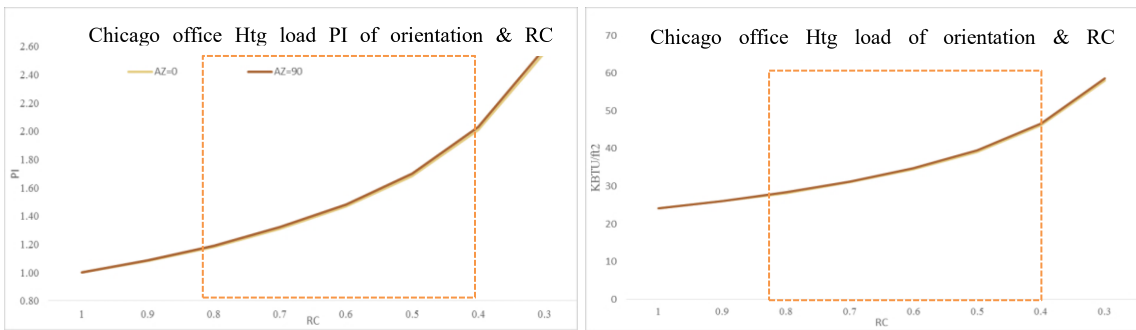


Figure 43- Heating load and PI by orientation and RC of office building in Chicago

In site EUI PI, the similar trend could be found in all locations and building type with only quantity differences. In a hotter climate, the orientation of the building obviously plays a bigger role in the impact the thermal load. For example in Phoenix office building, the site EUI will increase by 18% when the design case has RC of 0.3 with elongated west and east façade oppose to the baseline. When AZ is 90, the site EUI of same building form will only change 5% in Chicago for an office building. In the design process, architects need to be conscious of the surface are of east and west façade, especially in the cooling dominant area.

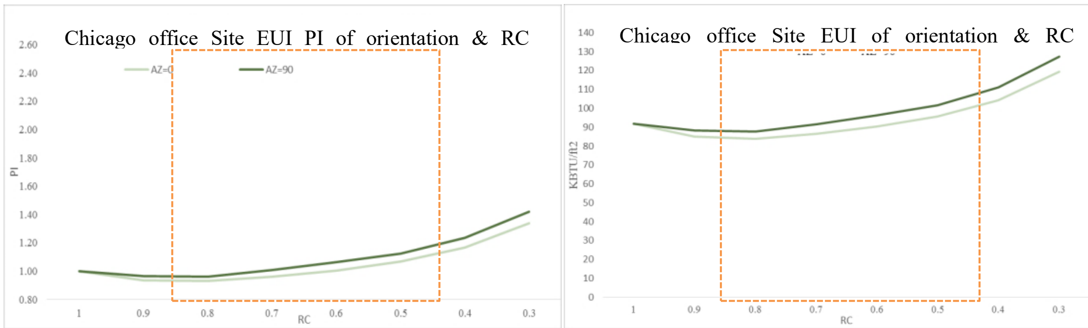


Figure 44- Site EUI and PI by orientation and RC of office building in Chicago

Table 13- Percentile change of cooling and heating loads change by building orientation

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail(strip mall)	14%	13%	14%	13%
Clinic	9%	7%	1%	1%
High School	8%	8%	1%	1%
Hotels	11%	8%	2%	2%
Multifamily	17%	15%	1%	1%
Office	17%	16%	1%	1%
Warehouse(15% WFR only)	21%	1%	1%	0%

As it has been explored, the building orientation is not sensitive to changing the building energy performance. This could be applied to all tested locations and building types. Besides, when AZ=0 with elongated south and north facade, the PI is always smaller regardless of the building type and climate type. In all locations and building types, the orientation could impact on energy performance more as the building becomes less compact.

Figure 45 Site EUI PI comparison between 2 building orientations under different building type and climate zones

4.6 Performance of building form

From the analysis of section 4.2 to 4.5, it is clear that building massing, window sizes, window distribution and orientation are interactive in terms of its role in energy use. This section examines how much load and energy usage intensity the building form as a whole could impact with other simulation variables held with “ASHRAE 90.1” 2010 baseline.

When comparing the performance of building form a whole, the baseline should have every variable fixed with its own absolute baseline. There is only one single baseline compared to rest 239 cases in certain climate zone and building types.

The performance Index (PI) calculation in this layer of analysis is:

$$PI = \frac{E\ design}{E\ baseline}$$

$$E\ design = f(\boldsymbol{RC = w; WFR = x; oreintation = y; win. dist. = z;})$$

$$E\ baseline = g(\boldsymbol{RC = 1; WFR = 15}\%\boldsymbol{; oreintation(AZ) = o; win. dist. = even;})$$

As the Table 14 shows, the site and source EUI could be impacted by the building form greatly when comparing to the absolute baseline in this research. Architectural design is a practice with plenty of uncertainty and flexibility, and it is difficult to set a realistic boundary of all 4 design variables in this phase. The realistic range shown in Table 14 is only with the boundary of RC from THE WEIDT GROUP database except for the warehouse has one addition retraction of WFR of 15% only. It proves that the architectural design could greatly impact on then building energy usage with key design elements in academic research. It is necessary to conduct further study to compare the building form against another aspect in a building to further evaluate if modifying design is rational in a multi-criterion decision process.

Table 14 Percentile change of cooling and heating loads change by building form

	Unconstrained Cooling Load Change	**Constrained Cooling Load Change**	**Unconstrained Heating Load Change**	**Constrained Heating Load Change**
Retail (Strip mall)	286%	263%	533%	286%
Clinic	143%	129%	422%	239%
High School	136%	136%	396%	279%
Hotels	183%	161%	546%	353%
Multifamily	529%	494%	302%	190%
Office	439%	412%	534%	333%

Table 14 continued

Warehouse (15% WFR only)	708%	37%	393%	100%

Table 15- Percentile change of Site and source EUI percentile change by building form

	Unconstrained Site EUI change	Constrained Site EUI change	Unconstrained Source EUI change	Constrained Source EUI change
Retail (Strip mall)	152%	105%	143%	119%
Clinic	64%	57%	53%	47%
High School	82%	75%	87%	80%
Hotels	74%	58%	95%	76%
Multifamily	115%	85%	126%	104%
Office	206%	170%	163%	141%
Warehouse (15% WFR only)	206%	70%	229%	51%

4.6.1 Comparison of energy performance impact by 4 elements in different conditions

As the total energy consumption increases when the climate becomes colder, the energy performance impacted by each element could be potentially different. However, the energy saving potential of each element shouldn't be overlooked. Appendix D presents the energy performance difference by climate zones and building types.

4.7 Building form extract for phase II study

In phase I, 242 different building forms are tested in each climate zone and building type. It is redundant to bring all of the test samples into phase 2 to compare with other strategies. In addition, due to the nature of space usage by different building type, it is impractical to force all building types to be compared to the same building forms. For instance, it is rare for a warehouse to design the window to floor ratio to 60%, but it could be easily achieved by an office building. Therefore, the best, median and worst performed building forms are extracted as shown in Table 16 into phase II to continue the study.

Table 16 Extracted building forms for phase II

Best Building Form							
	RC	AZ	WFR1	WFR2	WFR3	WFR4	Window area
retail	0.5	0	6%	6%	1%	6%	2400
clinic	0.5	0	1%	12%	12%	12%	4800
high school	0.6	0	1%	8%	8%	8%	2400
hotel	0.8	0	1%	12%	12%	12%	2400
multifamily	1	0	15%	15%	15%	15%	2400
office	0.7	0	10%	10%	1%	10%	2400
warehouse	0.7	0	9%	9%	9%	9%	2400
Median Building Form							
	RC	AZ	WFR1	WFR2	WFR3	WFR4	window area
retail	0.5	90	12%	12%	12%	12%	4800
clinic	0.5	0	11%	1%	11%	1%	2400
high school	0.6	0	27%	27%	27%	2%	4800
hotel	0.7	0	4%	38%	38%	38%	9600
multifamily	0.8	0	4%	47%	47%	147%	9600
office	0.5	90	12%	12%	12%	12%	4800
warehouse	0.5	0	6%	6%	6%	6%	2400

Table 16 continued

Worst Building Form							
	RC	AZ	WFR1	WFR2	WFR3	WFR4	Window area
retail	0.5	0	6%	6%	1%	6%	2400
clinic	0.5	0	1%	12%	12%	12%	4800
high school	0.6	0	1%	8%	8%	8%	2400
hotel	0.8	0	1%	12%	12%	12%	2400
multifamily	1	0	15%	15%	15%	15%	2400
office	0.7	0	10%	10%	1%	10%	2400
warehouse	0.7	0	9%	9%	9%	9%	2400

CHAPTER 5. THE SIMULATION SET UP OF PHASE TWO

5.1 Simulation workflow

In phase two, the simulations and analysis focus on the relationship of building form and other major inputs categories in an energy modeling representing several major consulting team members including mechanical engineers, electrical engineers, and contractors. The energy saving strategies most frequently applied in a whole building energy simulation process from each of the members will be analyzed in details to understand the energy saving potential.

For mechanical related strategies, it includes 1> system types, 2> cooling efficiency, 3> heating efficiency, 4> heat recovery; for electric related input, it includes 1> lighting power density, 2> occupancy sensor control, 3> dimming daylighting control; For building envelope related input, it includes, 1> Wall R-value, 2> Roof R-value, 3> Glazing U-value 4> Glazing SHGC. Other simulation variables will be set as constant by "ASHRAE 90.1-2010" to form a complete building energy model. As these strategies could impact on building energy consumption from multiple aspects, the actual site and source EUI will be applied as the major measures in phase two. The system type will fundamentally change the fuel source, which could reveal a completely different conclusion when the analysis is carried to the source EUI level.

5.2 Choose the simulation variables

For each of the variable, the definition of the boundaries is directly impacted on the energy saving results of the strategies. With the phase I simulation, the best, medium and worst performed building form variables of each building type is extracted as explained in chapter 4.7. It greatly reduced the amount of simulation runs that carries to the phase two study. In phase two, the simulation variables are not set in a consecutive approach, as the evaluated variables in consulting practice are set based on several standards. Evaluating several critical performance levels of these variables would cover a wide range of the possible results, which is sufficient to the purpose of this study. It would also significantly reduce the amount of the simulation runs in phase II.

Based on EIA database, more than 32% of existing building are built around 1980 - 1990s (U.S. Energy Information Administration 2012). These buildings are built with "ASHRAE 90.1"-1989" Standard or similar level of efficiency. Meanwhile, these buildings were built at a faster pace and lower quality, which potentially require a certain level of renovation and retrofit. Therefore, "ASHRAE 90.1"-1989" standard are used as the lowest limits for each evaluated strategy. "ASHRAE 90.1-2013", on the other side, represents many of current advanced standard in energy efficiency. In 2015, Jason Glazer published a new technical report revealing the maximum technology (Glazer 2015). Therefore, the upper limit of each strategy is chosen either based on "ASHRAE 90.1-2013" or Glazer's report. Each of the strategies has different potential in conserving energy within the testing ranging from the nature of the setting of this analysis and practice.

The following section introduces detailed/numeric input of each strategy:

1> Mechanical section

Besides ASHRAE Appendix G, System types are difficult to be identified simply by a standard. Three commonly used systems are chosen based on thousands of finished projects at The Wedit Group with multiple utilities covering a wide territory in the U.S. These systems are 1> constant volume Package Single Zone with gas furnace for heating and DX for cooling; 2> Variable Air Volume system has gas furnace for heating and DX for cooling; 3> Water Source Heat Pump as an all-electric system with zone electric supplemental heating. The cooling and heating efficiency are both coming from a different version of "ASHRAE 90.1" standards. The AHSRAE 90.1-2013 code is quite stringent, which is rarely implemented by any state level regulations. Certain strategies are derived from best strategies in Jason Glazer's paper (Glazer 2015). For the heat recovery, it took 75% effectiveness of both sensible and latent heat from the exhaust air streams to the unconditioned ventilation air. This is typically accomplished using an enthalpy wheel or permeable membrane cross-flow heat exchanger.

Table 17. Details of Mechanical strategies selection

			Worst	Medium	Best
System type	Package Single zone (Gas Furnace and DX cooling)	Cooling efficiency	8.5 EER	11.0 IEER	12.0 IEER
		Heating efficiency	72% AFUE	78% AFUE	82% AFUE
	Variable Air Volume (Gas furnace and DX cooling)	Cooling efficiency	8.5 EER	11.0 IEER	12.0 IEER
		Heating efficiency	72% AFUE	78% AFUE	82% AFUE
	Water source heat pump connecting	Cooling efficiency	10.5 EER	16.3 EER	22.68 EER
		Heating efficiency	10.5 EER	16.3 EER	22.68 EER
Heat recovery			No	Refers to "ASHRAE 90.1" 2010	100%

2> Electrical strategies

Reduce electric lighting energy through appropriate lighting equipment selection and layout. Occupancy sensor control is for lights to be on when no one is present for periods throughout the day. A wall switch is still required to allow occupants to turn lights off when space is occupied. Dimming Daylighting Control Systems uses interior photo-sensors to control electronic dimming ballasts that gradually dim or brighten lamps within the daylight zone. This system can be transparent to the building occupant since the dimming system continuously maintains the designed light levels without switching lamps on or off.

Table 18 - Details of Electrical strategies selection

	Worst	Medium	Best
Lighting power density	"ASHRAE 90.1" 1989	"ASHRAE 90.1" 2010	30% of "ASHRAE 90.1" 2013
Occupancy sensor control	No	ASHRAE 2010 standard	100%
Dimming Daylighting control	No	ASHRAE 2010 standard	100%

3> Envelope strategies

The envelope insulation strategies incorporate additional insulation to the roof and walls of the building. The insulation R factors listed in the table below are overall average thermal resistance values of the entire wall or roof assembly, accounting for 1> Effects of thermal bridging of structural elements (studs, joists, columns, etc.), 2> Average thickness of tapered roofs, 3> Average for multiple wall or roof assemblies, 4> Exterior and interior finishes and air films.

Table 19 Details of Envelope strategies selection

	Worst	Medium	Best
Glass U-value	ASHRAE 90.1-1989	"ASHRAE 90.1"-2010	20% of "ASHRAE 90.1-2013"
Glass SHGC	0.35	0.25	0.2
Roof insulation	R-15	R-20	R-40
Wall insulation	R-10	R-15.6	R-25

CHAPTER 6. RESULTS ANALYSIS OF PHASE TWO

6.1 Analysis logic and procedure

This chapter focuses on analyzing the result of the phase two simulation. The analysis flow and structure will be outlined with 2 layers. It will reveal the energy saving potentials of multiple strategies. At the same time, it will analyze how strategies perform differently under 3 different building forms. The simulation is structured under a whole building level analysis. The strategies chosen in this research could potentially mitigate thermal loads and/or actual energy usage. Therefore, the Site and Source EUI savings will be used as the performance measure in this chapter. The actual energy saving and usage are also potentially dependent on the size of the building, which is not considered as one variable in this study. The difference of energy usage between 2 efficiency levels of each strategy provides a more streamlined comparison. It is vital to emphasize that setting of all strategies are analyzed under the framework of "ASHRAE 90.1-2013"(or Glazer's paper) and 1989, and each strategy doesn't necessarily have the same capacity in reducing energy usage based on neither version of the ASHRAE Standard. The results should be understood as a set of comparative analysis, which outlines the relative savings potentials among these strategies. The energy usage results for each individual case need a further simulation to accurately present the detailed energy saving components. This section of this research provides a high level understanding of energy saving potential and consumption distribution to an early design stage under a multi-aspect framework.

In the early design phase, the building form is always the top priorities to architects as it connects the project to its urban setting and contains the future interior function. To engineers, the mechanical system type has fewer uncertainties due to the budget, climate restrictions. The analysis and comparison will be conducted in three steps, 1> energy consumption by all potential strategies, 2> energy consumption by potential strategies under different building forms, 3> energy consumption by different mechanical systems. It provides possibilities for the design team to understand the performance difference between these strategies and optimize their strategy selection when the building form and mechanical system types have been determined. The analysis process is listed as the diagram below.

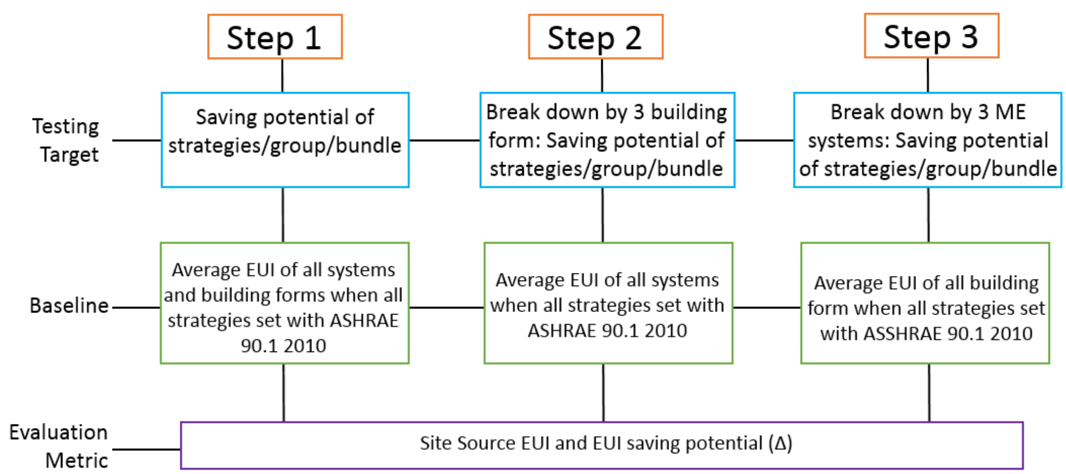


Figure 46-Analysis procedure in phase II

6.2 Performance analysis of all strategies based on technology choices

As it has been described in chapter 5, the simulation variable in phase II covers the interests from multiple energy saving strategies as concluded below. These strategies will be compared individually and also grouped together by different project team members to evaluated results.

Table 20 – Strategies, Group, and Bundle

Bundle	Group	Strategies
Combined effect (Bundle)	Architecture design (Building form)	Relative compactness(RC)
		Window Distribution
		Window Area(WFR)
		Building Orientation
	Mechanical Engineering	System Type
		Cooling Efficiency
		Heating Efficiency
		Heat Recovery
	Electrical Engineering	Lighting power density
		Daylighting control
		Occupancy control
	Envelop Property	Glazing U-value
		Glazing SHGC
		Wall R-value
		Roof R-value

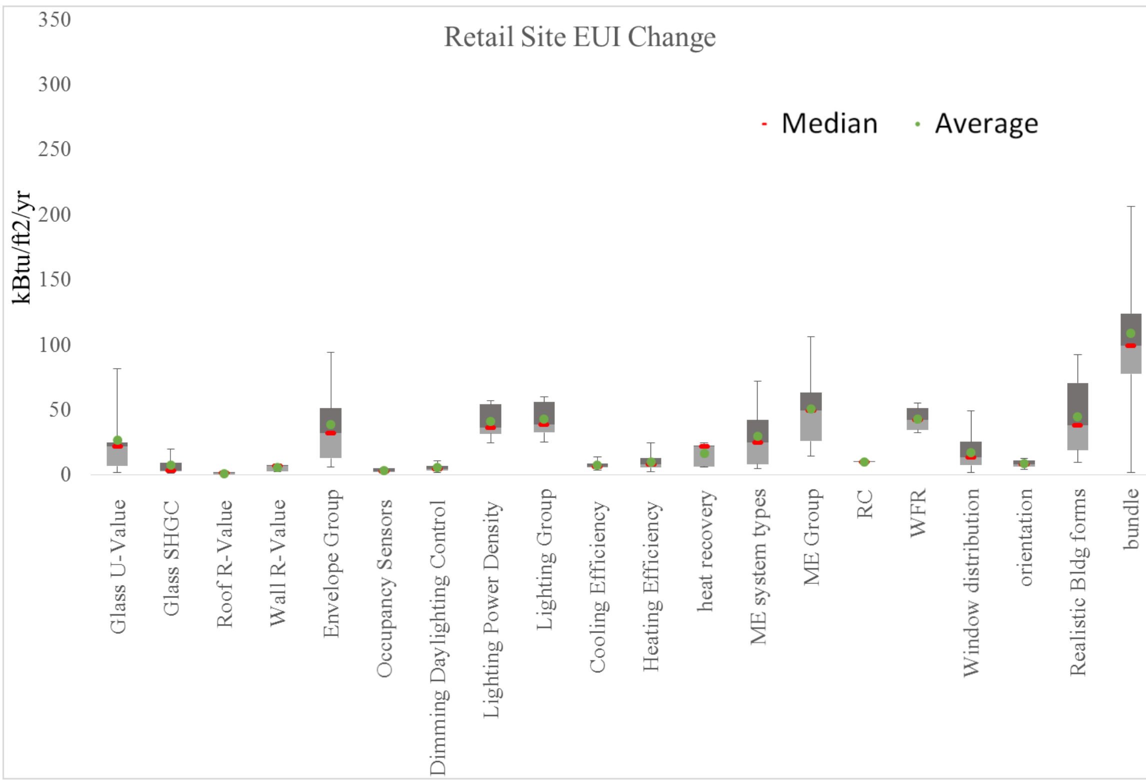
6.2.1 Performance comparison by strategy

As it has been explained in the previous section, the interactive energy saving of a group of strategies applied at one time is often different with the effect of the simple accumulation of all single strategies. It is important to understand the quality and quantity of the difference and how we could utilize the combined effect on energy usage of multiple strategies. This section examines how each single, grouped, or bundled strategies as listed in Table 20, could impact on energy saving effect; what are the typical combinations of the strategies that could maximize the energy saving potential.

The energy saving potential in this section is expressed as a difference of EUIs of best and worst strategy. In addition, the difference between E worst and E best should be the efficiency of the strategy.

$$\text{Energy Saving} = \text{E}\,worst - \text{E}\,best$$

6.3 Energy saving potential of strategy, group, and bundle



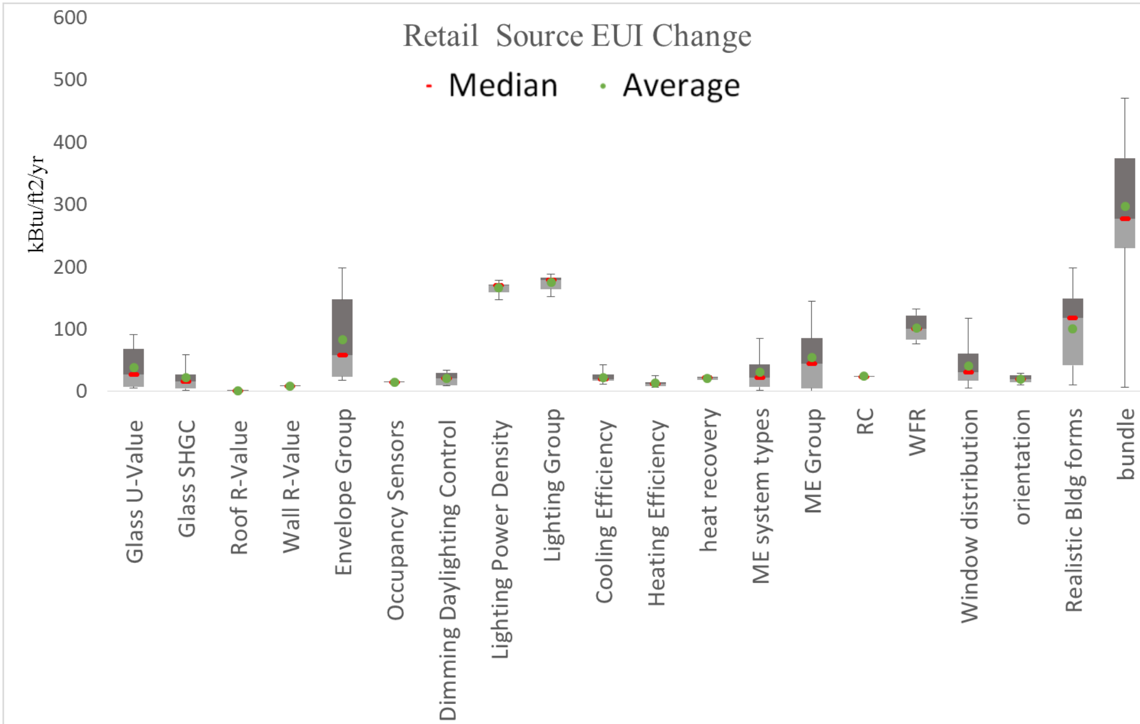


Figure 47 – Site and Source Energy saving potential of a retail building in Chicago

Figure 47 shows the overall energy saving potentials of the evaluated strategies for the retail space in Chicago. The energy saving penitential of building envelope group are mostly from the glazing U-value. Also, the glazing SHGC is another strategies that contributes to relatively high energy saving potential. The Glazing SHGC determines the solar radiation that is transferred through the glazing system. In Chicago as the heating dominant climate zone, the SHGC is actually increasing the heating load during the heating season. Improvement of the wall and roof R-value, doesn't have much saving potential as the ASHRAE code doesn't improve as much from 1989 to 2013. From the quartile distribution of each vertical bar, the single strategy performs quite consistently when other settings in the research change. The major saving from the envelope related strategies is realized by mitigating thermal load. Therefore, the accumulation of energy saving by each envelope related strategies are similar to the grouped effect in both Site and Source EUI.

When further zoom into the distribution of performance of each strategy, it is found that the top 25% of saving potential of glazing U-value could reach up to 88 kBtu/ sq. ft./yr. The common characteristics of these design cases are 1> low compact building form, 2> high WFR, and 3> running with Variable air volume system with zonal reheat. When the glazing insulation is reduced from "ASHRAE 90.1" 2013 to 1989 standard, the gas consumption could increase up to 303% by zonal reheat. In comparison, when this 3 conditions are changed to 1> high compact building form, 2> low WFR, and 3> running with Water source heat pump, the impact from improving the glazing U-value is lowered to only 1.67 kBtu/sq. ft./yr. It makes a huge difference when poorly-performed building forms and VAV system are integrated into one design. The more specific impact from these 3 elements will be studied in next sections.

The lighting control and lighting power reduction is relatively independent to other strategies besides impacting the thermal loads, as the lighting efficiency improvement is directly related to the electricity usage in addition to generating certain level of heat. From the results, it is observed that the Lighting related strategies don't have much variation in improving the energy saving when other conditions change the lighting technology has been improving rapidly. With long life span and a reasonable budget, the high efficiency LED fixture is widely applied in new construction and renovation projects, and the associated the internal heat generation will be reduced as one reason of energy usage reduction especially in hotter climate zone. Associated with the high efficiency of lighting systems, the energy saving from lighting control will be reduced.

The mechanical system is commonly understood as the major energy saving approach, also proved by the results of this research. It is found that the mechanical system type is the most influential single strategy under this group. Among 3 different chosen systems, both the VAV system and Package single zone system have the same fuel source. These 2 systems aren't necessarily more efficient than the other. It has multiple impact factors such as the operational schedule, and how other simulation variables trigger the heat balance calculation at the backstage of the simulation engine. The Water source heat pump connecting to a ground loop is fully electric, and the mechanism of the system determines it to be more efficient. However, the conclusion is only applicable at the Site EUI level, and the Source EUI saving may reveal a different aspect. From Figure 48, the energy saving of Water source heat pump presents a significant saving potential, and much lower energy consumption compare to the other 2 systems in Site EUI level. As it shifts to the Source EUI, WSHP system doesn't appear to have many advantages compare the VAV system. The highest Source EUI of the WSHP is 485.51 kBtu/sq. ft./yr when other simulation setting reached the worst possible combination, and it is even higher than VAV system when the rest of simulation setting reaches equally bad conditions. It explains that an all-electric system is not always more energy efficiency if the rubrics are Source EUI. This relationship may not be same when the building type and climate zone changes, which will be explored.

Meanwhile, the comparison is conducted on the average U.S. electricity conversion factor of 3.14 (ENERGY STAR® 2013). The results may also varies if the electricity generation are generated with different with different resource such or such as gas, coal, nuclear or renewables.

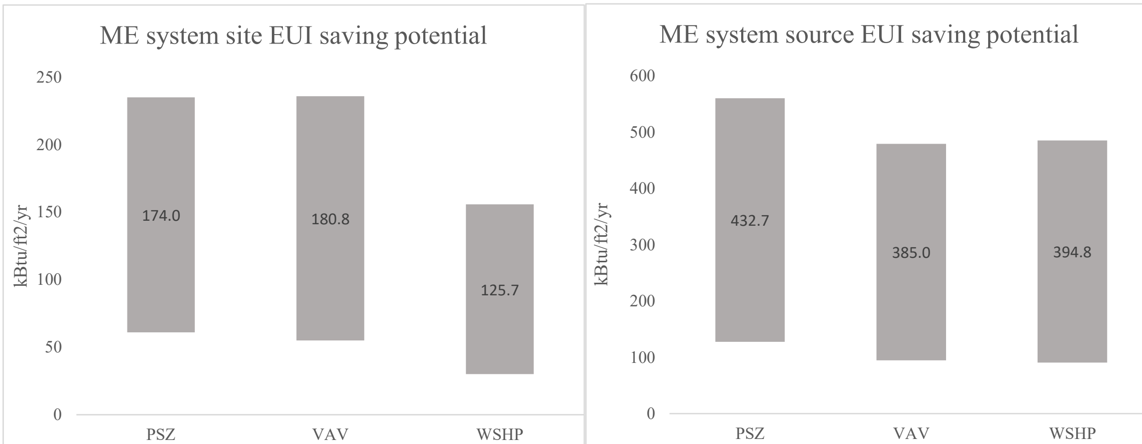


Figure 48 – Energy saving potential between Site and Source EUI between 3 systems of a retail building in Chicago

In Climate zone 5 Chicago, the research reveals that the improvement of heating efficiency will have more positive impact on energy saving. From "ASHRAE 90.1" standard, it is found the requirement to the efficiency improved for different systems hasn't been improved as much in the past "ASHRAE 90.1" Standard. Therefore, the saving by improving the efficiency is not significant due to the nature of the boundary setting. Heat recovery strategy is tightly related to the outside air requirement by building types. In a retail space in Chicago, the heat recovery strategy shows a decent amount of saving to the high outside air requirement. The energy saving distribution variation increases significantly when these strategies are combined together as a mechanical bundle, as these strategies are highly interactive. For instance, the heat recovery reduces the energy usage directly cooling heating, and weakens the effectiveness of cooling and heating efficiency.

Shown in Figure 47, when these strategies are compared against the building forms and its four components, it ties the phase I and II together. It reveals that the WFR could impact the energy saving potential tremendously. The average saving potential of the WFR is the highest by a single strategy. Besides, the window distribution also presents a high saving potential.

In Figure 47, the bundles of all four major categories are shown with tremendous variations. From the distribution of the bundle, the top and bottom quartile of the saving potential varies the most, and middle 50% of the simulation test presents a relative narrow variation and consistent savings. It needs to be emphasized that the energy savings potential doesn't represent low energy consumption. From Table 21, it reveals that the site EUI when the bundle is designed with the worst combination of the strategies when the building form is not well designed.

Shown in the table 21, as the efficiency of the strategies is improved, the site EUI of different building forms turn to be quite close, and the impact by the building form design is not as significant in terms of energy usage. This reduction is weakened if the system type turns to be more efficient in site EUI prospect such as the water source heat pump. The building must at least remain one good standing from either mechanical system type, system efficiency or building form. Otherwise, the combined effect of all these inefficiencies is going to cause more severe poor performance results than linear accumulation. On the other hand, when these components of a building design moving to high efficiency, it needs to find out an optimized balance point with additional consideration such as cost or aesthetic aspect.

Table 21 Energy saving potential of 3 different system types as a retail space in Chicago

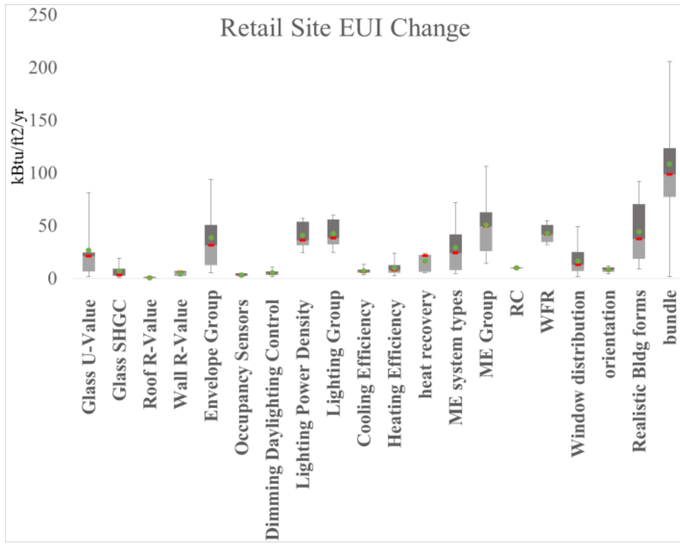
Building forms	System types	"ASHRAE 90.1-2013"/best bundle	"ASHRAE 90.1"-1989/worst bundle	Saving potential by bundle
Good BF	PSZ	61	138	77
	VAV	55	123	77
	WSHP	30	103	73
Medium BF	PSZ	61	162	101
	VAV	55	154	99
	WSHP	30	118	88
Bad BF	PSZ	69	235	166
	VAV	64	236	172
	WSHP	32	155	123

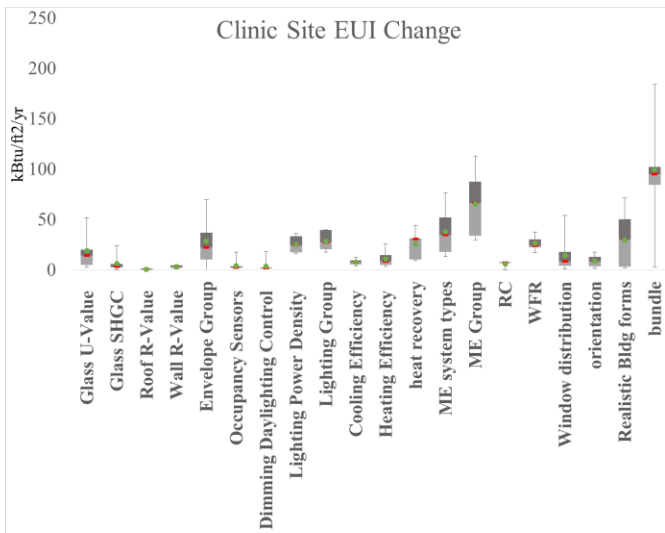
6.3.1 Performance by building types in different climate zones

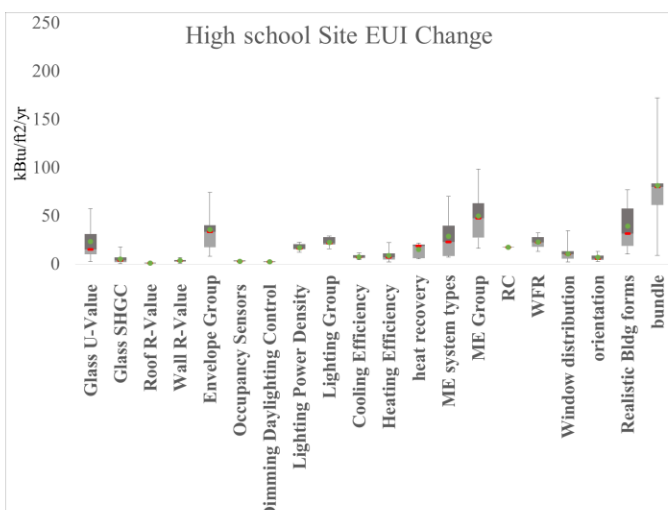
The performance of these strategies, groups, and bundle will be different with different building types. The following Figure 49 listed all 7 tested building types in Chicago. The total energy saving potential largely depends on actual energy EUI of each building type. For instance, the site EUI of a warehouse is already quite low compared to a clinic. Therefore the comparison in the section is more geared to explore the impact on energy saving and strategies selection by the building operation.

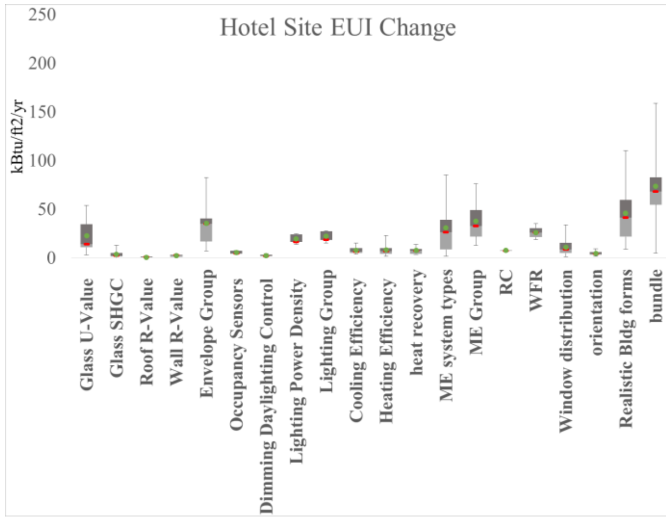
Each building type has used different building forms based on the database of THE WEIDT GROUP. The chosen building form are mostly concentrated at the RC ranging from 0.4-0.8. It is the found that the energy saving potential of wall and roof R-value are consistently low even the total envelope changes by building type. It further proves the insensitivity of the insulation level of wall and roof in energy saving. The lighting section largely depends on the operation schedule as revealed in Figure 49. Except for the multifamily and warehouse, the lighting power density is within the range of 25-50 kBtu/sq. ft./yr. Similar to the lighting system, the mechanical system related strategies presents a similar impact on the energy saving across all 7 building types. The amount of saving varies due the total energy usage determined by the nature of the building types. Based on the Figure 49, the relative impact of the mechanical system in comparison to the building envelope and building forms are weakened in low internal heat gain building types. In other words, the overall mechanical system efficiency and system type selection is relatively less critical in building types such as multifamily, office or warehouse.

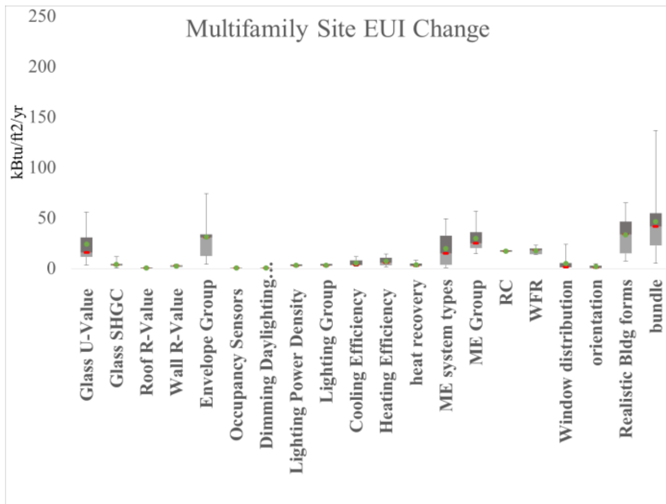
The energy saving potential of building form remains stable across different building types, which plays a more significant role in these less energy intensive building types. In addition, the elements of building forms perform consistently in different building types. In bundle level, all building types present a large variation of energy saving potential. To optimize energy saving, the combination of different strategies is always crucial regardless of building types.

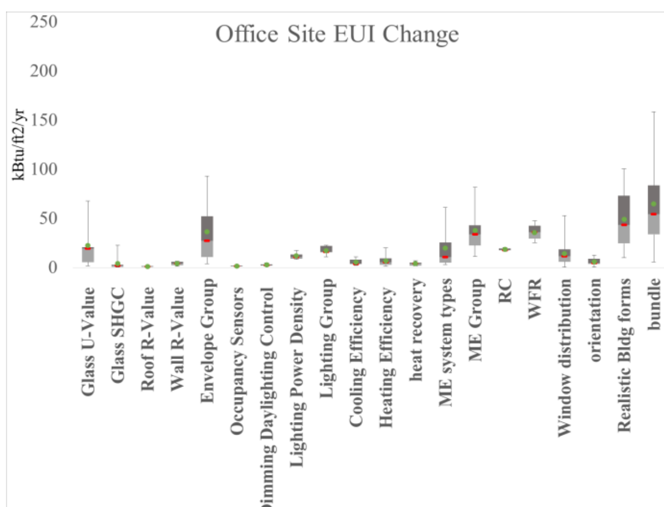

Retail Site EUI Change
kBtu/ft2/yr
250
200
150
100
50
0
Glass U-Value
Glass SHGC
Roof R-Value
Wall R-Value
Envelope Group
Occupancy Sensors
Dimming Daylighting Control
Lighting Power Density
Lighting Group
Cooling Efficiency
Heating Efficiency
heat recovery
ME system types
ME Group
RC
WFR
Window distribution
orientation
Realistic Bldg forms
bundle


Clinic Site EUI Change
kBtu/ft2/yr
250
200
150
100
50
0
Glass U-Value
Glass SHGC
Roof R-Value
Wall R-Value
Envelope Group
Occupancy Sensors
Dimming Daylighting Control
Lighting Power Density
Lighting Group
Cooling Efficiency
Heating Efficiency
heat recovery
ME system types
ME Group
RC
WFR
Window distribution
orientation
Realistic Bldg forms
bundle


High school Site EUI Change
kBtu/ft2/yr
250
200
150
100
50
0
Glass U-Value
Glass SHGC
Roof R-Value
Wall R-Value
Envelope Group
Occupancy Sensors
Dimming Daylighting Control
Lighting Power Density
Lighting Group
Cooling Efficiency
Heating Efficiency
heat recovery
ME system types
ME Group
RC
WFR
Window distribution
orientation
Realistic Bldg forms
bundle


Hotel Site EUI Change
kBtu/ft2/yr
250
200
150
100
50
0
Glass U-Value
Glass SHGC
Roof R-Value
Wall R-Value
Envelope Group
Occupancy Sensors
Dimming Daylighting Control
Lighting Power Density
Lighting Group
Cooling Efficiency
Heating Efficiency
heat recovery
ME system types
ME Group
RC
WFR
Window distribution
orientation
Realistic Bldg forms
bundle


Multifamily Site EUI Change
kBtu/ft2/yr
250
200
150
100
50
0
Glass U-Value
Glass SHGC
Roof R-Value
Wall R-Value
Envelope Group
Occupancy Sensors
Dimming Daylighting...
Lighting Power Density
Lighting Group
Cooling Efficiency
Heating Efficiency
heat recovery
ME system types
ME Group
RC
WFR
Window distribution
orientation
Realistic Bldg forms
bundle


Office Site EUI Change
kBtu/ft2/yr
250
200
150
100
50
0
Glass U-Value
Glass SHGC
Roof R-Value
Wall R-Value
Envelope Group
Occupancy Sensors
Dimming Daylighting Control
Lighting Power Density
Lighting Group
Cooling Efficiency
Heating Efficiency
heat recovery
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ME Group
RC
WFR
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orientation
Realistic Bldg forms
bundle

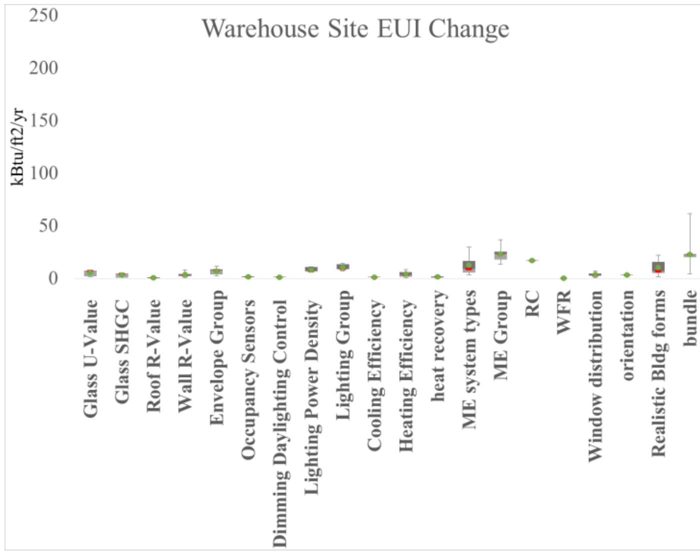


Figure 49- Site EUI saving potential of all building types in Chicago

When compared to different climate zones, the energy consumption is changed fundamentally because the heating/cooling needs vary drastically. As chapter 4 has explained, the energy consumption and thermal load across 8 climate zones increase from warmer to a colder climate, when evaluating the energy saving potential under the framework of phase II, the energy saving potential also presents a bigger variation, and the variation shows the similar pattern under each building type.

Based on the Appendix B, the saving potential of the glazing SHGC increases considerably as the climate is warmer in envelope group,. Ultimately, its energy saving potential exceeds the U-value of the glazing in Miami located in Climate zone 1. It is because the SHGC indicates the amount of solar radiation through the glazing, and the low SHGC glazing doesn't have high energy saving potential in a colder climate as it reduces the possibility of heat transfer from outside to indoor in sunny weather during the heating season in cold climate. In relative mild climate, the energy saving potential still remains positive because the low SHGC glazing blocks the solar radiation during hot peak cooling time, and reduces the peak cooling load. In general, the envelope grouped strategy as a whole presents an increasing energy saving in colder climate, where the heat transfer through envelope is more significant.

In Appendix B, the lighting system presents a smaller saving potential as the climate becomes colder. The lighting system converts electricity to excessive heat and increases the cooling load. It could significantly reduce energy consumption in colder climate zone. The impact of the lighting strategies as a group provides a higher saving potential in comparison to the building envelope group. As the most influential group on energy saving, mechanical system related strategies and the group also presents a much significant energy saving difference across 8 climate zones. In Miami, the mechanical system grouped strategy only presents 29.5 kBtu/sq. ft./yr, which is only 26% of the saving potential in Fairbanks with 114.8 kBtu/sq. ft./yr. As it is predicted in chapter 4, the cooling efficiency provides more saving potential in hotter climate zone and the heating efficiency should draw more attention in a colder climate.

The overall energy saving from different strategies in different climate zones and locations can be concluded in Figure 49. It is worth mentioning that basic load of different climate zone and building types are different. Therefore a higher saving potential of a certain condition is not necessarily better it is applied in different building types and climate. Depending on what conclusion the reader plan to draw out of the research, the “comparative definition” should be changed.

6.4 Performance analysis of multiple strategies by 3 building forms

With 3 different building forms with energy performance from worst, medium and best, it is crucial to understand how it could impact on the energy performance and saving potentials of the strategies. Figure 50 presents that the energy saving potential increases substantially in the worse performed building form. In other words, the energy saving potential of the strategies could be largely impacted by the building form information input into the model. At the same time, the Site EUI is still higher with worse building forms in comparison to the best building forms when other strategies are held under the same level of efficiency as indicated in Figure 51. It means that when the building form is not designed with poor energy saving performance, the improvement of the efficiency of other strategies become more crucial in order to avoid high energy usage.

In addition, the result also reveals that it is important to secure the energy simulation result to be accurate, it is necessary to properly model the building form, especially the definition of the glazing including Window area and distribution. From the envelope property, the energy saving of the glazing could be explained by the effect of both glazing area increase and U-value decrease. On the other side, the wall and roof insulation remain quite insensitive to energy saving even the building form before has been changed drastically. In early design phase or certain purpose of energy model, the building form typically remains undetermined. In this phase, it is sufficient to input correct level of Relative compactness, window related information.

The lighting strategies perform consistently when the building form changes except for the daylighting control. As the building form become less compact with more glazing area (bad form), the day-lit area, 15-ft zone from glazing, will increase and with more natural daylight potential. From Figure 50, this strategy could save energy usage but rather small in comparison to the mechanical system or even window property. The mechanical system present increase on the energy saving potential when the building form becomes worse due to the increase of thermal load.

Compare the strategies, groups, and bundles, it is concluded that neither of the single strategy or single strategy group could overcome the energy usage increase by energy intensive building forms. It has to be a combination of all strategies of a bundle to minimize the energy consumption. Overall, all strategies impact on each other and couldn't guarantee the energy saving potential without additional endorsement from another aspect of a project.

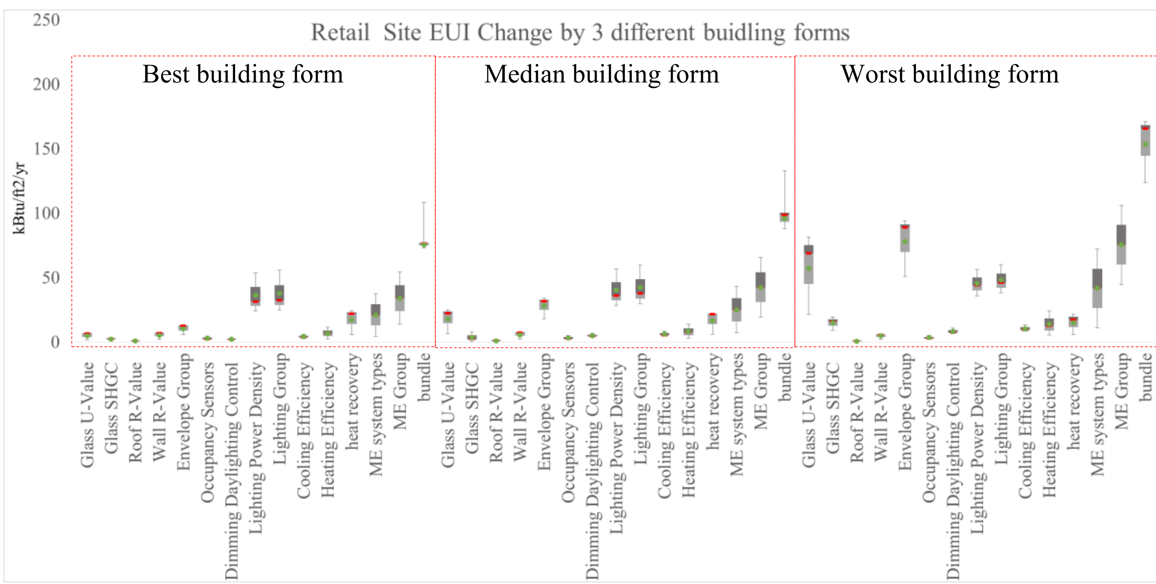


Figure 50- Site Energy saving potential by 3 different building forms of a retail space in Chicago

Figure 51 – Site EUI by 3 different building forms of a retail space in Chicago

The performance difference of the chosen strategies under 3 different building forms remains relatively similar in climate 5 Chicago. The worse designed building form has a higher impact on energy saving potential of the evaluated strategies in this study. On the other hand, the bundle level energy usage in the worst building form is only around 20 kBtu/sq. ft./yr higher than the medium building form. As the bundle reaches the maximum efficiency level, the energy consumption of all three different building forms is smaller than 10 kBtu/sq. ft./yr. It reveals that if the building form design is restrained by certain factors such as the site, aesthetic requirement or interior spatial requirement, the energy efficiency of these building could be made up by implementing the high efficiency energy saving strategies with relatively high initial cost. As the more advanced technology coming out on the market, this path of reducing energy usage will become more feasible.

The saving potential under 3 different building forms presents similar pattern across all 8 climate zones. When building form doesn't perform well, both energy saving potential and energy consumption by each strategy or group will increase accordingly. It is worth comparing the EUI of 2 extreme climate conditions, Miami and Fairbanks. Shown in Figure 52, the site EUI variation, caused by different efficiency of the evaluated strategies in Miami, remains in a narrow range of all three building forms in comparison to Fairbanks. The difference of average and median result of a retail building in Miami are almost identical. Contrarily, the Fairbanks presents a quite huge difference between median and average EUI. Especially, the median value stays in a relatively high position in each bar diagram, which means more than half of the test samples present energy consumption at top 20% of the energy usage value. It further reveals a pattern that the building saving strategies in cold climate have more uncertainty and variations. How designers and energy consultant evaluate and apply saving strategies is crucial in a colder climate. It is quite possible that the energy usage of the projects in Fairbanks could fall into the top 20% high energy consumption At the same time, if the strategies are chosen appropriately, the energy consumption in this climate of a certain type of building could be as low as it is in warm climate zone.

The energy saving from the building massing is not significant and it doesn't cause much variations as other simulation input changes. In general, the building form with its designed boundary is highly interactive; a well-designed building form could be as effective as the high efficiency mechanical system. Meanwhile, a well-designed building form doesn't cost additional budget in comparison to improve the mechanical system efficiency.

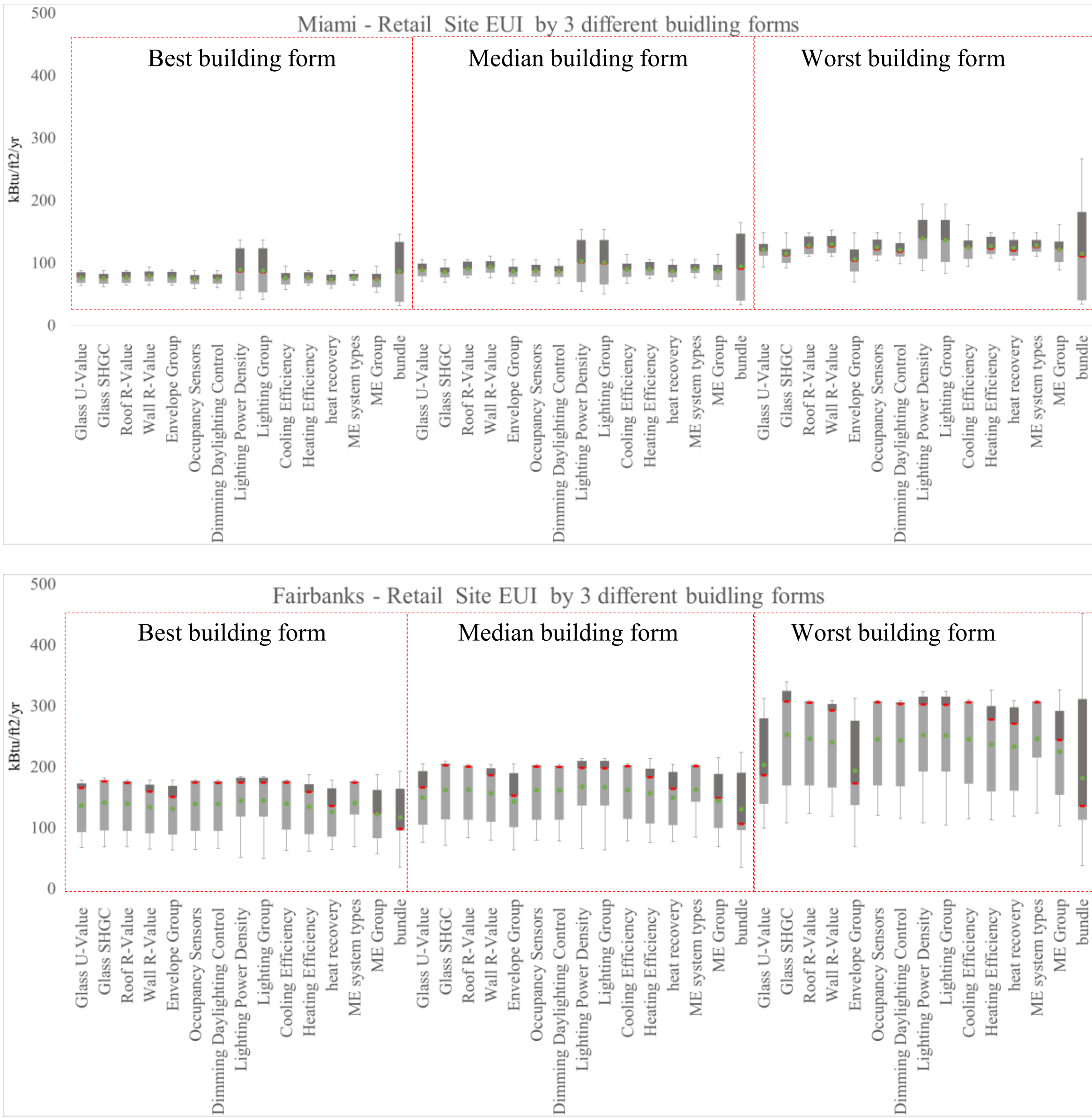


Figure 52 Site EUI of retail in Fairbanks and Miami

6.5 Performance analysis of multiple strategies by 3 mechanical systems

Mechanical system types are regarded as the other major input impacting energy consumption and savings. This chapter is to explore how 3 different mechanical systems, PSZ, VAV and WSHP simulated in this research, impact on the energy performance of other strategies including different building forms.

Figure 53 reveals that the VAV and PSZ have almost identical impact on the energy performance of other strategies. However, the performance of several crucial saving strategies are in favor of the VAV system, such as CO_2 sensor control of outside air on VAV boxes are not evaluated in this study. The comparison of the mechanical related single strategies is valuable. The energy consumption of VAV systems that reach "ASHRAE90.1-2013" standard has the higher saving penitential than PSZ system. As explored in chapter 6.3, when the system is set in certain type and efficiency levels, the energy consumption of VAV system could be higher due to reheat issue. Therefore, the system layout, capacity, and zoning with a VAV system need to be more carefully designed to actually utilize the efficient aspect of the system.

As for the WSHP system, the mechanism of the system determines the low site energy consumption even with low system efficiency. However, the energy efficiency of the WSHP is not as significant when evaluating Source EUI. In most of the utility rate structure, the electricity is more expensive than gas per kBtu, which further weakened the benefit of the system when considering energy cost. A Midwest located apartment project enrolled in Utility incentive program has evaluated the energy consumption between PSZ and WSHP systems for a multifamily building in climate zone 6A. Under the rate structure of this utility program for electricity and gas, the results reveal that the WSHP system has an advantage in EUI but the energy cost are almost same with a regular PSZ system.

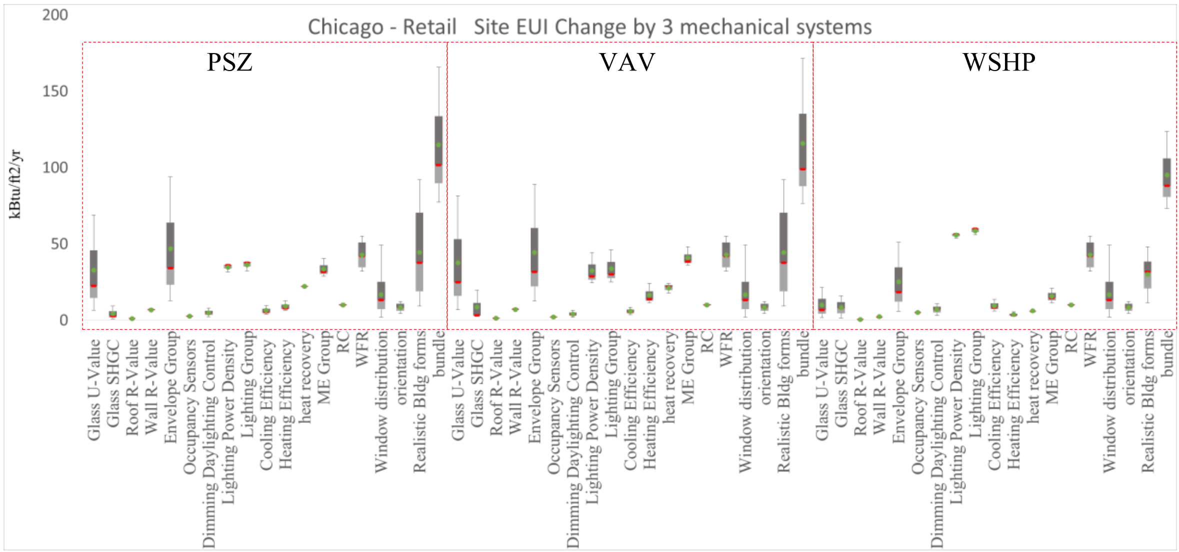


Figure 53 - Site Energy saving potential by 3 different mechanical systems of a retail space in Chicago

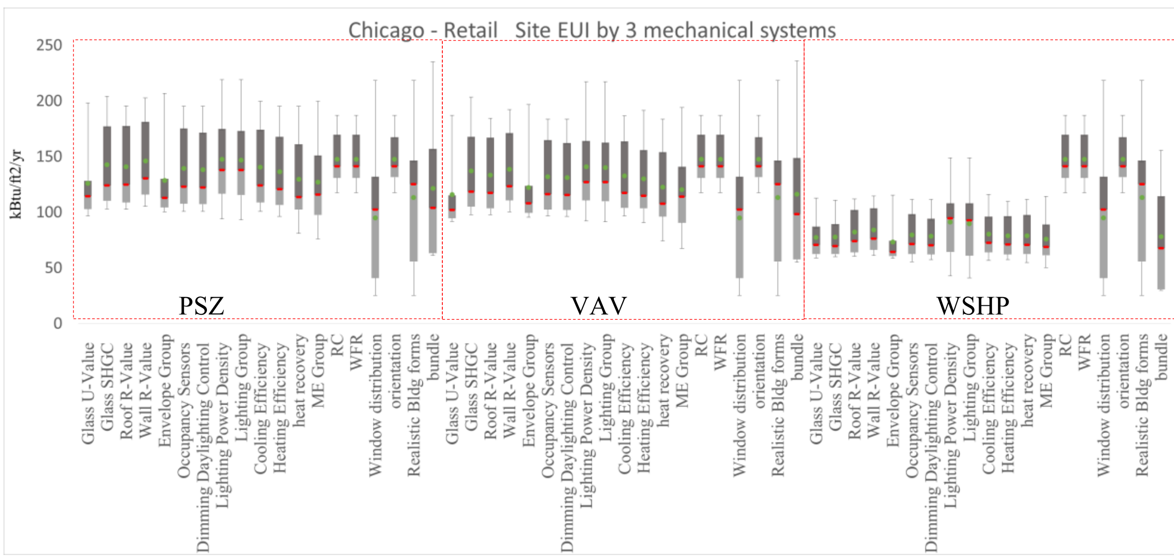


Figure 54- Site EUI by 3 different mechanical systems of a retail space in Chicago

The relative energy saving potential among 3 different systems are quite similar across 7 tested building types as shown in Appendix E. The difference among different cities presents quantitative but not qualitative difference. The accurate digit could be varied by multiple other factors not included this research. The accurate simulation results need to be conducted in a case by case condition.

Due to the different operation requirement and loads by the nature of the building type, the utilization of high efficient system may not contribute as much to total energy usage in low loads building types such as warehouse or multifamily. This is more concerned in an incentive based simulation project. With low operation and small loads, the energy saving by multiple strategies could be quite small. Beyond the energy saving, the payback periods could be extended with low energy saving depending on the cost upgrading the system efficiencies or implementing the new technologies. If the project still stays in the early design phase, improving the performance of the building form could cut off the loads and therefore the energy consumption for the origin.

When the comparison is conducted among different climate zones with the same building types and mechanical system types, the results reveals that the energy saving potential doesn't vary as much by climate zones. In order to reduce energy consumption in a colder area, the crucial approach is to select high performed mechanical system with additional high efficiency strategies.

CHAPTER 7. CONCLUSION AND FUTURE WORKS

The research reveals the energy performance of building form and its four “internal” components with a value range defined by industry practice in 8 US climate zones. In addition, this research compared the energy saving potential of building form and another major energy saving strategies from mechanical, electrical and envelop aspect by analyzing heating, cooling load, site EUI. It sets up a decision making framework for a design team with multiple specialties during the early design phase or energy conservation consulting process.

The research takes this consequence that design discipline sub-optimizes shape at the first place, followed by sub-optimal selection of technologies or other system related energy conservation strategies. The research is conducted in two phases. In phase I, the research focused on decision making with respect to building form. In phase II, the research focused on the decision making with respect to system related energy conservation strategies.

Phase I: Building massing represented by RC, impact on the energy usage significantly under a wide range (1-0.3). The orientation of the building impacts on energy usage minimally among all the elements of a building form. Window related strategies including WRF and window distribution show a significantly higher impact on building energy performance with. Although the building massing design as an individual element shows a relative smaller impact on energy usage in comparison to the window related strategies, it could influence the performance of 3 other elements, as it is the carrier of three other design elements. For instance, if the building is designed with limited south and north façade, the window design will be limited and influence the energy usage associated with the windows. Therefore, the design of building massing should not be isolated from other elements when evaluating the architectural design.

The building massing design is typically considered as the first step in architectural design, and it will not have much opportunity to be modified once it is determined. The energy performance of the building form components shows a wide variation with the lower and upper limits of these elements defined by THE WEIDT GROUP's database, which means this energy performance impact is theoretically achievable in the early design stage.

Phase II: When Building form is compared with different technology choices or including mechanical, electrical and building envelope related parameters, it is found that the mechanical related system related energy saving shows highest saving potential among these 4 major groups of the strategies. The system type is the most critical mechanical related strategy to bring the energy usage down, and the system installation is costly and difficult to be replaced. The lighting related strategies show a relatively independent energy saving potential; especially the lighting power density is significantly reduced with the LED technology and further reduced the internal heat generation. The building envelope presents a wider variation of the energy saving with different building form, because the building surface condition is tightly related to the architectural design. Among the building envelope related strategies, the window U-value and SHGC are the most efficient strategies in reducing building energy usage.

The energy saving potential of all the evaluated strategies are impacted by the building form design. With a worse performed building form, the energy saving potentials is higher potential among all the evaluated strategies. It doesn't necessarily mean that the energy usage with all the high efficient efficiency strategies in a worse performed building form is less. It is still crucial to design the architectural building with the well-performed standards.

The climate conditions and building types also plays a significant role in impacting the energy saving potential of the building form, mechanical, electrical and building envelope related strategies. As shown in Appendix D, the amount of associated energy saving by the building forms, presents a sharp increase as the weather becomes colder. By viewing 56 radar charts in Appendix D, it is found that the relative energy saving among building massing, window distribution, WRF and building orientation remains relative consistent under each building type (profile of the shape in radar chart). The actual amount of the energy saving (aptitude of the shape in radar chart) is determined by the climate type.

When comparing several groups including mechanical, electrical, building envelope and building, the appendix E, the energy saving potentials also shows several trends along with climate zone and building type. The mechanical system related strategies presents relative higher energy saving potential in comparison to 3 other groups in colder climate zone. The lighting related strategies presenst a relatively higher saving potential in hotter climate, as the lighting system purely added internal heat gain in all cases. Building form and envelope related strategies show higher saving as the weather is colder, and the building usage doesn't impact on the energy saving potential of these strategies as much.

In addition to the finished study, there are several questions worth further exploring. In some project such as utility incentive based consulting projects, the energy usage is not the only concern or rubrics in evaluating the performance level of a building. The peak energy usage is also another significant factor the design teams need to consider, which is not fully explored yet in the research. Moreover, there are several system specific strategies need to be studied to further validate the energy saving potentials, such as the CO2 or Occupancy sensor control to the outside air in VAV systems.

The energy usage is important to determine the performance level of a project but not the only rubric. To a design team or building user, it is often take the indoor thermal comfort level as the priority. The energy efficiency strategies are not always intended to serve to provide the comfort level in a space. As shown in the study, the wall and roof R value is not the most efficient strategies to reduce the energy usage with a reasonable financial cost. However, high R value of the wall and roof could provide a more stable and avoid the fluctuation in indoor temperature, which potentially increase the thermal comfort level.

As the study intents to a decision making framework for a design team with multiple contributors during the early design phase or energy conservation consulting process. It would be convenient to utilize the simulation database and set up an interactive interface for design team to filter through the evaluated strategies and determine the closest situation to their design case and help them making a general decision as soon as they can and determine the approach next step. A more detailed study should be conducted when the building design develops further with more details are added. The evaluated saving strategies could be dramatically changing as the efficiency of these strategies never seizes improving.

APPENDIX A. BUILDING FORMS PERFORMANCE RESULTS

A.1 Miami database

A.1.1 Percentile change in cooling and heating load PI by RC

	Unconstrained Cooling Load Change by RC	Constrained Cooling Load Change by RC	Unconstrained Heating Load Change by RC	Constrained Heating Load Change by RC
Retail (strip mall)	63%	10%	235%	30%
Clinic	43%	10%	179%	32%
High School	42%	25%	155%	78%
Hotels	47%	12%	217%	114%
Multifamily	74%	28%	181%	57%
Office	82%	39%	183%	92%
Warehouse(15% WFR only)	128%	14%	208%	58%

A.1.2 Percentile change in cooling and heating load PI by WFR, Orientation (AZ), and window distribution

	WFR Cooling Load Change	WFR Heating Load Change	AZ Cooling Load Change	AZ Heating Load Change	Win. Dis. Cooling Load Change	Win. Dis. Heating Load Change
Retail (strip mall)	50%	151%	9%	4%	41%	122%
Clinic	37%	140%	6%	5%	28%	99%
High School	35%	116%	6%	3%	28%	91%
Hotels	42%	259%	6%	3%	31%	128%

Multifamily	47%	160%	9%	6%	59%	136%
Office	72%	195%	11%	5%	49%	112%
Warehouse(15% WFR only)	0%	0%	0%	0%	0%	0%

A.1.3 Percentile change in cooling and heating load PI by building form

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail(Strip mall)	261%	249%	502%	179%
Clinic	158%	105%	582%	263%
High School	154%	130%	525%	310%
Hotels	171%	133%	969%	721%
Multifamily	313%	249%	500%	305%
Office	334%	232%	690%	400%
Warehouse (15% WFR only)	420%	78%	701%	132%

A.1.4 Percentile change in Site and Source EUI PI by building form

	Unconstrained Site EUI change	Constrained Site EUI change	Unconstrained Source EUI change	Constrained Source EUI change
Retail(Strip mall)	133%	86%	132%	86%
Clinic	36%	31%	34%	29%
High School	46%	40%	48%	43%
Hotels	51%	35%	64%	44%

Multifamily	160%	79%	102%	82%
Office	115%	82%	121%	86%
Warehouse (15% WFR only)	155%	24%	154%	24%

A.2 Phoenix database

A.2.1 Percentile change in cooling and heating load PI by RC

	Unconstrained Cooling Load Change by RC	Constrained Cooling Load Change by RC	Unconstrained Heating Load Change by RC	Constrained Heating Load Change by RC
Retail (strip mall)	79%	12%	300%	32%
Clinic	55%	12%	210%	36%
High School	53%	31%	191%	91%
Hotels	34%	9%	161%	38%
Multifamily	74%	35%	247%	101%
Office	101%	48%	225%	104%
Warehouse(15% WFR only)	153%	14%	238%	58%

A.2.2 Percentile change in cooling and heating load PI by WFR, Orientation (AZ), and window distribution

	WFR Cooling Load Change	WFR Heating Load Change	AZ Cooling Load Change	AZ Heating Load Change	Win. Dis. Cooling Load Change	Win. Dis. Heating Load Change
Retail (strip mall)	47%	81%	11%	3%	40%	70%
Clinic	36%	79%	7%	4%	27%	19%
High School	34%	67%	8%	3%	8%	3%
Hotels	49%	240%	7%	1%	38%	133%
Multifamily	68%	108%	12%	6%	53%	46%
Office	133%	257%	12%	4%	46%	71%
Warehouse(15% WFR only)	0%	0%	0%	0%	0%	0%

A.2.3 Percentile change in cooling and heating load PI by building form

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail(Strip mall)	261%	249%	502%	179%
Clinic	158%	105%	582%	263%
High School	154%	130%	525%	310%
Hotels	171%	133%	969%	721%
Multifamily	313%	249%	500%	305%
Office	334%	232%	690%	400%
Warehouse (15% WFR only)	427%	93%	484%	138%

A.2.4 Percentile change in Site and Source EUI PI by building form

	Unconstrained Site EUI change	Constrained Site EUI change	Unconstrained Source EUI change	Constrained Source EUI change
Retail(Strip mall)	149%	91%	146%	93%
Clinic	57%	41%	57%	38%
High School	73%	65%	78%	68%
Hotels	63%	49%	80%	62%
Multifamily	134%	101%	146%	114%
Office	115%	82%	163%	141%
Warehouse (15% WFR only)	207%	49%	202%	46%

A.3 Atlanta database

A.3.1 Percentile change in cooling and heating load PI by RC

	Unconstrained Cooling Load Change by RC	Constrained Cooling Load Change by RC	Unconstrained Heating Load Change by RC	Constrained Heating Load Change by RC
Retail (strip mall)	27%	6%	228%	27%
Clinic	25%	12%	156%	29%
High School	21%	14%	145%	73%
Hotels	17%	5%	151%	79%
Multifamily	36%	16%	169%	73%
Office	47%	28%	174%	81%
Warehouse(15% WFR only)	95%	14%	289%	58%

A.3.2 Percentile change in cooling and heating load PI by WFR, Orientation (AZ), and window distribution

	WFR Cooling Load Change	WFR Heating Load Change	AZ Cooling Load Change	AZ Heating Load Change	Win. Dis. Cooling Load Change	Win. Dis. Heating Load Change
Retail (strip mall)	43%	101%	10%	2%	38%	83%
Clinic	27%	91%	6%	1%	22%	64%
High School	25%	80%	7%	1%	22%	62%
Hotels	33%	173%	6%	1%	26%	93%
Multifamily	88%	72%	12%	2%	67%	42%
Office	64%	122%	13%	1%	49%	73%
Warehouse(15% WFR only)	0%	0%	1%	01%	0%	0%

A.3.3 Percentile change in cooling and heating load PI by building form

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail(Strip mall)	157%	157%	983%	145%
Clinic	96%	74%	514%	274%
High School	87%	83%	473%	317%
Hotels	107%	83%	750%	503%
Multifamily	306%	266%	376%	250%
Office	256%	204%	630%	400%
Warehouse (15% WFR only)	435%	70%	440%	110%

A.3.4 Percentile change in Site and Source EUI PI by building form

	Unconstrained Site EUI change	Constrained Site EUI change	Unconstrained Source EUI change	Constrained Source EUI change
Retail(Strip mall)	157%	116%	157%	95%
Clinic	56%	49%	48%	42%
High School	70%	64%	75%	68%
Hotels	50%	36%	65%	47%
Multifamily	96%	69%	91%	70%
Office	115%	82%	142%	114%
Warehouse (15% WFR only)	204%	39%	165%	19%

A.4 Seattle database (other location to be added soon)

A.4.1 Percentile change in cooling and heating load PI by RC

	Unconstrained Cooling Load Change by RC	Constrained Cooling Load Change by RC	Unconstrained Heating Load Change by RC	Constrained Heating Load Change by RC
Retail (strip mall)	10%	0%	235%	29%
Clinic	55%	12%	210%	36%
High School	53%	31%	191%	91%
Hotels	34%	9%	161%	38%
Multifamily	74%	35%	247%	101%
Office	101%	48%	225%	104%

Warehouse(15% WFR only)	153%	14%	238%	58%

A.4.2 Percentile change in cooling and heating load PI by WFR, Orientation (AZ) and window distribution

	WFR Cooling Load Change	WFR Heating Load Change	AZ Cooling Load Change	AZ Heating Load Change	Win. Dis. Cooling Load Change	Win. Dis. Heating Load Change
Retail (strip mall)	80%	108%	16%	2%	80%	87%
Clinic	36%	79%	7%	4%	27%	60%
High School	34%	67%	8%	3%	27%	57%
Hotels	49%	240%	7%	1%	38%	133%
Multifamily	77%	72%	12%	6%	53%	46%
Office	68%	108%	12%	4%	46%	71%
Warehouse(15% WFR only)	0%	0%	3%	5%	0%	0%

A.4.3 Percentile change in cooling and heating load PI by building form

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail(Strip mall)	296%	290%	1021%	296%
Clinic	158%	105%	580%	264%
High School	154%	130%	526%	309%
Hotels	171%	133%	1065%	718%
Multifamily	313%	249%	501%	305%

Office	334%	232%	690%	401%
Warehouse (15% WFR only)	427%	93%	484%	138%

A.4.4 **Percentile change in Site and Source EUI PI by building form**

	Unconstrained Site EUI change	Constrained Site EUI change	Unconstrained Source EUI change	Constrained Source EUI change
Retail(Strip mall)	154%	961%	147%	118%
Clinic	57%	42%	51%	38%
High School	73%	65%	78%	68%
Hotels	63%	49%	80%	62%
Multifamily	134%	101%	146%	114%
Office	115%	82%	158%	121%
Warehouse (15% WFR only)	207%	49%	202%	46%

A.5 Chicago database (included in the paper)

A.6 Minneapolis database

A.6.1 Percentile change in cooling and heating load PI by RC

	Unconstrained Cooling Load Change by RC	Constrained Cooling Load Change by RC	Unconstrained Heating Load Change by RC	Constrained Heating Load Change by RC
Retail (strip mall)	10%	2%	46%	8%
Clinic	12%	3%	123%	23%
High School	9%	5%	118%	61%
Hotels	10%	3%	139%	69%
Multifamily	17%	9%	138%	63%
Office	21%	14%	150%	66%
Warehouse(15% WFR only)	41%	18%	169%	58%

A.6.2 Percentile change in cooling and heating load PI by WFR, Orientation (AZ), and window distribution

	WFR Cooling Load Change	WFR Heating Load Change	AZ Cooling Load Change	AZ Heating Load Change	Win. Dis. Cooling Load Change	Win. Dis. Heating Load Change
Retail (strip mall)	93%	86%	16%	2%	87%	74%
Clinic	51%	75%	8%	2%	44%	55%
High School	49%	69%	10%	2%	44%	56%
Hotels	64%	104%	10%	3%	42%	160%
Multifamily	128%	53%	18%	2%	81%	152%
Office	132%	100%	21%	2%	107%	220%
Warehouse(15% WFR only)	0%	0%	0%	2%	6%	2%

A.6.3 Percentile change in cooling and heating load PI by building form

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail(Strip mall)	333%	333%	723%	333%
Clinic	152%	140%	384%	222%
High School	141%	141%	372%	264%
Hotels	202%	181%	468%	307%
Multifamily	628%	598%	280%	180%
Office	504%	463%	499%	323%
Warehouse (15% WFR only)	855%	31%	382%	95%

A.6.4 Percentile change in Site and Source EUI PI by building form

	Unconstrained Site EUI change	Constrained Site EUI change	Unconstrained Source EUI change	Constrained Source EUI change
Retail(Strip mall)	158%	93%	149%	111%
Clinic	64%	51%	49%	48%
High School	78%	75%	83%	79%
Hotels	83%	63%	103%	80%
Multifamily	113%	85%	127%	106%
Office	115%	82%	170%	143%
Warehouse (15% WFR only)	109%	54%	233%	29%

A.7 Duluth database

A.7.1 Percentile change in cooling and heating load PI by RC

	Unconstrained Cooling Load Change by RC	Constrained Cooling Load Change by RC	Unconstrained Heating Load Change by RC	Constrained Heating Load Change by RC
Retail (strip mall)	18%	1%	209%	24%
Clinic	5%	1%	139%	26%
High School	2%	0%	135%	69%
Hotels	8%	1%	116%	60%
Multifamily	6%	6%	138%	63%
Office	11%	5%	171%	73%
Warehouse(15% WFR only)	27%	24%	178%	58%

A.7.2 Percentile change in cooling and heating load PI by WFR, Orientation (AZ), and window distribution

	WFR Cooling Load Change	WFR Heating Load Change	AZ Cooling Load Change	AZ Heating Load Change	Win. Dis. Cooling Load Change	Win. Dis. Heating Load Change
Retail (strip mall)	118%	63%	21%	1%	115%	55%
Clinic	57%	56%	10%	1%	49%	42%
High School	55%	52%	12%	1%	50%	42%
Hotels	75%	103%	11%	2%	62%	65%
Multifamily	207%	47%	25%	1%	176%	29%
Office	169%	74%	28%	1%	150%	50%

Warehouse(15% WFR only)	0%	0%	0%	2%	0%	0%

A.7.3 Percentile change in cooling and heating load PI by building form

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail(Strip mall)	494%	474%	598%	494%
Clinic	162%	156%	325%	168%
High School	159%	159%	323%	216%
Hotels	258%	217%	427%	293%
Multifamily	952%	886%	263%	175%
Office	744%	721%	418%	243%
Warehouse (15% WFR only)	1271%	12%	338%	102%

A.7.4 Percentile change in Site and Source EUI PI by building form

	Unconstrained Site EUI change	Constrained Site EUI change	Unconstrained Source EUI change	Constrained Source EUI change
Retail(Strip mall)	149%	74%	156%	105%
Clinic	71%	55%	54%	43%
High School	73%	65%	78%	68%
Hotels	82%	64%	104%	83%
Multifamily	113%	84%	132%	109%
Office	115%	82%	175%	139%

Warehouse (15% WFR only)	239%	64%	208%	37%

A.8 Fairbanks database

A.8.1 Percentile change in cooling and heating load PI by RC

	Unconstrained Cooling Load Change by RC	Constrained Cooling Load Change by RC	Unconstrained Heating Load Change by RC	Constrained Heating Load Change by RC
Retail (strip mall)	18%	0%	179%	21%
Clinic	7%	2%	119%	23%
High School	4%	2%	119%	61%
Hotels	9%	2%	90%	46%
Multifamily	10%	7%	119%	56%
Office	14%	8%	154%	66%
Warehouse(15% WFR only)	30%	29%	171%	58%

A.8.2 Percentile change in cooling and heating load PI by WFR, Orientation (AZ), and window distribution

	WFR Cooling Load Change	WFR Heating Load Change	AZ Cooling Load Change	AZ Heating Load Change	Win. Dis. Cooling Load Change	Win. Dis. Heating Load Change
Retail (strip mall)	121%	64%	13%	1%	108%	52%
Clinic	60%	58%	6%	1%	49%	41%
High School	56%	54%	7%	1%	49%	42%
Hotels	80%	100%	7%	2%	62%	62%

Multifamily	212%	57%	17%	1%	163%	33%
Office	168%	747%	17%	1%	138%	48%
Warehouse(15% WFR only)	0%	0%	0%	0%	0%	0%

A.8.3 Percentile change in cooling and heating load PI by building form

	Unconstrained Cooling Load Change	Constrained Cooling Load Change	Unconstrained Heating Load Change	Constrained Heating Load Change
Retail(Strip mall)	457%	454%	527%	457%
Clinic	164%	158%	300%	165%
High School	155%	155%	525%	310%
Hotels	257%	220%	366%	265%
Multifamily	918%	852%	266%	187%
Office	692%	665%	400%	242%
Warehouse (15% WFR only)	1174%	19%	339%	95%

A.8.4 Percentile change in Site and Source EUI PI by building form

	Unconstrained Site EUI change	Constrained Site EUI change	Unconstrained Source EUI change	Constrained Source EUI change
Retail(Strip mall)	149%	74%	151%	97%
Clinic	72%	56%	59%	46%
High School	103%	84%	107%	88%
Hotels	93%	49%	110%	88%

Multifamily	120%	89%	134%	108%
Office	115%	82%	195%	147%
Warehouse (15% WFR only)	250%	64%	208%	43%

APPENDIX B. ENERGY SAVING POTENTIAL OF MULTIPLE STRATEGIES, GROUPS AND BUNDLE

B.2.1 Miami site EUI potential by strategies, groups and bundle (kBtu/sq. ft./yr)

	Retail	Clinic	High-school	hotel	Multi-family	office	Ware-house
Glass U-Value	7%	2%	2%	8%	10%	5%	4%
Glass SHGC	13%	8%	13%	9%	10%	18%	9%
Roof R-Value	1%	1%	1%	1%	1%	1%	1%
Wall R-Value	5%	2%	3%	2%	2%	4%	6%
Envelope Group	**18%**	**11%**	**15%**	**18%**	**21%**	**24%**	**3%**
Occupancy Sensors	6%	4%	5%	8%	1%	4%	11%
Dimming Daylighting Control	9%	2%	4%	3%	1%	6%	8%
Lighting Power Density	48%	30%	24%	22%	7%	24%	43%
Lighting Group	**68%**	**41%**	**34%**	**28%**	**8%**	**38%**	**69%**
Cooling Efficiency	23%	19%	22%	18%	18%	21%	18%
Heating Efficiency	2%	1%	1%	2%	2%	1%	1%
heat recovery	7%	8%	6%	4%	2%	3%	2%
ME system types	5%	11%	8%	6%	5%	7%	10%
ME Group	**27%**	**30%**	**26%**	**21%**	**21%**	**23%**	**30%**
RC	7%	4%	13%	6%	8%	17%	27%
WFR	40%	16%	11%	15%	25%	26%	0%
Window distribution	22%	8%	7%	7%	7%	14%	8%
orientation	13%	4%	4%	3%	2%	5%	20%
Typical Building forms	**29%**	**11%**	**24%**	**26%**	**36%**	**41%**	**13%**
bundle	125%	81%	76%	68%	45%	87%	106%

B.2.2 Phoenix site EUI potential by strategies, groups and bundle (kBtu/sq. ft./yr)

	Retail	Clinic	High-school	hotel	Multi-family	office	Ware-house
Glass U-Value	23%	13%	17%	25%	38%	23%	6%
Glass SHGC	8%	7%	10%	7%	6%	14%	6%
Roof R-Value	1%	1%	1%	1%	1%	1%	1%
Wall R-Value	4%	2%	3%	2%	3%	4%	7%
Envelope Group	**39%**	**24%**	**33%**	**36%**	**50%**	**45%**	**18%**
Occupancy Sensors	4%	3%	4%	7%	1%	2%	7%
Dimming Daylighting Control	7%	2%	3%	3%	1%	4%	5%
Lighting Power Density	39%	24%	19%	20%	6%	17%	31%
Lighting Group	**51%**	**31%**	**26%**	**25%**	**7%**	**26%**	**45%**
Cooling Efficiency	18%	16%	19%	15%	16%	18%	20%
Heating Efficiency	3%	2%	2%	3%	3%	3%	2%
heat recovery	5%	7%	4%	2%	2%	1%	1%
ME system types	8%	12%	10%	8%	6%	9%	12%
ME Group	**23%**	**29%**	**23%**	**18%**	**20%**	**23%**	**32%**
RC	9%	5%	13%	4%	11%	17%	51%
WFR	37%	18%	15%	22%	24%	34%	0%
Window distribution	19%	9%	8%	9%	7%	14%	11%
orientation	15%	7%	8%	4%	3%	8%	28%
Typical Building forms	**36%**	**16%**	**33%**	**33%**	**40%**	**54%**	**29%**
bundle	119%	80%	81%	81%	76%	91%	94%

B.2.3 Atlanta site EUI potential by strategies, groups and bundle (kBtu/sq. ft./yr)

	Retail	Clinic	High-school	hotel	Multi-family	office	Ware-house
Glass U-Value	13%	7%	10%	10%	17%	14%	7%
Glass SHGC	5%	4%	6%	4%	4%	8%	5%
Roof R-Value	1%	1%	1%	1%	1%	1%	1%
Wall R-Value	7%	3%	4%	3%	4%	7%	11%
Envelope Group	**27%**	**14%**	**23%**	**20%**	**27%**	**33%**	**15%**
Occupancy Sensors	4%	3%	4%	6%	1%	2%	7%
Dimming Daylighting Control	7%	2%	3%	3%	1%	4%	5%
Lighting Power Density	38%	24%	19%	19%	5%	18%	30%
Lighting Group	**53%**	**31%**	**28%**	**24%**	**6%**	**29%**	**47%**
Cooling Efficiency	10%	9%	11%	9%	9%	10%	5%
Heating Efficiency	6%	5%	5%	5%	5%	6%	7%
heat recovery	10%	12%	8%	4%	2%	3%	2%
ME system types	14%	17%	15%	14%	13%	15%	19%
ME Group	**33%**	**38%**	**31%**	**17%**	**21%**	**34%**	**47%**
RC	7%	5%	16%	4%	12%	20%	29%
WFR	40%	16%	18%	16%	20%	45%	0%
Window distribution	12%	10%	8%	6%	5%	17%	8%
orientation	15%	6%	7%	4%	2%	10%	16%
Typical Building forms	**33%**	**12%**	**29%**	**29%**	**33%**	**47%**	**19%**
bundle	111%	73%	73%	61%	50%	82%	88%

B.2.4 Seattle site EUI potential by strategies, groups and bundle (kBtu/sq. ft./yr)

	Retail	Clinic	High-school	hotel	Multi-family	office	Ware-house
Glass U-Value	19%	10%	15%	13%	24%	20%	12%
Glass SHGC	6%	3%	4%	3%	5%	5%	8%
Roof R-Value	1%	1%	1%	1%	0%	1%	2%
Wall R-Value	14%	6%	8%	6%	8%	14%	26%
Envelope Group	**34%**	**21%**	**29%**	**27%**	**35%**	**40%**	**25%**
Occupancy Sensors	3%	2%	3%	5%	1%	2%	5%
Dimming Daylighting Control	5%	1%	2%	2%	1%	3%	4%
Lighting Power Density	31%	16%	16%	16%	4%	15%	23%
Lighting Group	**41%**	**21%**	**23%**	**20%**	**4%**	**23%**	**34%**
Cooling Efficiency	3%	2%	3%	3%	3%	3%	1%
Heating Efficiency	7%	6%	6%	6%	7%	7%	9%
heat recovery	11%	15%	10%	4%	2%	3%	2%
ME system types	17%	19%	18%	20%	23%	17%	22%
ME Group	**36%**	**38%**	**34%**	**23%**	**28%**	**36%**	**49%**
RC	6%	6%	17%	6%	13%	22%	56%
WFR	39%	21%	20%	26%	27%	47%	0%
Window distribution	13%	9%	9%	10%	7%	16%	12%
orientation	7%	8%	11%	5%	4%	10%	35%
Typical Building forms	**34%**	**14%**	**31%**	**34%**	**38%**	**50%**	**25%**
bundle	102%	66%	71%	58%	55%	81%	85%

B.2.5 Chicago site EUI potential by strategies, groups and bundle (kBtu/sq. ft./yr)

	Retail	Clinic	High-school	hotel	Multi-family	office	Ware-house
Glass U-Value	23%	13%	20%	18%	29%	26%	14%
Glass SHGC	6%	4%	4%	3%	4%	5%	8%
Roof R-Value	1%	1%	1%	1%	0%	1%	1%
Wall R-Value	4%	2%	3%	2%	3%	5%	9%
Envelope Group	**30%**	**19%**	**29%**	**26%**	**35%**	**39%**	**16%**
Occupancy Sensors	3%	3%	3%	4%	1%	2%	4%
Dimming Daylighting Control	4%	2%	2%	2%	1%	3%	3%
Lighting Power Density	27%	15%	13%	14%	3%	12%	18%
Lighting Group	**35%**	**19%**	**19%**	**16%**	**4%**	**19%**	**26%**
Cooling Efficiency	6%	5%	6%	6%	6%	6%	3%
Heating Efficiency	8%	7%	7%	6%	8%	7%	11%
heat recovery	13%	17%	12%	6%	4%	4%	3%
ME system types	20%	22%	21%	21%	23%	20%	28%
ME Group	**41%**	**43%**	**40%**	**28%**	**34%**	**41%**	**59%**
RC	6%	3%	12%	5%	16%	16%	33%
WFR	46%	20%	24%	25%	24%	55%	0%
Window distribution	14%	10%	9%	9%	6%	17%	9%
orientation	7%	6%	6%	4%	2%	7%	9%
Typical Building forms	**36%**	**20%**	**33%**	**34%**	**38%**	**55%**	**26%**
bundle	93%	67%	69%	57%	54%	74%	62%

B.2.6 Minneapolis site EUI potential by strategies, groups and bundle (kBtu/sq. ft./yr)

	Retail	Clinic	High-school	hotel	Multi-family	office	Ware-house
Glass U-Value	25%	16%	23%	20%	32%	31%	14%
Glass SHGC	7%	3%	4%	3%	4%	6%	8%
Roof R-Value	1%	1%	1%	1%	0%	1%	1%
Wall R-Value	7%	4%	5%	3%	5%	8%	9%
Envelope Group	**32%**	**21%**	**32%**	**29%**	**37%**	**42%**	**16%**
Occupancy Sensors	2%	1%	2%	3%	0%	1%	4%
Dimming Daylighting Control	4%	1%	2%	2%	1%	2%	3%
Lighting Power Density	22%	11%	10%	11%	3%	9%	18%
Lighting Group	**27%**	**14%**	**14%**	**13%**	**3%**	**14%**	**26%**
Cooling Efficiency	4%	3%	4%	4%	4%	4%	3%
Heating Efficiency	10%	9%	9%	8%	10%	9%	11%
heat recovery	14%	21%	14%	7%	5%	5%	3%
ME system types	24%	26%	25%	26%	28%	23%	28%
ME Group	**48%**	**46%**	**46%**	**36%**	**42%**	**47%**	**59%**
RC	7%	5%	14%	6%	15%	19%	47%
WFR	46%	16%	24%	27%	26%	59%	0%
Window distribution	12%	11%	9%	9%	6%	17%	10%
orientation	7%	5%	4%	4%	2%	6%	10%
Typical Building forms	**37%**	**16%**	**34%**	**35%**	**38%**	**58%**	**26%**
bundle	87%	66%	69%	57%	59%	73%	62%

B.2.7 Duluth site EUI potential by strategies, groups and bundle (kBtu/sq. ft./yr)

	Retail	Clinic	High-school	hotel	Multi-family	office	Ware-house
Glass U-Value	30%	19%	28%	25%	37%	37%	19%
Glass SHGC	9%	4%	5%	3%	7%	8%	11%
Roof R-Value	1%	1%	1%	1%	1%	1%	2%
Wall R-Value	1%	1%	1%	1%	1%	1%	2%
Envelope Group	**32%**	**22%**	**34%**	**33%**	**38%**	**44%**	**12%**
Occupancy Sensors	2%	1%	2%	4%	0%	1%	2%
Dimming Daylighting Control	3%	1%	2%	2%	1%	2%	2%
Lighting Power Density	19%	11%	11%	12%	2%	8%	10%
Lighting Group	**23%**	**13%**	**15%**	**15%**	**2%**	**13%**	**14%**
Cooling Efficiency	2%	2%	2%	3%	3%	2%	0%
Heating Efficiency	10%	10%	9%	8%	11%	9%	13%
heat recovery	15%	20%	13%	7%	5%	5%	4%
ME system types	27%	29%	26%	28%	32%	25%	34%
ME Group	**51%**	**50%**	**48%**	**37%**	**47%**	**49%**	**68%**
RC	8%	4%	16%	5%	17%	22%	47%
WFR	36%	15%	20%	28%	26%	51%	0%
Window distribution	10%	9%	7%	9%	5%	14%	5%
orientation	6%	5%	5%	4%	2%	6%	5%
Typical Building forms	**31%**	**14%**	**33%**	**33%**	**38%**	**54%**	**36%**
bundle	81%	61%	67%	60%	57%	70%	42%

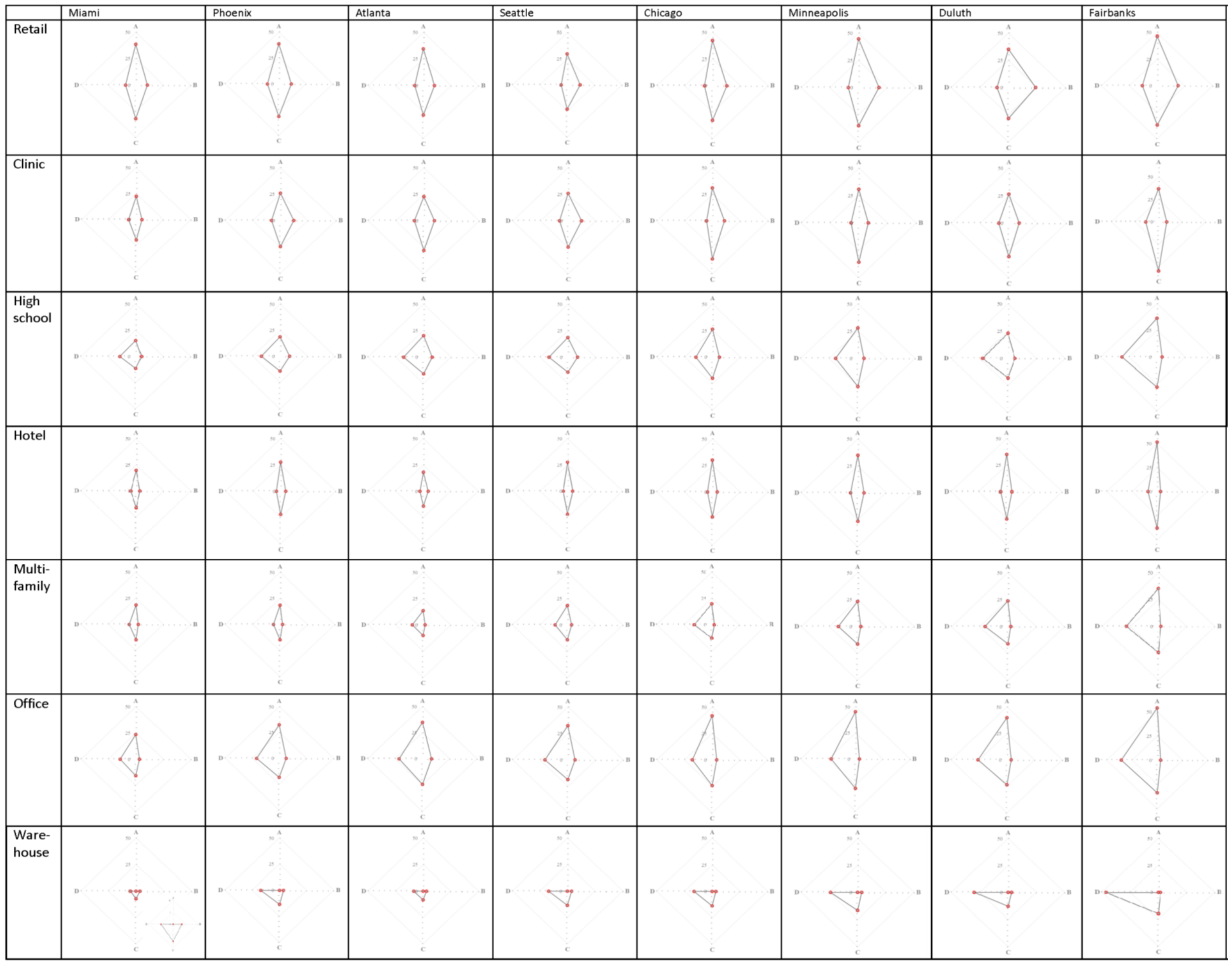
B.2.8 Fairbanks site EUI potential by strategies, groups and bundle (kBtu/sq. ft./yr)

	Retail	Clinic	High-school	hotel	Multi-family	office	Ware-house
Glass U-Value	23%	15%	22%	20%	26%	29%	13%
Glass SHGC	6%	2%	3%	5%	5%	4%	5%
Roof R-Value	1%	0%	1%	1%	0%	1%	1%
Wall R-Value	7%	4%	5%	4%	4%	7%	13%
Envelope Group	**31%**	**22%**	**34%**	**31%**	**33%**	**41%**	**23%**
Occupancy Sensors	1%	1%	2%	2%	0%	1%	1%
Dimming Daylighting Control	2%	0%	1%	1%	0%	1%	1%
Lighting Power Density	13%	8%	7%	9%	1%	6%	6%
Lighting Group	**15%**	**9%**	**10%**	**10%**	**2%**	**8%**	**8%**
Cooling Efficiency	2%	1%	1%	2%	2%	1%	1%
Heating Efficiency	11%	12%	11%	9%	11%	11%	14%
heat recovery	15%	20%	14%	8%	6%	5%	3%
ME system types	33%	35%	34%	34%	39%	31%	38%
ME Group	**61%**	**58%**	**60%**	**49%**	**59%**	**59%**	**73%**
RC	9%	6%	20%	7%	20%	27%	51%
WFR	37%	16%	24%	35%	30%	56%	0%
Window distribution	9%	10%	9%	12%	6%	17%	7%
orientation	3%	3%	3%	2%	1%	4%	2%
Typical Building forms	**35%**	**14%**	**37%**	**35%**	**40%**	**59%**	**40%**
bundle	69%	55%	60%	54%	52%	62%	46%

APPENDIX C. BUILDING OPERATION KEY INPUTS

	Size	lighting loads			people loads				vent. loads		set points				other loads						SHW				
		lighting w/sf	occ. sensor area	DL illu. Level	people den. ft/per	sen. Htg	lat. Htg	cmf/ per	cfm/ sf	max ACH	htg occ.	clg occ.	htg unocc	clg unocc.	plug load w/sf	sen htg	lan htg	other loads BUT/hr	sen. Heat	lan. Heat	gal/ day-per	OCC. MBTU	LGT MBTU	EQUIP MBTU	SUM MBTU
retail	16000	1.4	0%	50	67	250	200	7.5	0.12	n/a	70	75	60	86	0.3	1	0	0	1	0	0.26	50	119	7	**176**
clinic																						26	66	147	**238**
a. office	7200	0.9	30%	30	200	250	200	5	0.06	n/a	70	75	60	80	0.75	1	0	0	1	0	1				
b. treatment	6400	0.87	0%	50	200	250	200	n/a	n/a	6	70	75	60	80	2	1	0	0.33	1	0	3.01				
c. operatory	2400	1.89	0%	300	100	250	200	n/a	n/a	25	70	75	70	75	2	1	0	0.33	1	0	3.01				
high school																						78	65	94	**236**
a. classroom	8960	0.9	0%	30	40	250	200	10	0.12	n/a	70	75	60	80	0.88	1	0	0	1	0	0.61				
b. gym	2400	1	0%	30	33	710	1090	0	0.3	0	70	75	60	80	0.5	1	0	0	1	0	0.26				
c. office	3200	0.9	30%	30	200	250	200	5	0.06	n/a	70	75	60	80	0.75	1	0	0	1	0	1				
d. ed lab	480	1.81	0%	50	200	250	200	10	0.18	0	70	75	70	75	3.96	0.7	0.2	3.72	0.7	0.2	10				
e. dining	960	0.9	0%	30	10	275	275	7.5	0.18	0	70	75	60	86	1.53	1	0	0	1	0	3.35				
hotel																						100	90	126	**316**
a. guest rooms	11680	1	0%	5	200	250	200	5	0.06	0	70	72	70	72	2	1	0	0	1	0	11.5				
b. conference	2560	1.23	0%	30	20	250	200	5	0.06	0	70	75	60	80	0.25	1	0	0	1	0	0.26				
c. dining	960	0.9	0%	30	10	275	275	7.5	0.18	0	70	75	60	86	1.53	1	0	0	1	0	3.35				
d. office	800	0.9	30%	30	200	250	200	5	0.06	n/a	70	75	60	80	0.75	1	0	0	1	0	1				
multifamily																						30	42	45	**117**
a. apartment	12320	1.54	0%	5	380	250	200	5	0.06	0	70	75	70	75	0.62	0.7	0.25	0	0.7	0.25	18				
b. common area	1920	0.73	0%	30	100	275	275	5	0.06	0	70	75	65	80	0.5	1	0	0	1	0	0.26				
c. garage	1760	0.25	100%	1	na	250	200	0	0	0	50	na	50	na	0	1	0	0	1	0	0				
office	16000	0.9	30%	30	200	250	200	5	0.06	n/a	70	75	60	80	0.75	1	0	0	1	0	1	22	51	90	**162**
warehouse	16000	0.66	0%	5	0	275	475	10	0.06	0	60	80	60	80	0.24	1	0	0	1	0	0.61	0	56	23	**79**

APPENDIX D. BUILDING FORM PERFORMANCE SUMMARY



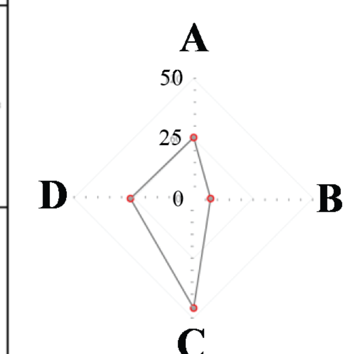
A: WFR

B: AZ

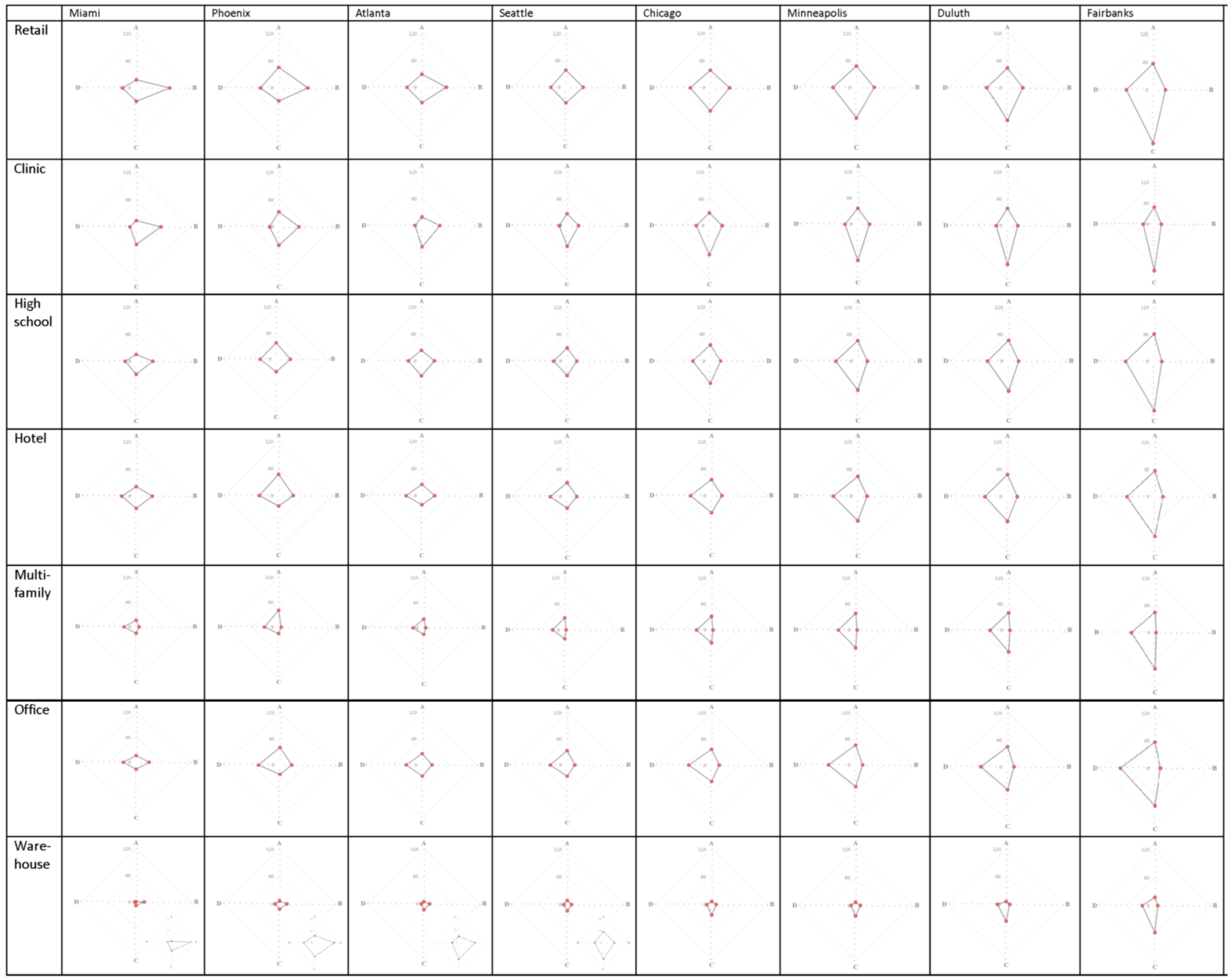
C: Win. Distribution

D: RC

Example



APPENDIX E. WHOLE BUILDING ENERGY PERFORMANCE SUMMARY



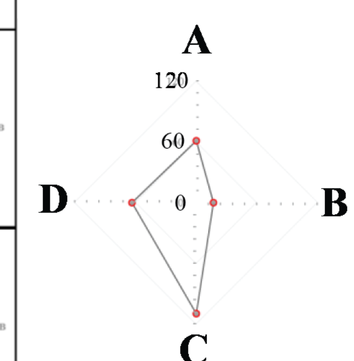
A: Envelope Group

B: Lighting Group

C: Mechanical Group

D: Building Form

Example



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