MODELING THE SPATIO-TEMPORAL VARIABILITY OF SOLAR RADIATION ON BUILDINGS:

A CASE STUDY OF LEWIS HALL

by

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LIST OF ABBREVIATIONS

AHU	Air Handler Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ANSI	American National Standards Institute
BIM	Building Information Modeling
BLEMS	Building Level Energy Management System
BMS	Building management System
CAD	Computer Aided Drafting
DOE	Department of Energy
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ESRA	European Solar Radiation Atlas
FORTRAN	FORmula TRANsaltion
GIS	Geographic Information System
GRASS	Geographical Resource Analysis Support System
HVAC	Heating, Ventilation and Air-Conditioning
PIR	Passive Infrared (sensor)
RGL	Ralph and Goldy Lewis Hall
SEDS	State Energy Data System
SQL	Status Query Language
UO	University of Oregon

USC	University of Southern California
VAV	Variable Air Volume (Box)

ABSTRACT

The Sun is the center of our galaxy and its patterns have been studied by civilizations since the beginning of time. Solar energy is a complex phenomenon that is the basis for life on Earth. Understanding the position of the Sun during the day is critical for evaluating how its energy impacts our daily lives. In an urban environment, the Sun's energy can be considered as a service as well as a burden. Solar energy is beneficial when it can be harnessed using solar collectors for electric generation or when it contributes to heat energy with passive heat gains in the winter. However, solar energy can cause unwanted heat gains during warm summer months when buildings are trying to keep occupants cool. Solar radiation models used to evaluate favorable conditions and locations have traditionally only required two-dimensional data for evaluation of terrain and rooftops. However, in order to attempt a comprehensive assessment of solar radiation effects with a built environment, three-dimensional data must be used to evaluate vertical surfaces as well. The proposed research can be used to evaluate solar radiation variations at a temporal scale resulting from a building's location as well as spatial variations resulting from changes in the urban landscape. The investigation is centered on an educational building, Lewis Hall, located on the University Park campus of the University of Southern California. The impacts of solar energy evident in the following research should be considered when evaluating and designing efficient building energy systems in the future.

CHAPTER ONE: INTRODUCTION

Building energy efficiency is the first step toward achieving sustainability in building operations. Energy efficiency helps control rising energy costs, reduces environmental footprints, and increases the value and competitiveness of buildings. A building's location has a major impact on the amount of energy consumption required to keep its occupants comfortable. Depending on geographic location, sun angles, wind speed and wind direction are just a few of the climatic factors that affect building performance. This leaves the question to be asked: how do a building's location, geometry and orientation affect a building's interior conditions?

This thesis project focuses on how solar energy impacts a building's envelope based on its geographic coordinates. The study aimed to provide a basis for determining what effects a building's location has on its energy efficiency performance and will demonstrate the need to link spatially-explicit environmental information with building control systems. This information may facilitate advanced programming which could allow prediction models to adjust for various conditions and to optimize building performance as well as identify specific areas of a building that may need improvements. Current building energy management systems anticipate the dynamic environment of the interior of a building, but what about the continuously changing environment surrounding a building? Building orientation and site considerations are typically evaluated in the early design phases of a building, but can these factors be evaluated at a more intricate level after the building has been occupied?

The envelope of a building is not only a two-dimensional external surface; it is also a three-dimensional object, a space where connections between outdoor forces and indoor conditions occur influenced by building materials and geometries. The envelope also has a fourth dimension, it changes with time and season, which, in turn, has a noticeable effect on the façade. Solar energy is either absorbed or transmitted by these materials while daylight is admitted or rejected. Building efficiency is closely connected to climate as well as the sun’s energy. HVAC systems are either battling against the Sun’s heat trying to keep the occupants cool, or making up for its absence by warming the occupants. Solar energy will be the focus of this research and the motivating research question is as follows: How does solar energy impact a building’s envelope and how does this vary over the course of the year and with building and landscape changes?

1.1 Research Objective

The guiding principle for this thesis is that improved building operation is feasible with respect to energy management and indoor environmental quality using GIS technology. The main objective is to demonstrate that outdoor environmental factors directly impact a building’s internal environment through space and time. Although these effects are dynamic, they are also predictable, and may be used to program improved building control systems.

The Sun’s energy has the most significant impact on the building exterior compared to other external factors, such as weather patterns. The patterns of the Sun’s path, angles, and intensity are also very predictable. For these reasons, the main focus will be on solar energy impacts on the buildings themselves and their correlation to building performance.

Building orientation and exposures are usually considered in the beginning phases of building design, i.e. the southern exposure is acknowledged to receive the largest about of solar heat and light energy from the Sun in the northern hemisphere for example. However, these factors are not typically evaluated in detail when documenting an existing building's energy efficiency.

The research study is centered on the Ralph and Goldy Lewis Hall, which is located on the University Park campus of the University of Southern California, in Los Angeles, California The amount of solar energy reaching the building's envelope is dependent on the urban landscape and/or surrounding built environment. In an urban setting, landscape transformations are common yet predictable. Therefore, current changes in landscape and site context surrounding Lewis hall will be taken into account in three progressive phases as part of a GIS-inspired solar impact analysis. The key questions to this study are:

1. What areas of the building receive the most solar radiation considering its true orientation and position and how does this change throughout the year?
2. How large is the impact from surrounding landscape features on the total solar energy input compared to unobstructed access?
3. How large is the impact from existing and new buildings on the total solar energy input compared to an unobstructed view?

1.2 Purpose

The cost of building operations far exceeds the cost of building construction (Muneer 2004). A sustainable building uses intelligent systems which respond to conditions in real-time while maintaining the comfort of the occupants (Yang et al. 2011). The main focus of recent research about designing efficient building energy systems acknowledges the dynamic behavior of the building occupants through predictable patterns, class scheduling, and real-time data from sensors. The thermal comfort of a building's occupants is the ultimate goal of HVAC systems. Yet, the existence of HVAC systems is to compensate for the exterior conditions by raising or lowering temperatures to an acceptable pre-determined level. Coupling exterior conditions with internal occupancy information will provide more detailed information to smart HVAC computer systems. In addition, an examination of the solar impacts on an existing building may provide insight into permanent or temporary changes that may be considered, to the building's design that may, in turn, lessen the load on HVAC systems. The results may provide a framework to make further adjustments to existing building energy management systems, resulting in higher efficiency and greater understanding of external effects on a building envelope.

1.3 Motivation

The problems associated with rapid urbanization of the world and its future sustainability cannot be solved without new technologies (Maktav, Erbek, and Jurgens 2005). Traditional methods for designing buildings and their associated energy systems do not fully take into account the spatial aspects of a building's location. However, the capabilities of Geographic Information Systems (GIS) technology coupled with Building Information Modeling (BIM) and energy simulation modeling provide new and innovative ways of analyzing how buildings function within their environment.

According to the U.S. Department of Energy (DOE), buildings consume 70% of the electricity used in the U.S. (Kelso 2011). Therefore, small improvements in building performance can have a substantial impact on the current energy crisis. Buildings and their associated systems are designed and programmed to suit the needs of the majority of their occupants. However, using broad standards, many assumptions are made in the design process. Consequently, many of the occupants may not be satisfied with the building's performance. Incorporating geospatial information throughout this process means that design performance can be evaluated using actual local conditions providing potential for more precise control and meeting occupant's needs.

The overarching motivation for this thesis research project was to demonstrate how spatial data could be incorporated into current systems and protocols such as the behavior-based BLEMS study being conducted on Lewis Hall. The thesis documents how the Sun's patterns affect a specific building within the changing urban landscape. Contrary to traditional GIS solar studies, this evaluation will use a three-dimensional simulation model, to analyze all four exposures of the building's envelope. In addition, there will be a discussion and evaluation of how this new information may improve HVAC systems by incorporating spatially and temporally dynamic environmental attributes into energy simulation models. The final result of the thesis research will be a more comprehensive understanding of how solar energy impacts building performance at a thermal zone level, which may lead to future improvements in building energy management systems.

1.4 Organization of the Thesis

This remainder of this thesis is arranged as follows. Chapter two summarizes prior research and methods for conserving building energy. This chapter also includes an overview of solar energy fundamentals and concludes with a summary of software programs that were evaluated according to the needs of this study. Chapter three starts by describing the case study building and surrounding geographic area. This is followed by a discussion of the methods and data that were used to conduct a comprehensive solar analysis. An overview of software inputs and explanations of the different levels of analysis are also provided in this chapter. Chapter four presents and discusses the results of the solar analysis study, highlighting what happens to solar energy inputs as you add existing buildings, new buildings, and various landscaping elements. Chapter five discusses the broader significance of the results, presents the conclusions that can be drawn from the analyses in addition to addressing the validation of the methods used, and briefly offers some suggestions for future work.

CHAPTER TWO: BACKGROUND AND RELATED WORK

There is limited research combining the fields of spatial science and building information management. For realistic evaluations, site-specific factors need to be included within whole building energy simulations to accurately assess their influence on building operation. Current energy management systems tend to focus on internal factors to evaluate and improve building efficiency. For example, several studies that have been conducted evaluated how occupancy alone can be used to improve building operations. Other studies are interaction-based, using occupant's behaviors to adjust building energy systems. Though many of these studies acknowledge the impact of exterior conditions, nearly all fail to incorporate external influence factors, such as solar energy, into the final models.

2.1 Building Energy and Efficiency

The worldwide energy crisis is an enduring problem. The U.S. is moving from a period of inexpensive readily available energy to a period where energy is expensive and will need to be budgeted accordingly (Hofman 1980). Fossil fuels are finite resources which currently supply 81% of primary energy consumption. The use of these energy resources are major contributors to CO_2 emissions which have increased 43% in the last two decades. The increase in these emissions has a direct effect on global warming and as a result, collaborative global efforts to reduce energy consumption and CO_2 emissions are critical for the future.

2.1.1 U.S. Energy Consumption

As of 2010 the energy consumed by the U.S. accounted for 19% of global consumption, making it second only to China, in terms of the energy used by any country (Kelso 2011) (Figure 1). This is an increase of 48% since 1980. Of the amount of energy used by the U.S., 41% can be assigned to the building sector alone. This means that the energy used by residential and commercial buildings within the U.S. alone accounts for 7% of global consumption.

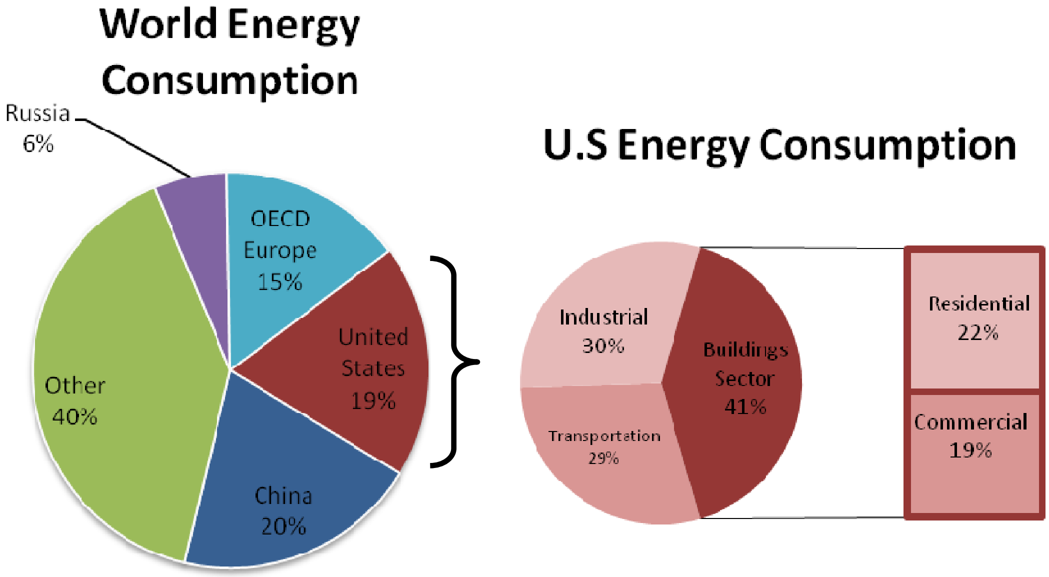

Figure 1 World and U.S. energy consumption
Source: Data adapted from Kelso (2011)

Heating, ventilation, and air conditioning (HVAC) operations are the main power loads within a building, consuming 49% of the total energy used for building operation (Kelso 2011) (Figure 2). Therefore, HVAC energy use in the U.S. alone is responsible for

3.43% of the entire global energy usage. Buildings also account for 82% (or $302 billion) of total U.S. electricity expenditures. Because HVAC systems account for a substantial portion of energy consumption, optimizing the efficiency of HVAC and associated systems is an ideal target for improvement.

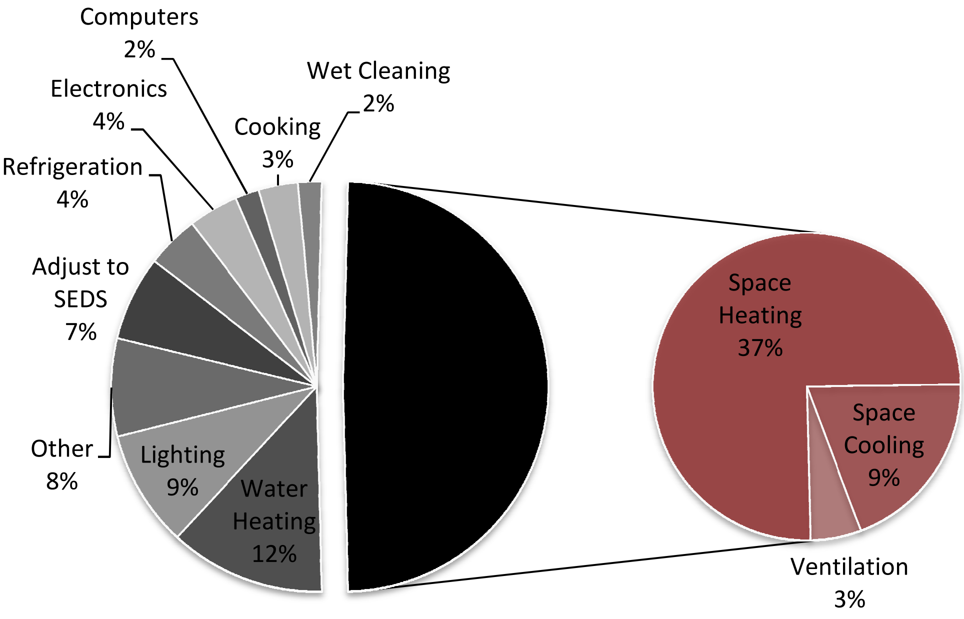

Figure 2 Building energy usage by percentage
Source: Data adapted from Kelso (2011)

2.1.2 HVAC Background

Efficient HVAC systems are the key to efficient buildings. The primary purpose of HVAC systems is to add or remove heat from the air. The secondary concern is to control humidity levels, typically by removing moisture in the summer and adding moisture in the winter. This is achieved through a variety of mechanical and electrical systems used to provide thermal control in buildings. Control of the thermal environment is a primary concern for practically all occupied buildings. This idea dates back thousands of years, when such control may have provided means of survival during cold winters. In the perspective of today's world, thermal controls are much more complicated given that thermal comfort and air quality directly influence occupant health, satisfaction and productivity. The sensation of feeling hot or cold is not dependent on air temperature alone. Thermal comfort is affected by heat conduction, convection, radiation, and evaporative heat loss. In some cases, thermal comfort can be achieved by ventilation alone, by increasing air movement to encourage evaporative cooling of the skin.

Understanding how a typical HVAC system operates is the first step to isolate major energy consumers and locate target areas to reduce energy consumption. HVAC systems typically include chillers and boilers which provide heated or chilled water to one or more buildings. Air handler units (AHUs) mix outside air with returned indoor air and cool or heat the mixed air according to a set point. The air is then distributed via ducts and fans to thermal zones throughout the building. A thermal zone is an indoor space or group of spaces with similar thermal loads. Each thermal zone is served by at least one variable air volume (VAV) box, which will reheat the air, if needed, to meet the temperature set point of that zone. Two major energy consumers in this process are the AHUs at a building level and the VAV boxes at the thermal zone level (Li, Calis, and Bercerik-Gerber 2012).

Standards must be recognized when evaluating building efficiency to maintain thermal comfort and quality of indoor air. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) publishes standards addressing energy efficiency, indoor air quality, refrigeration and sustainability of building systems which are commonly accepted by architects and engineers and further implemented in building codes. The ANSI/ASHRAE Standard 55, for example, refers to Thermal Environmental Conditions for Human Occupancy. The purpose of the standard is "to specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants in a space (ASHRAE 1992).

2.2 Building Energy Conservation Strategies

The drive to reduce overall energy consumption in dynamic environments is an important goal of effective building energy management. Although factors such as temperature, lighting and air quality are regulated by standards, temperature and lighting can be controlled within a specific range to save energy. There are many ambient factors that affect the behavior of building occupants as well as how they perceive their surroundings. These perceptions have a direct effect on productivity levels.

Many modern buildings today use HVAC systems that are programmed to operate assuming maximum occupancy during operational hours. However, average occupancy in office buildings has been observed to be only one-third of the design occupancy, even during peak times of the day (Brandenmuehl and Braun 1999). Most HVAC systems make adjustments throughout the day based exclusively on indoor air temperature and humidity inputs along with assumptions about occupancy (Li, Calis, and Bercerik-Gerber 2012; Yang et al. 2011). These assumptions result in many buildings and unoccupied spaces being over-conditioned and consequently, wasting energy and money in the process (Erickson and Cerpa 2010).

2.2.1 Demand Driven HVAC

Demand driven HVAC operation is a strategy that aims to reduce HVAC energy consumption by relying on occupancy information to adjust cooling/heating loads during peak- and off-peak times. Typically, HVAC systems must wait for thermostats to detect a change in temperature before responding. However, faster HVAC which respond to changes in heat loads using three levels (low, medium, and high), have produced energy savings of up to 50 percent in one simulation (Tachwali, Refai, and Fagan 2007). There is a range of strategies that can be used to adjust parameters, such as temperature and airflow, based on actual demand when operating HVAC systems (Table 1). The energy savings associated with each strategy are strongly dependent upon building type. Several studies indicate energy savings of 10-60 percent using different monitoring systems. Table 1 outlines several strategies, methods, and area of focus for demand controlled HVAC.

Occupancy information is important because it determines the heating and cooling loads in specific areas of a building. It is defined as the number and identities of occupants in a thermal zone and their associated activities occupancy (Li, Calis, and Bercerik-Gerber 2012). Current building management systems use occupancy information as a part of their functionality. However, most sensors installed in buildings are generic and only control lighting, which does not have as large of an impact on energy consumption. Also, the sensors involved are not accurate enough to provide

Table 1 Building energy management strategies

Study	**Building type**	**Method**	**Application Focus**	**Energy savings**
Pavlovas (2004)	Residential (multi-family)	Real time monitoring	Reduce ventilation flow for unoccupied areas	20% (ventilation energy only)
Agarwal et al.(2010)	Educational	Real time monitoring	Maintain higher temperatures in unoccupied areas	10-15%
Ogasawara et al. (1979)	Department store	Occupancy scheduling	Adjust outdoor air load according to predicted hourly occupancy estimates.	20-30%
Yang et al (2011)	Educational	Real-time monitoring	Minimum ventilation rates per ASHRAE standards based on occupancy estimations.	15% (ventilation energy only)
Sun, Wang,and Ma (2011)	High-rise	Real-time monitoring	Supplying airflow based on occupancy	56%
Klein et al. (2012)	Educational	Occupant preferences	Operating HVAC systems based on preferences	13.6%
Erickson and Cerpa (2010)	Office	Energy consumption patterns	Using energy profiles and trends to predict energy needs.	20%
Tachwali, Refai, and Fagan(2007)	Multi-zone	Real-time monitoring	Hierarchical cooling rates for HVAC based on quick response according to occupancy	50%
Erickson and Cerpa (2010)	Educational	Real-time monitoring	Adjusting outside air volume based on occupancy	14%
Lo and Novoselac (2010)	Office	Occupancy control	Increasing flexibility of control by dividing large open areas	N/A
Bourgeois, Reinhart, and MacDonald (2006)	Single office space	Energy consumption patterns	Automatic lighting control based on usage patterns	40%
Jazizadeh et al. (2012)	Office	Real-time monitoring	Lighting system control based on current occupancy information	N/A

sufficient energy savings for demand-driven HVACs. Detection systems are designed to function at various scales or levels. Some methods are only accurate for building level occupancy detection, while other systems can only predict occupancy at the room level. Building occupants have a range of activities that vary from stationary to mobile. Because of the dynamic behaviors of a building's occupants, building systems should be able to actively respond to these behaviors.

Each strategy uses different types of occupancy information for input: Real-time detection; occupancy scheduling; occupancy controls; and energy consumption patterns. There are two types of real time detection strategies: individualized and non-individualized. A non-individualized approach uses monitoring systems with binary logic to determine if a space is occupied or not. The individualized method uses sensors and monitoring devices to determine a specific count of persons in an occupied space. Occupancy scheduling predicts patterns of movement and usage throughout a building using predetermined schedules as inputs in Building Management Systems (BMS).

The occupancy control strategy records preferences of persons occupying a space and adjusts HVAC to maintain those settings when the space is occupied. Learning trends and creating energy profiles can be beneficial for more efficient HVAC by adjusting energy needs based on consumption patterns. Although the accuracy of these systems could be improved, any amount of energy savings is valuable compared to a building without occupancy detection methods. The real time detection strategy proves to be the most beneficial because HVAC systems are able to adjust for the actual demand instead of the predicted demand.

2.2.2 USC BLEMS Project

Research has been conducted on real-time occupancy information as an input to demand driven HVAC systems at USC. The Building Level Energy Management System (BLEMS) project used Lewis Hall as a test bed to study the behavior of a building and its occupants in real-time. Figure 3 illustrates how BLEMS communicates with other systems as well as its own internal hierarchy. The objective of the research is to reduce building energy consumption by integrating advanced occupancy detection while maintaining thermal comfort levels (Yang et al. 2011).

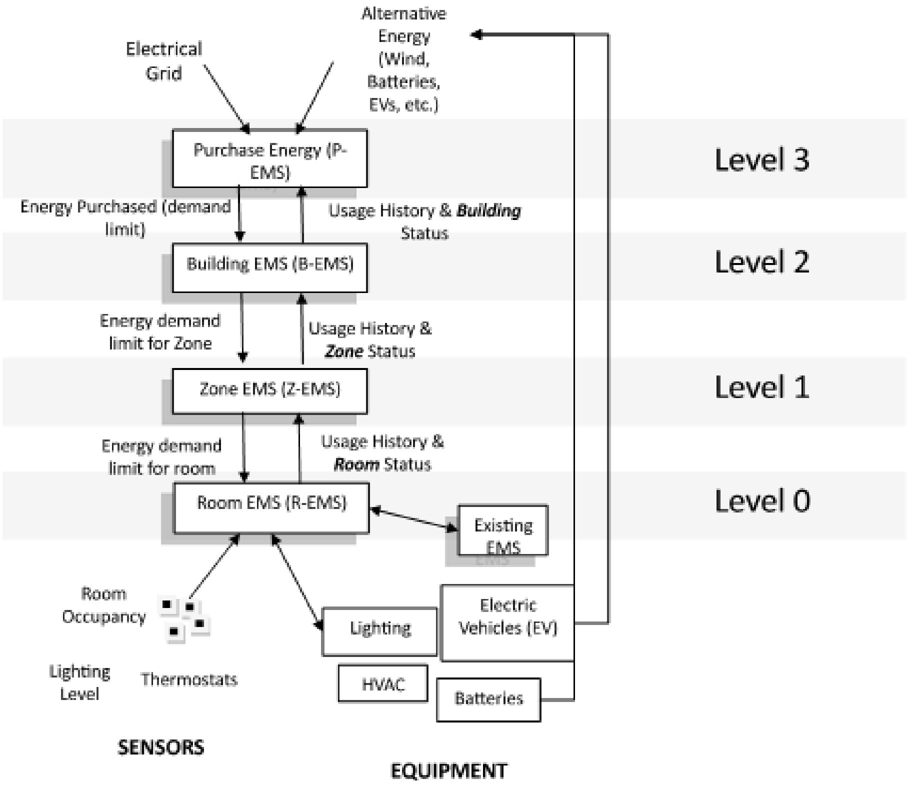

Figure 3 BLEMS hierarchy (from Rossler 2012)

Real-time sensing of the environment allows HVAC systems to run based on actual demand instead of estimated peak demand. This is accomplished by learning and adapting to occupant and building behavior by balancing consumption with occupant comfort levels. The self-contained system also recognizes existing systems and adapts to new systems and communicates with them to support integration. BLEMS is hierarchical because it supports the concept of a building composed of several zones; each containing one or more rooms. The goal is to design improved occupancy detection systems which are affordable, high-resolution, accurate, and non-intrusive.

One approach uses multiple sensors for occupancy detection and estimation (Yang et al. 2011). The BLEMS sensor nodes use wireless technology to minimize obstruction and allow for easy installation. Each sensor is installed in close proximity to room entrances to detect occupancy. Each sensor node consists of seven sensors which detect light, sound, motion, CO_2 concentration, temperature, relative humidity, motion, and people passing by. Eleven values retrieved from the sensors are reported at one minute intervals. These data are categorized into three sets of values; instances, counts and averages. The instance values are readings of each of the seven sensors at the time it is queried. The count variable tallies changes over the course of a minute from the motion sensor and passive infrared (PIR) sensors. The average variable averages data from the sound sensor in five second and five minute intervals. These data are time-stamped and stored in a SQL database. The results have the ability to estimate the number of occupants with up to 88% accuracy.

Another method for demand-driven HVAC addressed by the BLEMS research team at USC uses radio frequency identification (RFID) to track mobile and stationary occupants (Li et al. 2012). This individualized monitoring approach uses tracking tags which are attached to occupants to monitor their coordinates and identities. The RFID system has the ability to monitor multiple spaces simultaneously and reports the results in real-time. The results provide a framework for demand-driven HVAC operations which respond in real-time to the occupancy detection inputs. Average detection rates were simulated with accuracies of 62% for mobile occupants and 88% for stationary occupants. Through the integration of occupancy detection systems with demand-driven HVAC operations energy consumption is expected to be reduced.

The BLEMS models and research at USC addresses many issues regarding occupancy behavior and scheduling in efforts to program demand-driven HVAC systems. -It is clear that for more efficient HVAC operation, the dynamic behavior of a building’s interior environment must be anticipated. Yet, what about the exterior environment and how those conditions affect the building envelope itself? In the previous research few studies have accounted for how spatially-explicit environmental attributes regarding a building’s location can be used to program more efficient HVAC systems. Through research, Tachwali, Refei, and Fagan (2007) found that HVAC systems that respond quicker to temperature changes proved to be more efficient. Climate can be predicted similar to occupant behavior with high levels of accuracy. Sun patterns and solar energy received from the sun are in fact very predictable. The integration and correlation of interior and exterior environmental changes may afford new opportunities to further reduce building energy consumption.

2.3 Solar Radiation

The sun is the primary source of heat and light and responsible for life on Earth. Understanding the Sun’s relationship with Earth is critical for site planning, efficient building design, and controlling unwanted heat gains. The Sun is a giant star and the largest object in our solar system. The energy of the sun is a result of nuclear fusion that occurs at temperatures ranging from 18 to 25 million degrees F (Stein et al. 2006). This energy is released as electromagnetic radiation, at approximately 10 million degrees F and travels 93 million miles before it reaches the Earth. The portion of the electromagnetic solar spectrum that reaches the Earth is about 5% ultraviolet shortwave radiation (0.01µm-0.4µm), 46% visible light (0.39µm-0.78µm) and 49% infrared radiation (0.7µm-1,000mm) (Campbell and Wayne 2011).

Solar radiation (W/m²) refers to the amount of energy released from the Sun that reaches the atmosphere measured by energy over surface area (Muneer 2004). Luminance refers to radiation values received solely from the visible spectrum. Irradiation (Wh/m²) is the total energy incident on a surface during a specified period of time. Instantaneous incident energy on a surface is referred to as irradiance (W/m²) (Suri and Hofierka 2004).

The amount of energy that is received at the top of Earth’s atmosphere is relatively consistent at 1366.1 W/m², known as the solar constant (Stein et al. 2006). Approximately 30% of this radiation is reflected back into space by particles within the atmosphere, clouds, and from the surface of the Earth, resulting in a global albedo factor of 0.3. Around 19% of the solar radiation is absorbed by the clouds and dust within the atmosphere. Insolation is the term used to describe the remaining 51% absorbed by the Earth's surface, 696 W/m², which is composed of 341 W of infrared radiation, 320.16 W of visible light, and 35 W of ultraviolet radiation. Figure 3 illustrates the components of incoming solar radiation.

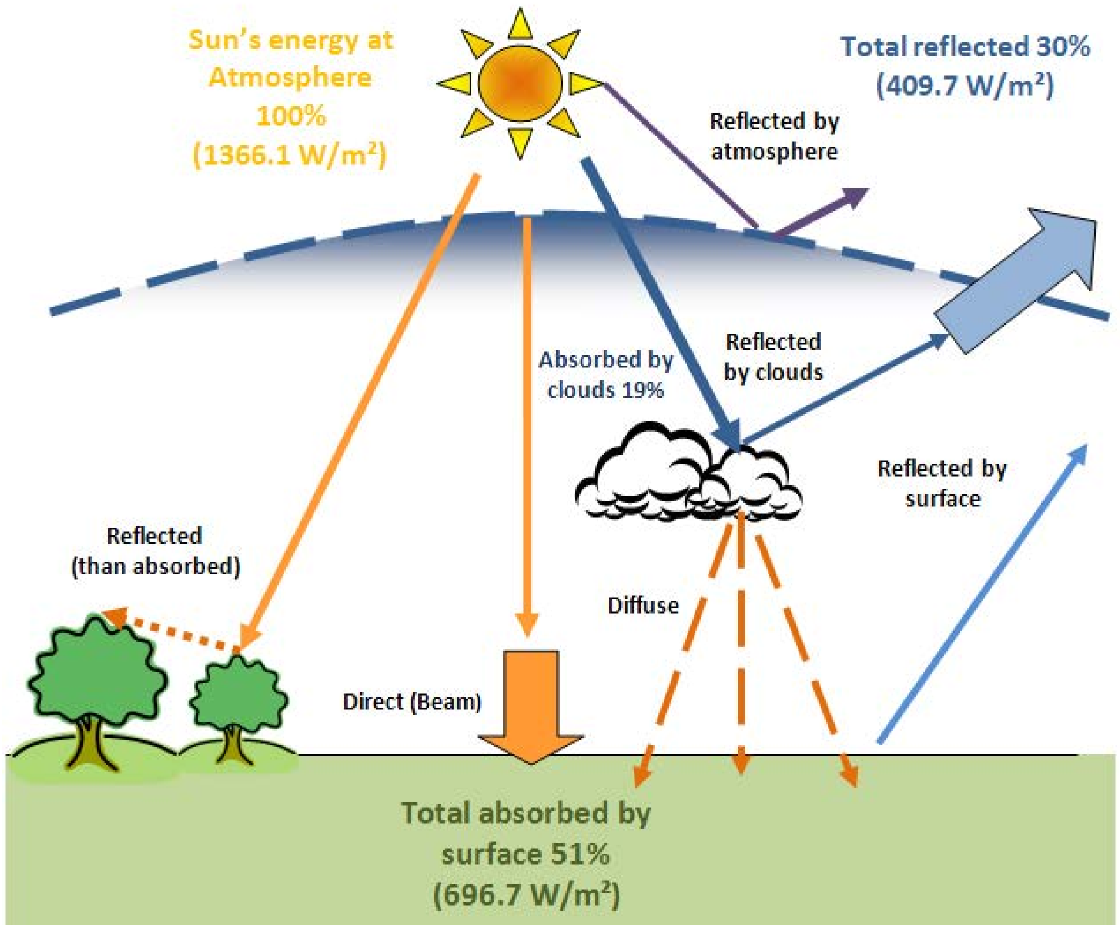

Figure 4 Components of solar radiation

Source: Data adapted from Campbell and Wayne (2011)

Global radiation is the sum of three components: direct, diffuse and reflected radiation (Súri and Hofierka 2004). Direct (beam) radiation is the largest component of global radiation because it travels the shortest path, reaching the surface unobstructed. Diffuse radiation passes through the atmosphere and is scattered by clouds and dust before being absorbed at the surface. Reflected radiation is absorbed on non-flat surfaces after being reflected from surface features. Shadows are exclusively the result of direct radiation because all rays travel parallel to each other in the same direction; therefore, an object is able to block all the rays at once.

The length of the radiation path is the primary factor in determining how much radiation is received at the Earth’s surface. The effects of solar radiation with the Earth’s atmosphere and surface can be grouped according to three factors (Súri and Hofierka 2004):

1. Global factors – Earth’s revolution and rotation (declination, latitude, solar hour angle)
2. Landscape factors – Elevation, surface inclination and orientation, shadows
3. Atmospheric factors – Clouds, gasses and particles

2.3.1 Global Factors

At a global scale, the Earth’s rotation, (every 24 hours) and tilt have the largest impact on global radiation. These factors cause variations in the length of atmosphere that radiation must pass through before it is received at the Earth’s surface. The Earth's axis of rotation is tilted at 23.5° and is also known as its declination (Stein et al. 2006). This tilt is responsible for the seasonal variations (Figure 5). In the Northern hemisphere the Earth tilts away from the Sun in December (-23.5°) resulting in fewer hours of sunlight and longer paths by which direct radiation travels in non-perpendicular angles to the surface. This is evident by winter's low sun altitude and cold weather. The effect is the opposite in June (+23.5°) where the sun reaches its highest altitude. Warmer weather is a result of increased amounts of direct radiation traveling a shorter distance perpendicular to the surface.

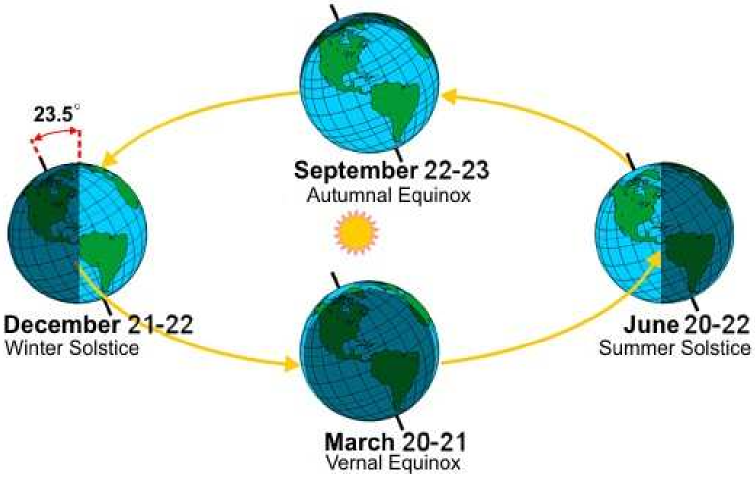

Figure 5: Annual elliptical path of the Earth around the Sun (from NOAA 2013)

The sun is the primary source of heat and light and when analyzing its effects on building function and design, it is necessary to account for how it moves through the sky. The Sun path refers to how the Sun appears to move through the sky with respect to a point on the Earth's surface. The angle between the horizon and the Sun's position above the horizon is the altitude angle which is 0° at sunrise and sunset (Stein et al. 2006). The maximum altitude the Sun reaches during the day is called the solar noon. The altitude of the solar noon varies throughout the year, reaching its highest point on June 21st (summer solstice) and lowest point on December 21st (winter solstice). The altitude angle has a significant effect on the amount radiation received at the building surface and in terms of the design and efficacy of shading devices. The Sun's path is unique for any given latitude. The altitude at solar noon can be found for any location by subtracting degrees latitude from 90° and adding (for locations north of the equator) or subtracting (for location south of the equator) the Earth's declination of 23.5°. Figure 5 illustrates the Sun's altitude angles for Los Angeles, California which has latitude of approximately 34° N.

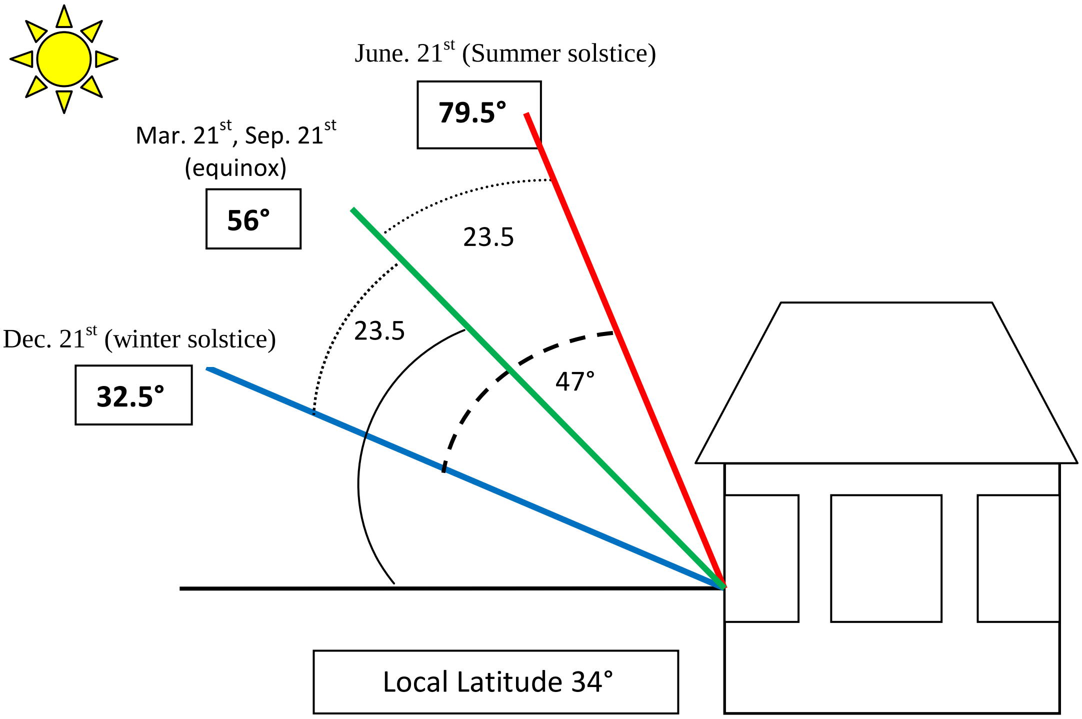

Figure 6 Solar altitude over a year based on Los Angeles, CA

The azimuth angle, or solar bearing angle, is the angle along the horizon between the position of the Sun and true south. In the Northern Hemisphere the sun rises due North of East in the summer, Due East at each equinox and due South of East during the winter. The azimuth angle is significant when considering building orientation, analyzing building exposures and reviewing shadowing angles (as will be discussed later).

The Sun path charts represent the three-dimensional characteristics of the Sun’s path throughout the year onto a two-dimensional surface in Cartesian coordinates (Stein 2006). A rectilinear Sun path chart for Los Angeles, CA can be found in Appendix A. This type of chart is a graph that is created from an observer’s perspective where the vertical center is an observer looking due south. The azimuth is plotted along the horizontal axis and altitude on the vertical axis. The horizon, a horizontal plane at the observer’s eye level, is represented at the line at the bottom of the chart. It is important to note, that the Sun’s path is only plotted for the months of January through June because after the summer solstice the Sun path repeats itself for July through December. The emphasis on the South orientation calls attention to the characteristics of receiving more sun in winter and less sun in any other orientation.

2.3.2 Landscape Factors

At local and regional scales the topography is the main factor in determining distribution of insolation. Variations in elevation, surface orientation (slope and aspect) and shadows cast from surface features result in high spatial and temporal differences in local radiation values. Variations within the urban surface result in high levels of heterogeneity for surface radiation at spatial and temporal scales (Fu and Rich,2000). There are thousands of weather stations around the world which monitor solar radiation yet, for urban areas point specific measurements are not useful for accurate insolation data because of the complexity of the landscape.

2.3.3 Atmospheric Factors

During dry and clear sky conditions, at solar noon; global radiation is at the maximum value for a given day and location. Clouds are the largest blockers of radiation. As cloud cover increases, the percentage of global radiation resulting from direct radiation decreases and the percentage resulting from diffuse radiation increases. Uniform overcast sky (UOS) refers to a consistently cloud covered sky. In this scenario direct radiation is at its lowest value and diffuse radiation accounts for the largest amount of global radiation (Hofierka and Zlocha 2012). Moisture within the air, measured as humidity, has a direct effect on temperature resulting from increased levels of solar absorption.

Aerosols and dust particles within the atmosphere, resulting from pollution, may reflect and absorb radiation and thereby impact the amount of total insolation at the Earth’s surface as well. Levels of pollution in urban areas have a drastic effect on sunlight increasing the amount of scattering and absorption of diffuse radiation by 40-70 percent and reducing the amount of direct solar radiation by 30-50 percent (Santamouris 2001). For example, research has indicated that Los Angles receives approximately 50 percent less sunlight compared to surrounding rural areas.

2.4 Solar Radiation and Heat Transfer Effects in Buildings

Thermal comfort is a function of personal health factors, air movement, relative humidity, ambient air temperature and mean radiant temperature. Heat transfer in buildings occurs through convection, conduction, and thermal radiation through the roof, walls, floors and windows. The flow of heat through a building varies by season and by path of heat flow (materials, intentional and unintentional air pathways). Thermal radiation moves from the warmer surface to a cooler one. The main source of heat transfer is radiant energy received from the Sun. Solar radiation that is absorbed heats the surface and is no longer solar energy. The absorbed energy is exchanged through conduction with the layer directly behind the exterior surface.

The effects of solar radiation heat transfer occur at the roof, the walls and via the windows. The U-factor is a coefficient that is used to measure the thermal transmittance of a material, expressed in Btu/h ft^2 °F (Campbell and Wayne 2011). Low U factors indicate a better insulation factor and therefore the decreased ability to transfer heat. Opaque building materials such as walls, floors, and roofs are usually insulated. Insulation and building materials have the greatest impact on how heat is transferred and stored within a building. The roof is the uppermost part of any building and is the main element impacted by solar radiation. It receives the most sun during the day and throughout the year. The temperature throughout the day can vary greatly making it susceptible to heat transfer into the building and increasing radiative heat transfer. When a floor is exposed to outside air, the heat transfer properties are similar to that of roofs and walls.

Windows are the most notable and predictable site for thermal radiation. They transmit solar heat into a building which is favorable in the winter and unfavorable in the summer. Windows allow thermal radiation to pass in a building during daytime and out of the building during the nighttime. The U factor for windows is generally high because they are difficult to insulate and store a minimal amount of heat. The effects of this heat transfer are varied by insulated glazing, internal and external shading and orientation. Solar heat gain in most building models will be greatest at the windows. The wall to window ratio is also important to consider in analyzing solar heat gain.

The objective of solar radiation control is to decrease the cooling load on a building. The intensity of summertime direct solar radiation on horizontal surfaces such as a large area of low slope roof makes the roof the primary target for solar radiation control.

Most research in the field of solar radiation effects on buildings has aimed to evaluate the potential of solar collectors for energy capture. In this context, models and calculations used only regard the roof surface of a building, and do not require three-dimensional analysis of the entire building envelope. The following case study regarding passive heat gains evaluates solar impacts on a temporal and spatial scale, but most importantly it acknowledges the entire building including the exposure of the vertical surfaces.

2.4.1 Case Study: Urban Density and Passive Solar Heat Gains

The basis of passive solar heating involves using the direct gain of solar heat through windows, usually south facing, to reduce heating costs during colder times of the year. Active solar heating refers to using solar collectors to store solar energy.

Research performed in northern Europe analyzed the concept of passive solar gain and how building energy consumption is affected by surrounding context (Strømann-Andersen and Sattrup 2011). The context which is the variable in this study refers to the urban canyon, which is measured as a ratio of building height to width of space between the building being studied and the next building. The lowest ratios represent areas that are typical of urban squares, and the highest ratios represent conditions that are typical of alleyways and narrow boulevards. Energy consumption was examined based on five primary needs: Heating load, cooling load, lighting, ventilation and Domestic Hot Water (DHW).

The results indicate an increase in general energy consumption as the density of the surrounding environment increases. Cooling demand was shown to be reduced due to overshadowing in warmer seasons, but the reduction in solar heat gains in cooler seasons caused an increase of heating costs. Though artificial lighting is highly variable, the estimation model indicates that energy usage doubles when comparing the unobstructed model to even the lowest density ratio. Lighting energy usage increased six times when compared to the highest density model. The study also compared energy usage depending on the building floor height. The results showed that the building energy consumption increases the closer to the ground a level is located. Comparing building orientations, the results showed that unobstructed context favors buildings oriented in a North/South direction, while East/West orientations were more efficient in increased urban density models.

2.5 Solar Modeling and Building Simulation Tools

Solar radiation is a very complex phenomenon. Methods and models used to understand and analyze the Sun’s energy range from simple to complex. Solar radiation models provide the means for understanding the spatial and temporal variation of insolation over various landscapes under varying conditions. Building simulation tools offer cost-efficient methods to evaluate factors that affect a building’s performance. It can be assumed that the less energy a building uses the more sustainable the building will be. Several software programs were reviewed before selecting methods that will produce the most ideal results for the thesis case study. Table 2 summarizes the characteristics of the software.

2.5.1 Calculation-Based Models

FORTRAN, an acronym for FORmula TRANsaltion, is one of the most widely used programming languages for engineering applications (Muneer 2004). Having been in use for over 55 years, there is a large number of programs that have already been developed. Muneer (2004) describes a series of FORTRAN programs that evaluate virtually all aspects of solar radiation and illuminance computations. As described before, there are several complex factors that need to be considered for the dynamic evaluation of solar energy .FORTRAN has the ability to calculate such complex algorithms quickly, for a

Table 2 Summary of software characteristics used for solar modeling and building energy analysis

Software	Level of knowledge	Input	Strength	Weakness	Availability
Calculation based					
FORTRAN	Advanced	Solar algorithms	Quick calculations	Output is not graphical	Requires many separate programs for full implementation
Energy PLUS	Intermediate	Hourly weather files plus Building characteristics in database format	Accurate detailed simulations	Text input	Free download
Two-dimensional					
PARASOL	Fenestration knowledge	Site and building specifications	Comprehensive analysis of window systems	Only focuses on window systems	Free Download
ArcGIS Solar Analyst	Basic GIS knowledge	DEM weather station data	Fast and accurate calculation	2-dimensional DEM data is not publically available at high resolutions	ArcGIS software license with spatial Analysis extension
Grass GIS *r.sun* module	GIS knowledge required	DTM	Best for use over large areas	2-D Data, Preparation for in input.	Free-open source code
Remote sensing	Basic	Aerial imagery	Most accurate Solar analysis for a given time and location	Limited Temporal scale	Location specific results are available at select city portals.
Green building studio	BIM knowledge	3-D CAD file	Entire building energy analysis	Process is complicated	Requires license
Three-dimensional					
SketchUp	Basic	Building dimensions/location	Simple to use	Shadow analysis only	Free download
Grass GIS *v.sun* module	GIS knowledge and Script development	raster, vector-voxel data formats	3-D	Not fully developed Limited output	Not publically available
Ecotect	Basic CAD knowledge	3D design data Weather Data Tables	Whole building analysis in 3D Flexible options	Varying data requirements Time consuming for detailed models	Free license for students

range of scenarios, at variable spatial and temporal scales. The files created can be embedded into infinite simulations or external energy simulation programs.

Although, FORTRAN code, in itself, was developed for easy understanding, intermediate knowledge of computer programming, as well as a variety of software programs, is required to edit, compile, and run the aforementioned simulations. While very efficient and accurate, the output of FORTRAN programs are primarily computationally bound, i.e. used to generate sets of numbers, providing no direct visual analysis. However, many of these solar models have been tested over time and evaluated for accuracy, requiring little need to edit actual source code and algorithms. Fortunately, many energy simulation programs incorporate these solar models within their software.

The U.S. Department of Energy's Energy Plus is a complete building analysis program that calculates energy performance and life cycle costs of operation. One of the main strengths is that is can be used to analyze energy efficacy given specific designs or new technologies. However, a high level of knowledge is required along with advanced training to use this program effectively.

2.5.2 Two-Dimensional Modeling

The Solar Analyst module in ArcGIS uses georeferenced digital elevation models (DEMs) to calculate radiation (Wh/m^2) at the surface and locals scales (Fu and Rich 2000). Solar radiation analysis tools are available with the ArcGIS software to analyze area or point radiation (Esri 2008). The point specific model calculates insolation at a location based on surface orientation and visible sky. Local topography is taken into account based on ground-based observations. While point specific models are highly accurate for a given location, an enormous number of calculations would be required to determine insolation over a landscape, and furthermore would prove difficult in an urban landscape.

The area-based model considers insolation over a geographic area by calculating surface orientation and shadow effect data from input DEMs. The results are only as accurate as the resolution of the DEM. High resolution DEMs are not always publically available and are typically not cost-effective to create within the scope of a project analysis. The solar flux model simulates how shadow patterns influence direct radiation, using the hillshade function at specific points in time. In addition to long computation time, there is relatively little flexibility in terms temporal scale. Also the results from using these methods are only available for 2-dimensional surfaces. There is a 3D Analyst extension, but the functionality of this product is currently limited to visual analysis.

GRASS (Geographical Resource Analysis Support System) is a free GIS developed in an open source environment used for geospatial data and analysis (GRASS 2013). Different modules and scripts can be added to this program to perform varying kinds of analyses. The r.sun module for example was developed and is primarily used to estimate photovoltaic potential on roof tops (Súri and Hofierka 2004). It uses raster data, such as Digital Terrain Models (DTMs) for input, output, shadowing algorithms and solar radiation calculations. It calculates all three levels of solar radiation (direct, diffuse, and reflected) for clear and real sky conditions. The *r.sun* module is ideal for measuring data over large areas with complex terrain. A drawback of this software is that complex data preparations are required to compile the inputs. In addition, the *r.sun* module is only capable of measuring values in 2-dimensions which is only effective for measuring solar insolation on land surfaces (terrain) and rooftops (Hofierka and Zlocha 2012).

Solar maps have been created for several cities throughout the US to estimate the solar potential of areas within the city. These maps are generated from a combination of aerial imagery, solar potential software, and solar engineering models (Dean et al. 2009). Two kinds of input are needed to generate a solar map; topographical and meteorological data. Topographical data can be obtained from Light Detection and Ranging data (LiDAR) imagery which is used to create a surface model. Solar potential software, ArcGIS for example, is then used to determine the amount of solar insolation which strikes the ground over the course of the year. Building information extracted from LiDAR data is used to create Digital Surface Models (DSMs) which take into account shading obstructions, roof tilt and surface area. This information is overlaid onto the resulting solar insolation model. The final product is a two-dimensional map that represents the amount of solar insolation received on the top of surface features. The Los Angeles County Geoportal provides access to a solar map for the entire county at http://solarmap.lacounty.gov/ for example.

Although the methods used to create solar maps may be very accurate, data is not always readily available, and can be expensive to obtain. Solar maps are primarily used as a source for determining the placement of solar panels on rooftops. Also, this type of solar map returns only one final value: Annual total radiation and further temporal adjustment of the results are possible.

2.5.3 Three- Dimensional Modeling

Trimble SketchUp is a three-dimensional modeling software program that is simple to use and available for free download. Many real-life 3-dimensional models are linked to Google Earth via .kml files. The inputs of geographic coordinates are useful for evaluating realistic shadow effects. SketchUp makes basic three-dimensional modeling simple, but cannot handle the complex, detailed models that will be used in this study. Many third party plugins are also available but may not be valid or stable.

The *v.sun* module, for example, is based on the methodology used in the r.sun module but has the added capability to process three-dimensional vector solar data (Hofierka and Zlocha 2012). Spatially variable solar parameters and shadowing algorithms are input in raster/voxel formats. Using a combined vector-voxel approach, the volume structure of a region (voxel data) is divided into smaller polygons which define the distribution of 3-D vector objects. The module has two modes for calculation. Mode 1 is used for instantaneous calculation of solar incident angles (degrees) and solar irradiance (W/m^2) which is output in a 3-D vector-based format. Mode 2 uses the 3-D vector based data to provide daily sums of solar radiation (Wh/m^2) and daily direct-sun duration (minutes). Further use of the *v.sun* module requires advanced knowledge of computer languages and scripting. The basic operation of this module could not be tested because it has not been made publically available by its developers.

PARASOL is a basic energy simulation tool used to evaluate solar protection devices and glazing types. The output is monthly totals of direct solar energy transmittance of the sun shade or window system. It also provides an evaluation of the influence of the shading device on building energy and performance. Although simple to use, this software must be used in addition to other tools and models because it provides a very limited portion of a complete building energy analysis.

Green Building Studio is a building information modeling program developed by Autodesk. It is a web service that generates detailed input files for energy simulation programs. It links architectural BIMs and 3D CAD designs with energy, water, and carbon analysis. The required input is a .gbxml file type which can be generated from BIM modeling software. The output is extremely detailed and accurate, but is time consuming to generate. A license is required to run this service unless a free trial is used for a specific period of time.

Ecotect is a comprehensive environmental and building energy analysis tool. This software, adapted by Autodesk, performs complete building energy analysis similar to other building energy software described, but is exceptional because it provides an advanced 3D modeling interface. It allows the user to analyze interior and exterior factors and the impact they have building performance. This program allows for wide-ranging visual and analytical outputs for analysis of, solar, lighting, thermal, wind and acoustic impacts on building performance. Valuable feedback can be received from scalable inputs ranging from simple massing models to complex cityscapes. The level of detail and accuracy can also be increased by assigning material properties to construction and defining occupancy scheduling. There is also high flexibility in the detail of the outputs including various temporal scales (Autodesk 2012). However, the computation requirements are time-consuming at detailed levels, and there are substantial data inputs are required for accurate analysis. Ecotect is also limited in its abilities because it does not account for vegetation within the landscape which can have a significant impact on building performance.

Notwithstanding these shortcomings, Ecotect was chosen as the most suitable software for this thesis because of its diverse capabilities and flexibility. The three-dimensional modeling capabilities, for example, allowed for easy visualization of the geometry and components of the buildings that were studied. This software also allowed further output in the form of tables, images and graphs, which were beneficial to the research at hand. After the model was defined for this study, further research can be completed using the same model for analyzing different aspects of building efficiency. The next chapter describes this modeling software and the data that were used for the work at hand in greater detail.

CHAPTER THREE: METHODS AND DATA SOURCES

Building simulation and solar modeling takes time. Accurate results depend on precise inputs for realistic results. Ecotect offers a several tools to perform building energy simulations. Since this thesis primarily deals with solar energy impacts on buildings, only the solar access tool will be described in this chapter. The essential inputs for the solar access analysis tool include location, weather and building construction data. To observe the effects of temporal changes, solar analysis will be conducted for each of the four seasons. The effects of spatial changes on a building's performance will be evaluated by comparing the results over three progressive phases, which will be discussed in more detail below.

3.1 Study Area

The case study used for this thesis involves an existing four-story educational structure titled Ralph and Goldy Lewis Hall on the USC's University Park campus in Los Angeles, California (Figure 6). The building houses the Sol Price School of Public Policy and has about 20,000 ft^2 of space, including classrooms, labs, offices and lecture halls. This structure was selected because of the availability of data and efforts to integrate this data with current BLEMS research at the same location, as was described in Chapter 2. The building has the characteristics of a typical educational facility. It is a relatively new building which was built in 1996.

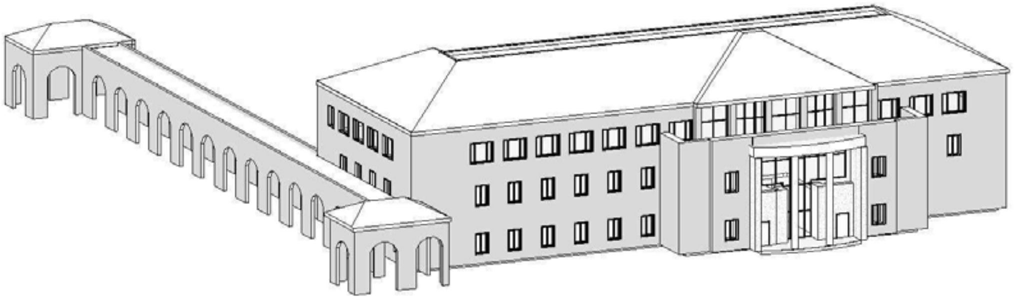

Figure 7 Lewis Hall sketch (North Façade)

Source: Data obtained from USC Facilities Management adapted using Autodesk REVIT (2011)

The building is located on the southeast part of the campus and is oriented 28° east of north, aligning with the layout of the majority of the buildings on the University Park campus (Figure 7). The impacts of the immediately adjacent buildings are considered for the shadowing effects that they may present for the building of interest. The area adjacent to the southern portion of Lewis hall was formally the location of the University Club that was demolished in 2012. The new Quantitative Social Sciences building that is being constructed here will also be considered for a portion of the analysis.

Understanding the climate and location of the area to be analyzed is important for setting up and understanding the many calculations performed by Ecotect. The city of Los Angeles is bordered to the east by the Santa Monica Mountains and to the south and west by the Pacific Ocean. The climatic conditions can be characterized as a Subtropical-Mediterranean climate, with average monthly temperatures ranging from 57.4 to 75.6 °F.

The highest precipitation occurs from December through March with an annual average total precipitation of 14.93 inches per year. Snow is a very rare occurrence in the Los Angeles area, with an exception being the high elevations of the surrounding mountain ranges. Annual sunshine averages more than 3,000 hours. The monthly averages range from 219 sunshine hours in December to 364 sunshine hours in July.

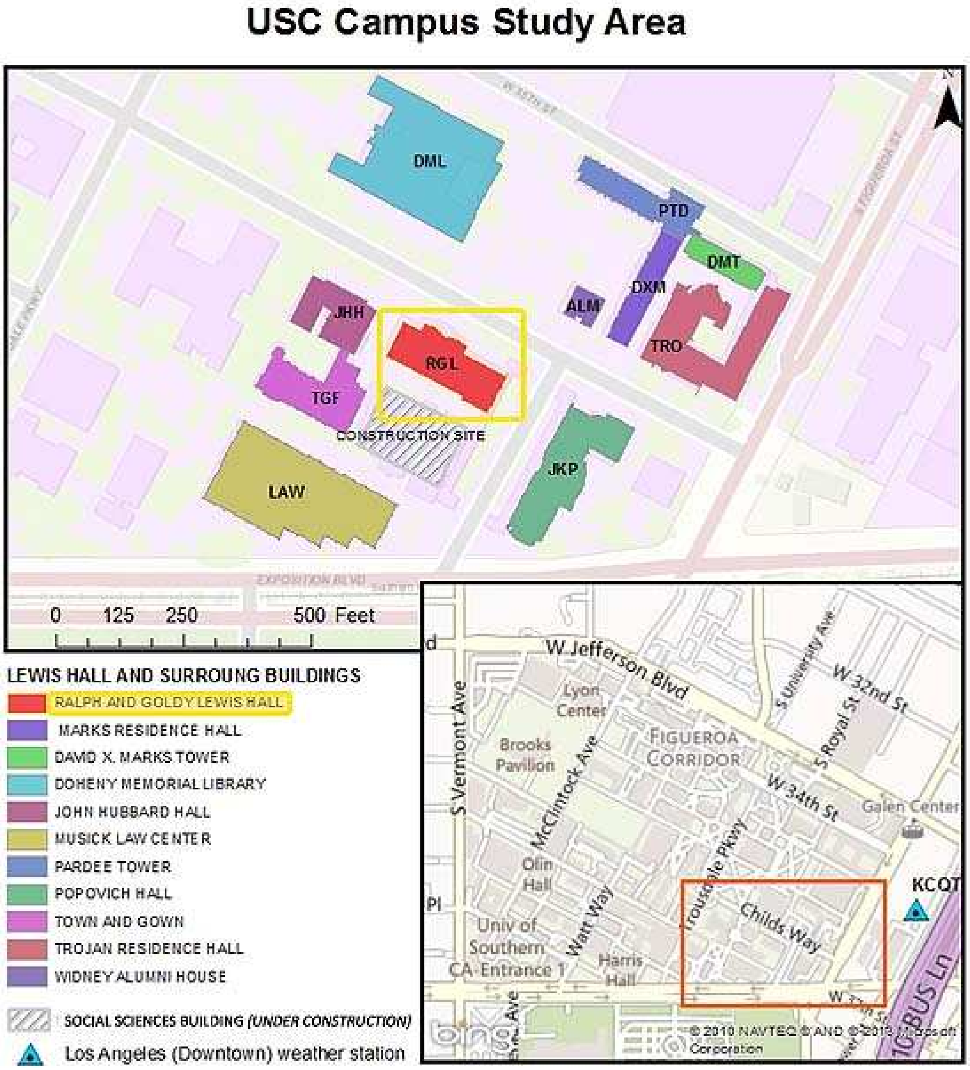

Figure 8 USC campus site map

Source: Data obtained from USC Facilities Management adapted using Esri ArcMap10

3.2 Workflow

For the most accurate solar simulation model, data must be integrated to include all three factors of solar analysis: global, landscape and atmospheric. In addition, the building's geometry must be carefully and accurately input to achieve realistic results. The accuracy of the analysis is dependent on the user's ability to properly build the structure in question. The focus of the model is on the building envelope, i.e. the components which contain the interior spaces and are exposed to outdoor elements. For the purpose of this study, the envelope components to be evaluated are the windows and walls of the vertical surfaces. Data is obtained from several sources and processed using the steps illustrated in Figure 8.

3.2.1 Data Processing

First, shape files which contain site context data including the building footprints for all structures on the campus were obtained from the Facilities Management Services group at the University of Southern California. The footprint's projections were converted from the Los Angeles County zone in the State plane coordinate system to a spherical global coordinate system in order to obtain the most precise global coordinates for building locations and orientations. The result was exported in CAD .DXF files and imported into Autodesk's REVIT software program.

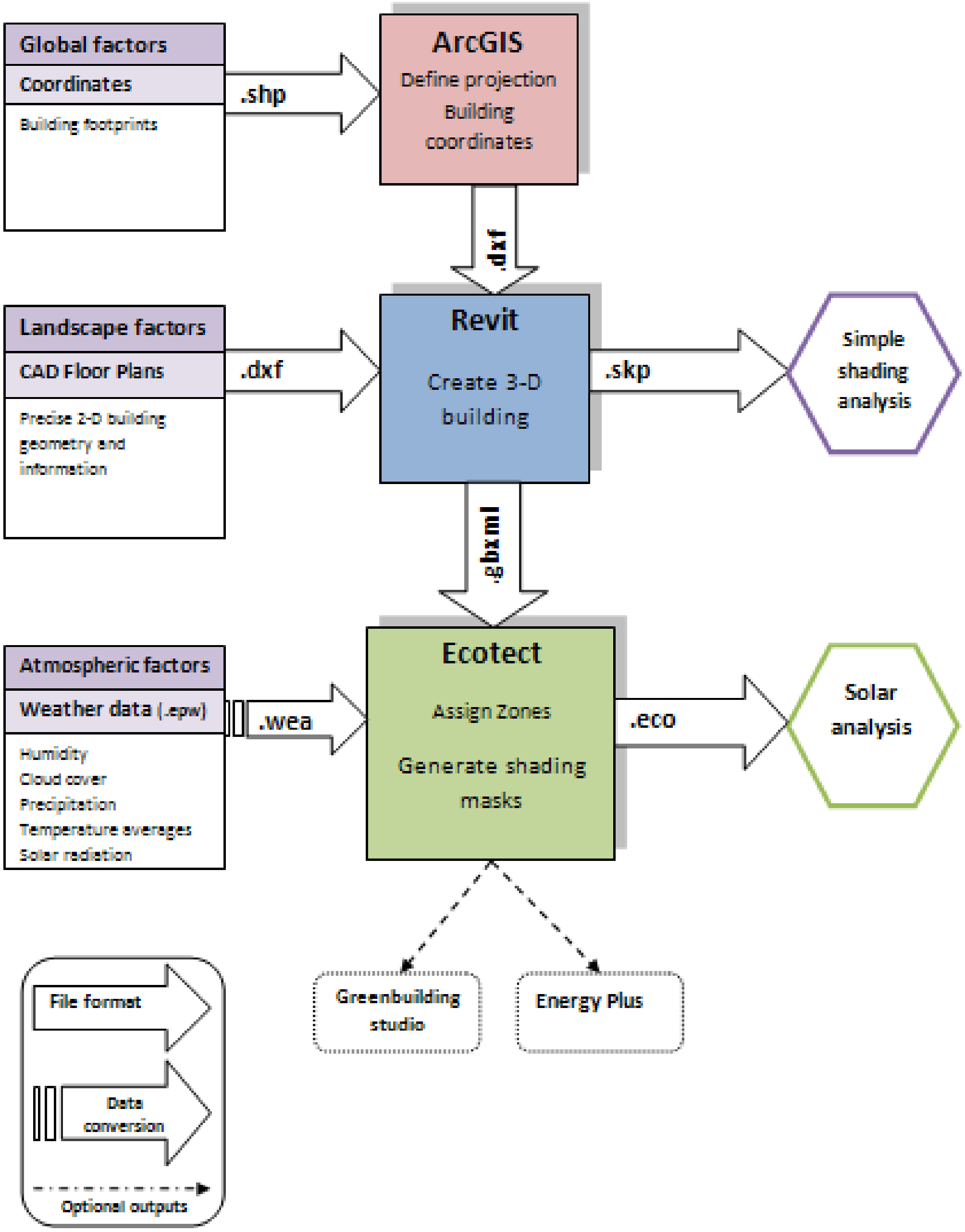

Figure 9 Data processing flow chart

In order to build an accurate building model, details regarding the building structure and floor plans were additionally loaded into Revit. The floor plans were aligned to the building footprints from the shape file and then extruded to the proper height to build a three-dimensional model of Lewis Hall and surrounding buildings. The result is a spatially explicit three-dimensional model. More intricate details such as window geometries and locations were also retrieved from floor plans and added to the model. General values for building materials were added to each building element of concern. For windows, values for aluminum framing with double glazing were input. The structure of the walls is concrete block with steel framing and curtain walls.

The resulting three-dimensional model was next exported into the Trimble SketchUp software program to create a shading heliodon for preliminary shading analysis. A shadow analysis can be used to evaluate overshadowing effects at different times of the day and at different times of the year to evaluate effects of the surrounding urban environment. A heliodon is created for key times, at four-hour increments, on key dates throughout the year and the results of this part of the analysis can be found in Appendix B (Figure 11). Shadows are solely the product of direct radiation and therefore shadow patterns will assist in overall knowledge of how and where direct bean sunlight is hitting the building. Long shadows are the result of a low solar altitude, when direct radiation values are lowest. Conversely, short shadows are the result of a high solar altitude which is when direct radiation values will be at their highest. The three-dimensional model of surrounding campus buildings provides a visual summary of the impact of overshadowing from neighboring buildings.

The three-dimensional model was then exported and converted into a .gbxml. This file type contains three-dimensional BIM data concerning the volumes of rooms and material types. These data were then imported into the Ecotect software program. The building was divided into 60 thermal zones. The aggregation of spaces into thermal zones is dependent on the locations of VAV thermal controllers as well as physical boundaries. Some thermal zones contain several spaces while others contain only a single room. The thermal zone layout is the same used in previous BLEMS studies at the same location. The auditorium on the first floor is an exceptionally large space and therefore this space was divided into two thermal zones. The various Lewis Hall floor plans and thermal zone divisions can be found in Appendix A (Figures 22-24). An internal zonal adjacency calculation was performed in Ecotect to ensure all spaces were aligned correctly.

The downtown Los Angles weather station (KDQT) is located directly on the USC campus at latitude 33.9° N, longitude 118°W (Figure 7). Data from the weather station including precipitation, humidity, average daily temperature, direct radiation and diffuse radiation can be downloaded from the US Departments of Energy website, in an .epw file format, and subsequently loaded into Ecotect. The weather tool extension converts the data into a weather (.wea) file format in order to be used in Ecotect. This data allows atmospheric factors to be accounted for in the solar analysis.

3.2.2 Solar Analysis Input Stage

The components comprising the building's envelope were isolated so that the solar analysis could be calculated for only the areas of concern. These areas are those that are potentially exposed to solar insolation and are adjacent to a thermal zone: Walls, windows, and exterior floors. The remaining elements such as the roof, columns, the arcade walkway, and exterior stairways were only considered for their shadowing impacts on thermal zones.

Once the building model was completed and all of the parameters were entered, the solar analysis calculations were performed using the solar access tool in Ecotect. The solar access analysis tool requires several inputs to achieve specific customized results. These inputs and the values that were are summarized in Table 3. The solar access analysis tool calculates the amount of solar radiation insolation on surfaces of concern within the model. For this analysis, the total solar radiation which is the sum of the direct and diffuse solar radiation was evaluated. Reflected radiation is typically insignificant and is not considered within this program.

Table 3 Input values for Ecotect solar access analysis tool

Input	**Selection**	**Explanation**
Calculation	Incident	Calculates total radiation(Sum of direct and diffuse) falling on objects
Time Period	8AM-8PM	Calculations are carried out each hour with the range.
Period	Season or All Year	Determines values based on Sunrise to sunset for given location. Will be completed five times total for each phase.
Period based values	Average Daily Values	Calculates total radiation for each Period specified and divide by the number surface over given period
Object selection	Use selected objects	By isolating selected objects, radiation values will only be calculated for objects that are part of the analysis.
Object Overshadowing	Perform detailed shading segmenting sky into 5°x5°subdivions.	Creates a shading mask for each object to determine which parts of the sky are visible and what percentage of object is in shade.

Solar calculations are carried out each hour for 12 hours, between 8 a.m. and 8 p.m., for each day of the evaluation. Values any time before sunrise or after sunset are ignored for that given day. Solar analysis was conducted for five separate time periods, each of the four seasons plus the whole year. For review, the seasonal time periods used were as follows: Winter, 21 December to 19 March; Spring, 20 March to June 20, Summer, 21 June to 20 September, and Fall, 21 September to 20 December. The annual value averaged the daily values over a typical 365-day year, from 01 January to 31 December.

Shading effects were the most complicated and most time consuming portion of solar access analysis. The Sun must be considered as a direct point source in addition to the entire sky dome, which approximates a dispersed hemispherical source (Marsh 2007). As the Sun moves through the sky, calculations become even more complex. The basis of this calculation is to find whether or not a specific object is shaded at any particular moment. This is accomplished by created a ray trace from the object to the Sun and checking for obstructions. When the objects in question are surfaces, they must be subdivided by a grid because only a fraction of each surface may be obstructed. In this case study, a 5x5 grid was chosen for medium accuracy which allowed each surface to be sampled 25 times. The sky dome was divided into 5 degree segments in both azimuth and altitude to produce a total of 1,296 segments (Figure 9). This level of detail was needed to account for the sun’s position as it moves through the sky.

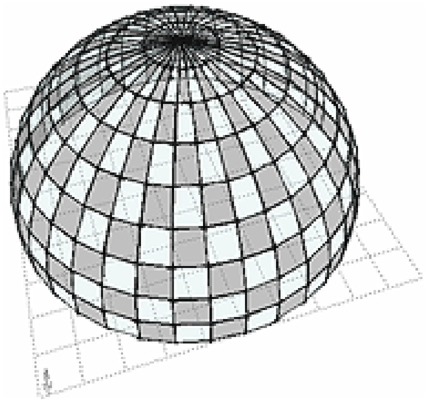

Figure 10 Sky dome in 5° by 5° subdivisions (from Marsh 2007)

Three layers of data were stored within each sky segment: shading from external obstructions; angle of incident effects; and radiation reflected from surrounding objects (Marsh 2007). Figure 10 illustrates a shading mask for a southwest facing wall on the second floor of Lewis Hall. After the appropriate weather data is loaded, diffuse and direct radiation values can be filtered and included used for the final calculations.

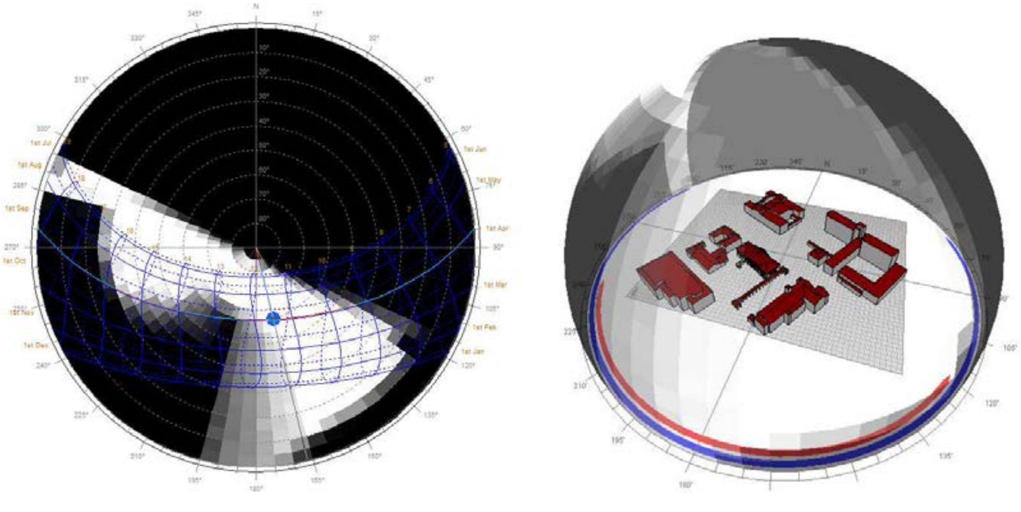

Figure 11 Example shading masks in stereographic view (left) and three dimensional views (right)
Source: Ecotect 2011

3.2.3 Phases of Analysis

The analysis was completed in three separate phases, progressively adding context to the prior phase (Figure 11). This approach was employed to demonstrate how spatial changes in the surrounding landscape can affect solar insolation values.

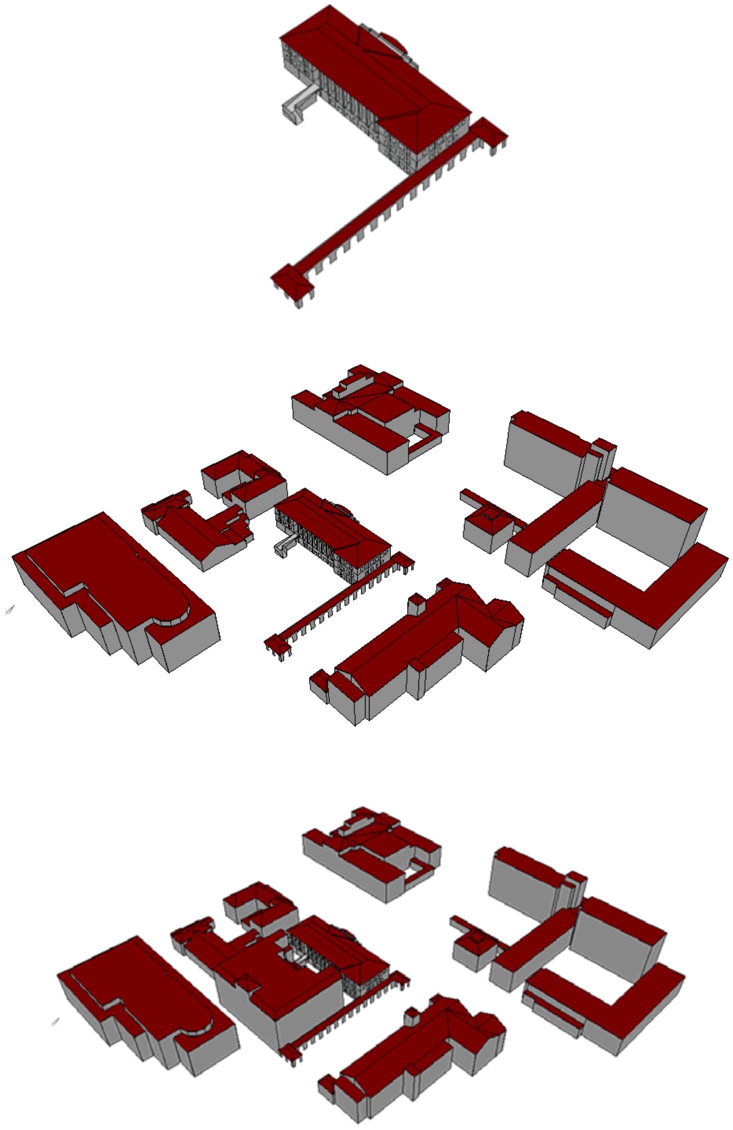

Figure 12 Progression of Phases: phase01 (top), phase02 (middle), Phase03 (bottom)

Phase 01 will evaluate Lewis Hall as a standalone structure in an unobstructed context. The resulting solar radiation values were based solely on the building’s orientation, geometry and roof overhangs. This provided a basis for comparison, for understanding how landscape changes impact the solar insolation at the building’s surfaces.

Phase 02 included the current site context provided by neighboring buildings. The proximity and height of neighboring buildings may have an overshadowing effect which will impact radiation values depending on the Sun path in each season. The results from this phase will be more realistic than those from Phase 01 as they represent current conditions.

Phase 03 will include the current site context plus the new Quantitative Social Sciences Building, which is currently under construction. The new building will be located on the site 11.5 m (37 ft) to the south of Lewis Hall and will stand at 26.5 m (87ft) in height, nearly twice the height of Lewis hall. The close proximity and large vertical height will greatly impact overall radiation values and especially the Southern exposure.

The roof is the main element impacted by solar radiation. It is considered part of the external envelope, but will be analyzed separately in all three phases because the spaces that are directly adjacent to the underside of the roof are not typically occupied or temperature controlled and do not impact any specific thermal zone within the building. Variations of solar energy at the roof will represent impacts on overall building energy efficiency and use and not any thermal zone in particular.

CHAPTER FOUR: RESULTS

This chapter describes the results of the solar access analysis using Ecotect. Seasons are compared to analyze the effects of temporal changes and the three progressive phases, previously outlined, are also compared to demonstrate the results of nearby changes on solar insolation values.

The Ecotect solar analysis tool was used to generate the average daily incident solar radiation values for each of the four seasons plus annual values. This process was run 15 times; five times for each separate time period and three times for each of the three phases. In each variation, average solar radiation values were calculated for 210 objects which comprise the building's envelope. The radiation values for each object were weighted according to the surface area of the building component and aggregated to produce totals for the corresponding zones. Most zones include both window and wall type objects, with the exception of a few which contained only window or wall object types. The weighted average values for the windows and walls of each zone are compared across each season.

The building's envelope primarily consists of windows, walls, horizontal floors and roof areas. Roof areas and materials are considered separately because they have an impact on overall building energy. Horizontal floor surfaces, found in the terraced areas of the building are assigned to the thermal zone immediately below the surface. They are grouped together with wall objects because they are about the same thickness and are composed of similar opaque materials. Incident solar radiation at the walls provides a good indication of how much energy will be absorbed by opaque surfaces of the building envelope. Solar energy values at the windows were evaluated separately because these values will be a good indication of how much energy is transmitted into the building and will have a greater influence on heat gains and resulting internal zone temperatures.

Each object type within in each thermal zone was assigned to its corresponding thermal zone by object type. The main façade is rotated 28° East of North and therefore, project North in the Floor plans is considered a northeastern solar exposure. Each zone corresponds to one of four orientations: North, east, south, or west based on its primary exposure to the Sun (Figure 13). Zones located within the corner areas of the building, are exposed to two orientations, and therefore assigned to the orientation which is most dominant for that zone. The detailed results for each zone can be found in Appendix B.

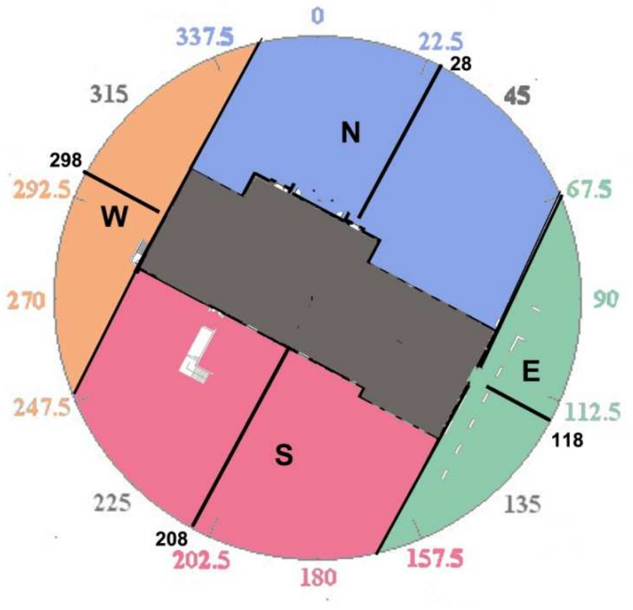

Figure 13 Building orientations (28° East of North)

4.1 Phase 01 Results

The values in Phase 01 are highest of the three phases because there are no obstructing site contexts and resulting overshadowing effects that were into account. Any overshadowing effects result solely from the building's orientation, geometry, global position, and atmospheric factors. The roof overhang provides shading to zones on the third floor, most noticeably in the summer months when the Sun's elevation reaches its maximum. The values for zones with surfaces within the alcove in the southern part of the building are lower due to the shading effects from the building's own geometry.

Figure 14 shows the results for each season aggregated by orientation. Lewis Hall in its unobstructed context receives the highest amounts of radiation at the roof with the exception of the winter months where the southern façade received the most radiation. This result is almost opposite in the summer months where the southern façade receives the second least amount of radiation and high amounts are received at the roof. The northern exposure receives the lowest amount of solar energy throughout all four seasons, as expected, although it is interesting to note the values at the northern exposure are very close to values at the southern exposure in the winter season. This is a result of the highest solar angles being achieved at the beginning of summer and less solar energy reaching the southern façade compared to other seasons. Overall, solar radiation is received fairly consistently at the eastern and western exposures throughout the year, with slight variations due to atmospheric conditions. It is interesting to note that values in the winter for the southern exposure are only slightly less than the values for the western exposure during the summer. This is a result of sun angles as well as the much greater surface area exposed at the southern end of the building.

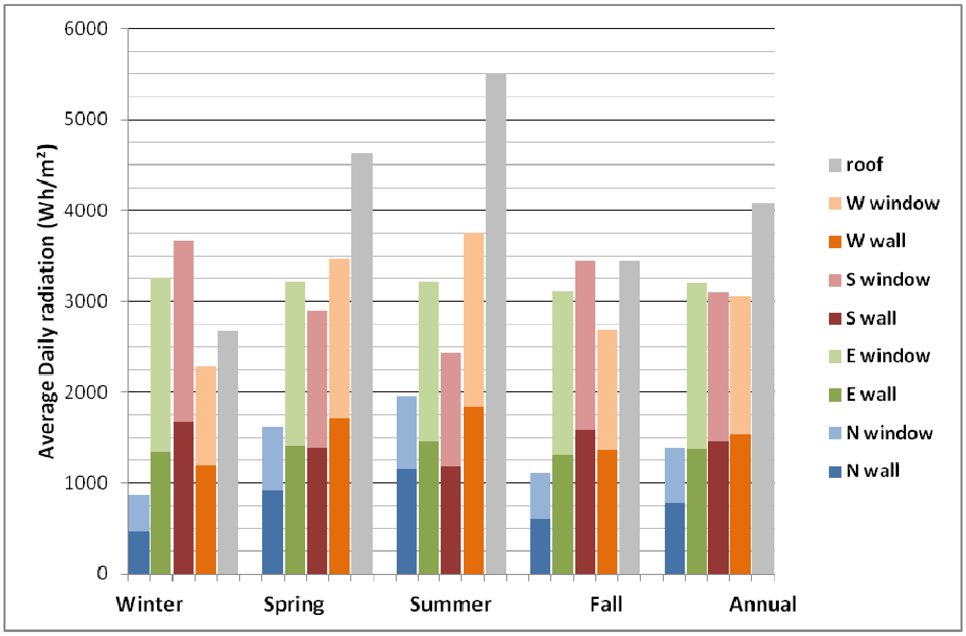

Figure 14 Phase 01 results by orientation

Figure 15 depicts the results for Phase 01 where zones are aggregated by one of three floors within Lewis Hall. The first floor contains no zones located in the south alcove and is also not impacted by the overhang on the roof resulting in the highest amount of radiation for all seasons. The lowest values for the first floor are during the winter season, which can be attributed to decreased daylight hours in the winter time. However, the Sun's low azimuth angles in the winter, results in very similar values for the first and second floor wall values, 1212 and 1213 Wh/m², respectively. Conversely, the winter months account for the highest seasonal values for the third floor, which results from the roof overhang having a lesser impact, when the sun's elevation is at its lowest elevation. Overall, the third floor receives the least solar radiation throughout the year due to the fact that it is impacted by the overhang of the roof.

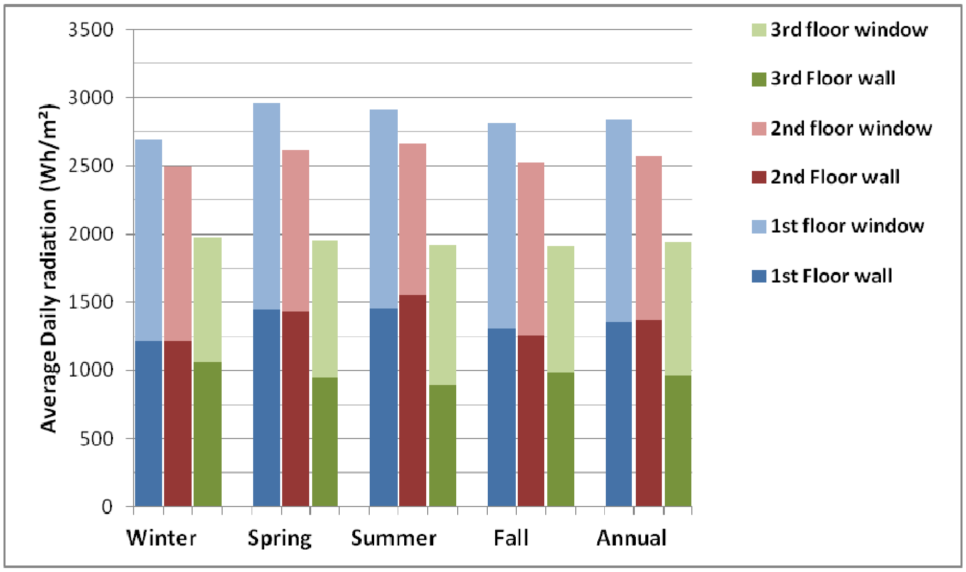

Figure 15 Phase 01 results by floor

Appendices B and C provide graphic and tabular results for each individual thermal zone. Table 4 highlights the zones, walls and windows, which receive the highest and lowest values in each season. For better understanding, this table also identifies the location of the zone object within the building, by floor and primary orientation. Zone 9 receives the highest radiation during spring and fall seasons, given its location on the first floor with a southern exposure. During the summer, Zone 2 receives the highest radiation at its walls, which may seem surprising given its northern exposure. Upon closer inspection, it can be noted that Zone 2 has a large exposed horizontal surface, which is not shaded and subject to a large amount of direct sunlight in the summer. The windows of Zone 39 receive the most radiation during the warmer months, due to its location on

Table 4: Summary of results by BLEMS zone

Object type		Phase01			Phase02			Phase03		
		Zone (Floor, Orientation)		Value (Wh/m^2)	Zone (Floor, Orientation)		Value (Wh/m^2)	Zone (Floor, Orientation)		Value (Wh/m^2)
Winter										
Walls	Max	37	(2,S)	2995	37	(2,S)	2959	29	(2,E)	1851
Windows	Max	37	(2,S)	2998	37	(2,S)	2961	58	(3,S)	1975
Walls	Min.	43	(3,N)	296	43	(3,N)	294	52	(3,S)	138
Windows	Min.	22	(2,N)	347	22	(2,N)	154	52	(3,S)	121
Roof				2671			2665			2405
Building				1132			1105			710
Spring										
Walls	Max	9	(1,S)	2514	9	(1,SW)	2499	37	(2,S)	2226
Windows	Max	9	(1,S)	2517	9	(1,SW)	2504	37	(2,S)	2234
Walls	Min.	56	(3,S)	217	56	(3,S)	216	56	(3,S)	186
Windows	Min.	56	(3,S)	212	56	(3,S)	210	52	(3,S)	178
Roof				4635			4582			4567
Building				1269			1241			1107
Summer										
Walls	Max	2	(1,N)	2914	2	(1,N)	2914	2	(1,N)	2914
Windows	Max	39	(2,W)	2243	9	(1,S)	2140	38	(2,W)	1975
Walls	Min.	52	(3,S)	222	52	(3,S)	221	52	(3,S)	199
Windows	Min.	52	(3,S)	225	52	(3,S)	224	52	(3,S)	196
Roof				5511			5469			5451
Building				1297			1265			1195
Fall										
Walls	Max	9	(1,S)	2860	37	(2,S)	2837	37	(2,S)	2118
Windows	Max	9	(1,S)	2871	36	(2,S)	2841	58	(3,S)	2216
Walls	Min.	55	(3, S)	264	55	(3, S)	262	52	(3,S)	164
Windows	Min.	22	(2,N)	196	22	(2,N)	193	52	(3,S)	143
Roof				3452			3415			3294
Building				1170			1152			872
Annual										
Walls	Max	9	(1,S)	2617	37	(2,S)	2590	37	(2,S)	1999
Windows	Max	9	(1,S)	2626	36	(2,S)	2597	58	(3,S)	2040
Walls	Min.	55	(3, S)	275	55	(3, S)	273	52	(3,S)	172
Windows	Min.	22	(2,N)	229	22	(2,N)	225	52	(3,S)	160
Roof				4082			4037			3956
Building				1217			1191			973

on the second floor with a primarily west orientation. It is important to note, due to the skewed orientation of the building, this zone also receives a portion of direct sunlight from the south as well. The zones receiving the least amount of radiation throughout the year are primarily located with the alcove at the south end of the building, with the exception of the winter months when the Sun's rays are able to reach deep into this recessed portion of the building. In the winter months, Zones 22 and 43 receive the least radiation due to their northern exposures and decreased daylight during this time of year. In an unobstructed context, Zone 37, with a southern exposure and location near the western corner of the second floor, receives the largest amount of sunlight, due to being the least overshadowed of all zones at the southern end of the building, during the winter months.

The lowest overall building averages occur in winter due to the lower solar elevation of the Sun and minimal sunlight hours. Although the Sun path is equivalent in both spring and fall, variations in weather and atmospheric conditions have a direct effect on the amount of direct and diffuse radiation received and as a consequence, the total radiation varies. The overall buildings radiation values are highest in the summer. The terrace on the northern portion of the building receives the highest amount of radiation resulting from the Sun's high solar elevation and increased direct sunlight. Horizontal surfaces, such as those found on the terraces are most susceptible to the highest heat gains because they experience the most direct sunlight. The terrace at the North end of the building has minimal shading which may have been overlooked due to the fact it is located on the northern side of the building. On the south side, the terrace is sheltered by a large roof overhang and also benefits from being setback into an alcove portion of the building. Zones within the alcove on the southwestern exposure receive the lowest amount of radiation because they are shaded by the roof's structure and set back from the majority of the southern façade.

4.2 Phase 02 Results

The proximity and height of neighboring buildings can impact the solar insolation received by a building's envelope. Although Hubbard Hall and the Town and Gown building are approximately equivalent in height compared to Lewis Hall, their close proximity directly blocks sunlight in the evening hours. These two buildings have the greatest effect on the western exposure at all times of the year.

Figure 16 shows the values for Phase 02 aggregated by orientation. The southern exposure continues to receive the highest amount of radiation during the winter months, while the western exposure has the highest values of the four exposures during summer. The values at the roof continue to be the highest during all seasons except summer, where the southern exposure, still receives a large amount of sunlight despite obstruction from the Musick (Law) Building.

Figure 17 shows the impacts on each orientation by percent that the addition of site context has on solar radiation values for each season. A review of the shading heliodon (Appendix B) reveals that Popovich and Musick Halls have the largest overshadowing effects in the winter months, reducing total radiation values on the eastern and southern exposures by 2 and 4 percent, respectively. Musick Hall is fairly large in

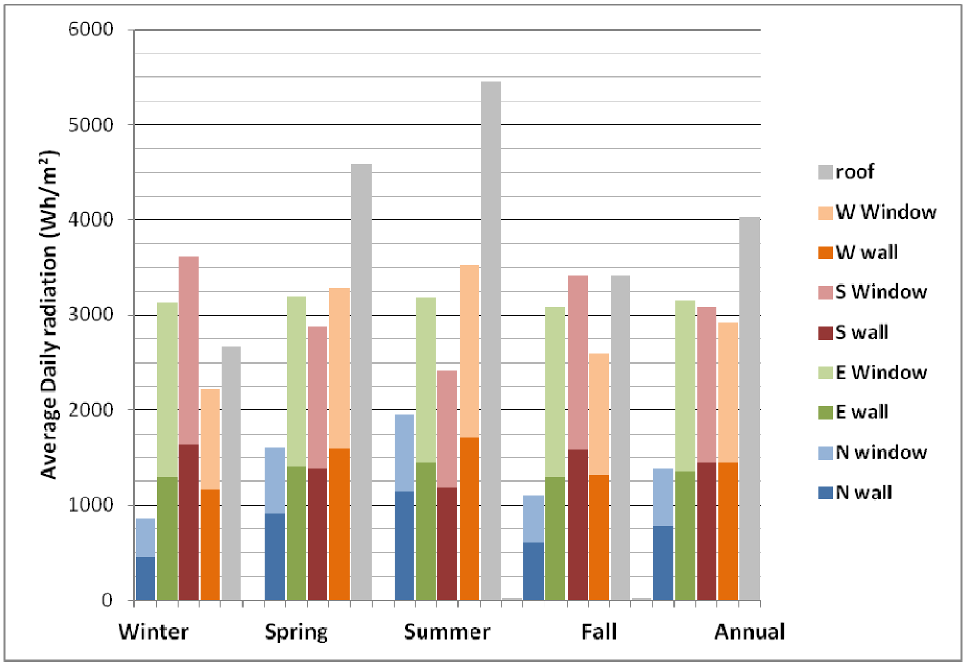

Figure 16 Phase 02 results by orientation

terms of height but its relatively small impact on zones with a southern exposure is due mostly to the large distance between Lewis Hall and itself. Hubbard Hall and the Town and Gown structures have the largest effect on solar access to Lewis Hall, most notably along the western exposure. The height and close proximity of these building blocks a large portion of the Sun rays, especially in the summer months. The impact is not felt as much in the winter due to the western exposures receiving minimal sunlight due to the Sun’s shortened path during this season. The locations of the remaining structures, from the north to northeast, are either too far away or too small to have significant impacts.

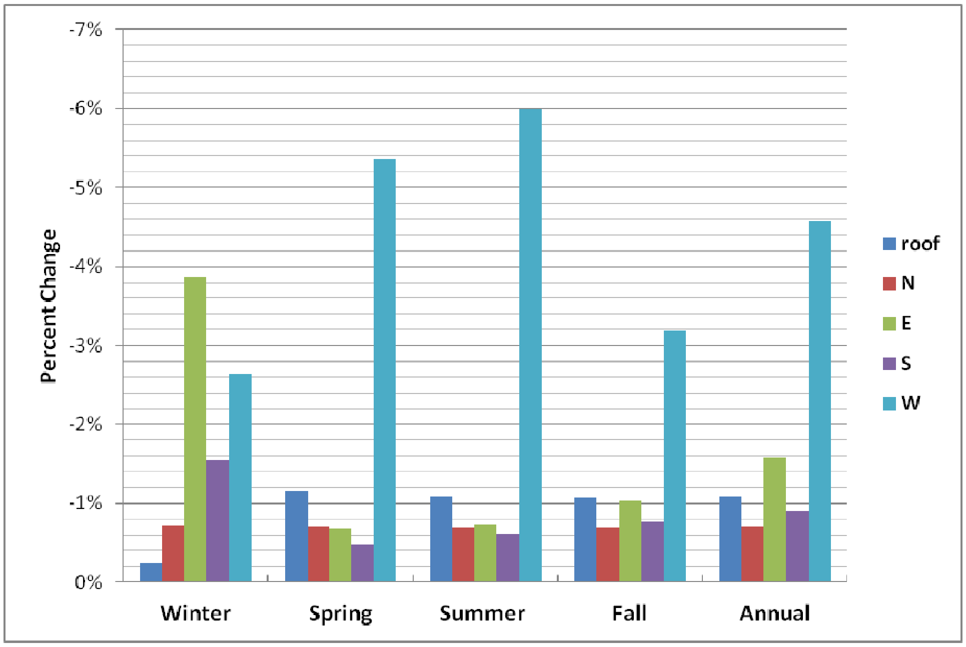

Figure 17 Phase 02 impacts

Figure 18 shows the results by floor which indicate that the first floor continues to receive the highest amounts of radiation. Compared to Phase 01, no significant impact can be noted. This is largely due to the fact that when data is aggregated by floor, this approach takes into account all exposures circumnavigating the building, and therefore averaging out major impacts with exposures that experienced little or no impact.

Zone 16, which is the western entrance to the first floor corridor, is the most significantly impacted zone following the addition of this existing site context (Table 4). The taller buildings, which cast longer shadows, are also responsible for a reduction in total radiation values. The zones receiving the least radiation input remained unchanged

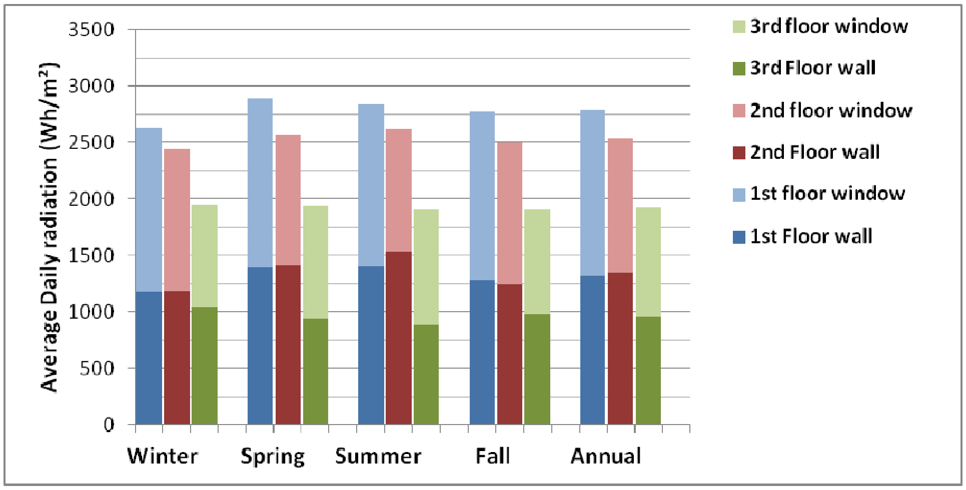

Figure 18 Phase 02 results by floor

throughout all seasons due to their primarily north-facing orientations. Zones 52 and 55 changed the least because they are location in the heavily shaded portion directly in the recessed area on the southwestern exposure (Appendices B, C). In the previous phase, the windows in Zone 39 on the second floor of the northwestern exposure received the highest total radiation in the summer months, but this value was reduced by 12 percent once Hubbard Hall was added to the analysis.

However, the impact on the roof and overall solar radiation values of adding the surrounding buildings was relatively minor. Across all four seasons, the solar radiation received from the roof was reduced by approximately 4.5 percent and the changes to other zones and exposures were less than 1 percent in most instances (Figure 17).

4.3 Phase 03 Results

As buildings become taller and density increases, the daylight reaching surrounding buildings is diminished. The height and close proximity of the new Verna and Peter Dauterive Hall will greatly impact the amount of total solar insolation, most notably for the zones with south and western orientations

Figure 19 shows the results of Phase 03 with zones aggregated by orientation. The highest radiation is still found on the roof surface, with the exception of the spring season, which is now dominated by the eastern exposure. The values for the southern exposure remain relatively consistent throughout the year, with the exception of the winter season, where the new building will obstruct the majority of the Sun's rays coming in at low elevations. It is also interesting to note that the summer values for the southern are the second highest of the four orientations, whereas in the two previous phases, these values were the lowest. The northern exposure values continue to be the lowest throughout the year, but almost equal the southern exposure values in the summer season.

Figure 20 shows the percent decrease of solar radiation for each season by grouped by orientation. The southern exposure is predicted to feel the largest impact, especially in the winter months when there is a decrease of over 60 percent. The western exposure also will experience a large drop in solar energy during the winter season. There is little to no change for the northern exposure as well as the roof, with the exception of the winter months. The shadow heliodons in the appendices show how the new building will cast a large shadow over most of Lewis Hall during the winter months. Because of

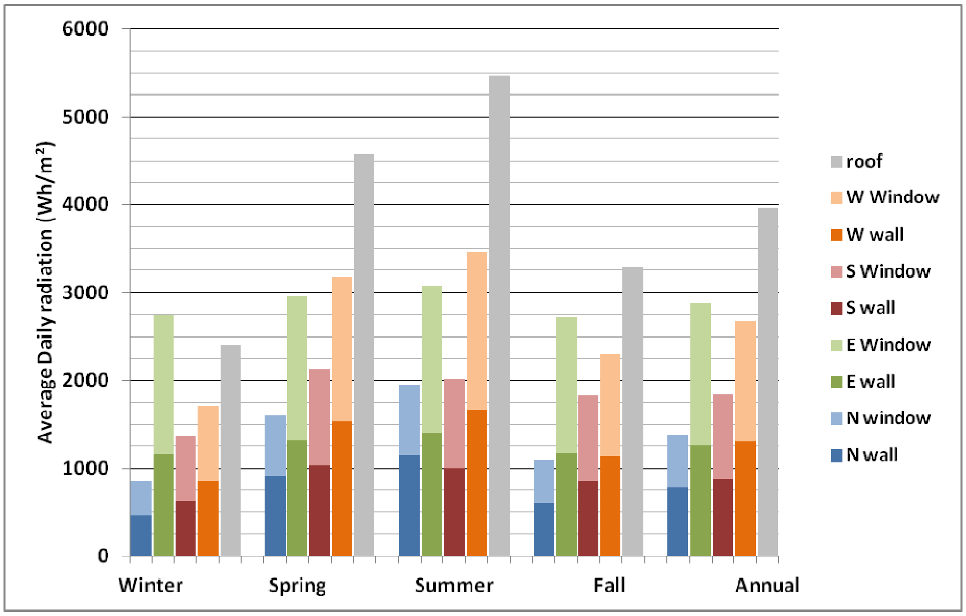

Figure 19 Phase 03 results by orientation

the skewed orientation of the University Park campus, the impact is also felt at the eastern exposure as well, most notable in fall and winter, where there is a 12% decrease of solar heating energy.

The results aggregated by floor are shown in Figure 21. The first floor no longer receives the most radiation in all seasons; it only does so during the spring and summer. During the winter and fall, the second floor now receives notably more solar radiation as compared to other floors. The third floor continues to receive the least radiation throughout all four seasons, with roughly similar values to the first floor during winter.

Zones on the third floor at the southern end of the building receive the least radiation in all four seasons in Phase 03. The amount of sunlight reaching the third floor under the roof overhang within the alcove was already low in previous phases. The new construction project diminishes any chance of sunlight of reaching those zones at all

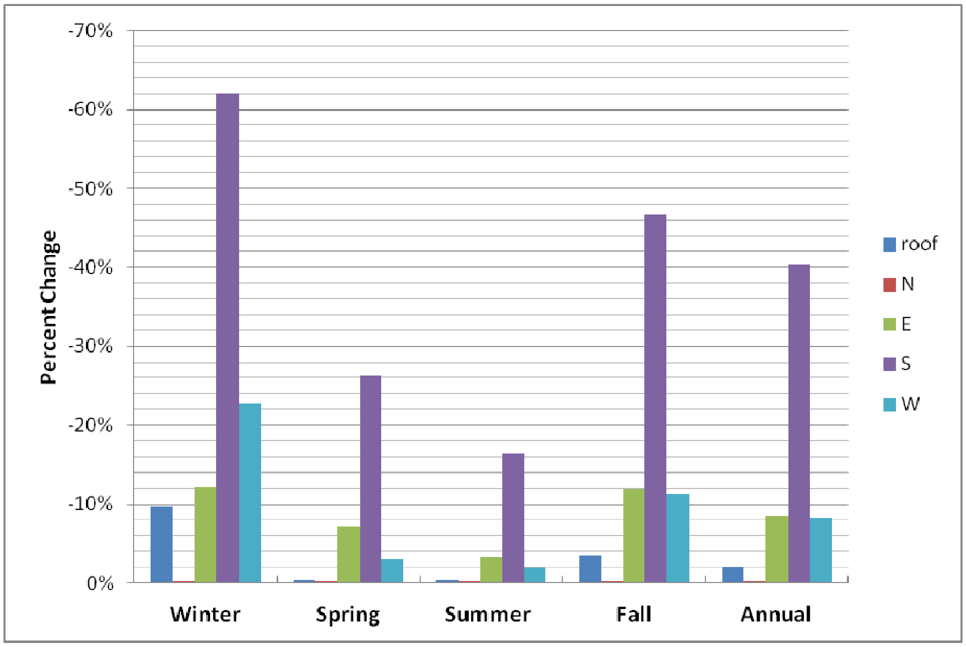

Figure 20 Phase 03 Impacts

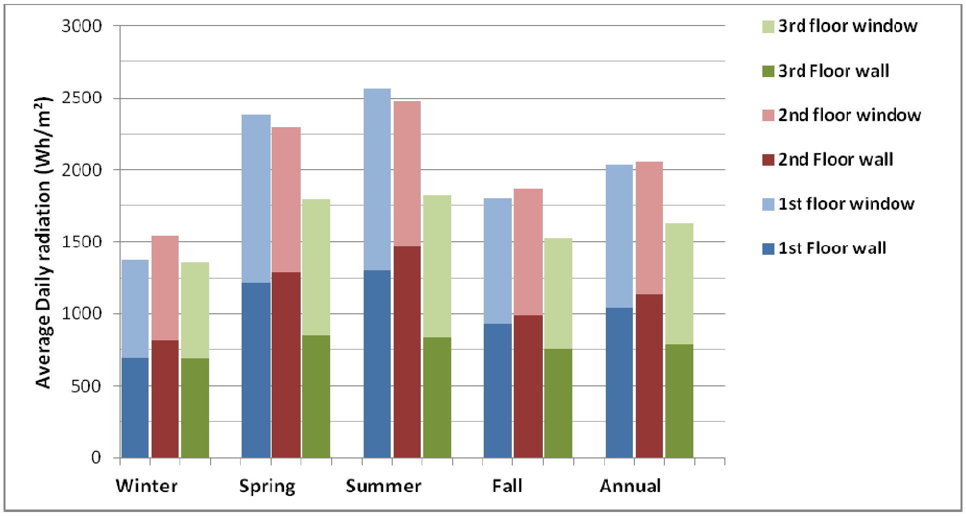

Figure 21 Phase 03 results by floor

times of the year, with Zone 52 now receiving the less sunlight than other parts of the building. The highest values still remain at Zone 2 during the summer months and at zones adjacent to it, which share a large portion of horizontal surface fully exposed to high amounts of direct sunlight. The windows at Zone 38 receive the highest amounts of sunlight during the summer months despite their southern exposure; their location near the corner of the building allows some sunlight to sneak by the new construction. This is true for other areas as well: Zones 29, 37 and 58, for example, are located near corners creating exposures from several directions throughout the year.

The impact of the new building on Lewis Hall is the greatest during the winter months when the sunlight hours are fewer and the Sun's position is low in the sky. Zones 10, 11, and 13 all have southern exposures and will receive up to 78% less solar radiation due to direct blockage of sunlight when the new building is finished. The overall impacts by zone are summarized in Appendix D. The summer months are the least impacted during this phase, due to the Sun's high altitude and direct rays reaching over the new building to the lower floors of Lewis Hall. The most impacted zones, on the third floor, are shown to have radiation values reduced by up to 25%. The maximum impact in the spring is 43% for Zone 43 compared to 63% in the fall, for example. The direct sunlight is greater and makes up the majority of solar energy in the fall season. This direct sunlight will be blocked directly by the construction of the new building.

As discussed earlier, the roof can be thought of as a solar energy receiver that heats the building as a whole. Assuming constant thermal properties throughout the roof structure, solar radiation received at the roof surface will be dispersed as heat throughout the building, but will be felt most noticeably on the fourth floor, a potentially useable space that was not evaluated in this project, as well as on the third floor. Similar results were predicted for the third floor which will experience a 10% reduction in Phase03 during the winter, compared to just a 1% reduction in the summer season, and a 3% reduction over the course of the whole year (Figure 22).

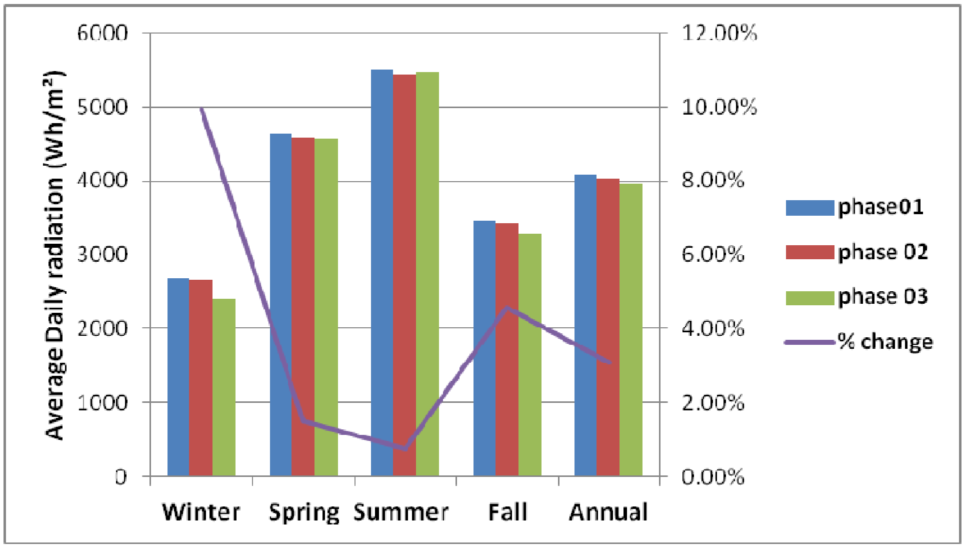

Figure 22 Variations in roof solar radiation predictions over the three phases

CHAPTER FIVE: DISCUSSION AND CONCLUSIONS

The primary purpose of HVAC systems is to compensate the indoor environment by either increasing or decreasing air temperature to an acceptable level. Current systems in place monitor the occupancy of the indoor environment as an input to HVAC demand controlled systems. This research case study has laid out the need to include changes in the outdoor environment which are dynamic and yet predictable as well most focus is on buildings that have not been constructed in the early design stage. In addition, the results can be used to identify target areas of a building that may be considered for temporary or permanent energy efficient design modification. This may be cost beneficial in comparison to making entire building changes. Improving and evaluating existing buildings will prove beneficial for energy consumption. The results of this research indicate a need to evaluate spatial context of a buildings location and how this impacts building energy management systems. This study proves that heat gains may be predictable at a thermal zone level. By evaluating heat gains and correlating with occupancy scheduling, heating cooling demands can be controlled at increased precision, saving energy and money.

In Mediterranean climates, like that found in Los Angles, cooling is the primary concern and makes up the majority of a building's energy usage. Winters are relatively mild, yet some energy usage also can be attributed to heating during cooler months and especially early in the morning and late in the evening.

The addition of Verna and Peter Dauterive Hall will have large impact on the solar radiation budget of Lewis Hall. This may be beneficial in terms of the cooling of the building during the summer and considering the year as a whole. However, the building will not receive the benefits of low sun and this may increase the demand for heating during the cool season. The shadow cast from the new building and the effect this has in terms of blocking direct sunlight also decreases the amount of natural sunlight that reaches interior spaces of the building. This will, in turn, increase the demand on lighting systems.

The current design and layout of the building is good and there is evidence that solar heat gains were considered in the design process. The skewed east of north orientation welcomes the morning sunlight without allowing in large amounts of direct sunlight during the day. The north façade has the most fenestrations (i.e. openings in walls for windows and doors), but receives the least amount of direct sunlight, thereby minimizing heat gain through windows and other openings. Large windows located throughout the north façade also allow diffuse sunlight into the building which benefits the conference center located on the third floor and the entrance alcove. Similarly, the spaces located within the alcove on the southern façade benefit from being located in the recessed portion of the building under the overhang of the roof because this helps reduce heat gain during the spring and fall months, when it was shown that the Sun’s rays have the greatest effect on the southern façade. This arrangement would also be beneficial during the winter months by allowing a small amount of heat gain during the coldest season. However, the new building will eliminate most, if not all, of these beneficial outcomes. Finally, the terrace at the northern end of the building is not shaded and receives large amounts of solar energy, especially during the summer months, leading to heat gains located in the zones directly below the terrace.

5.1 Implementation and Integration

Results from Phase 03 of this study can be used to anticipate changes in heat gain at locations throughout the building once construction of the new Verna and Peter Dautrive Hall is completed. Radiation values can be used to calculate anticipated heat gain at a thermal zone level at different times throughout the year. Quicker response to temperature changes has been proven to save energy (e.g. Tachweli, Refai, and Fagan 2007). In the summer when HVAC is primarily used to cool the indoor air, understanding which thermal zones may heat up more quickly may prove to be beneficial with the integration of current BLEMS research and the various detailed predictions laid out in this case study.

5.2 Solar Radiation Model Validation

The Ecotect software suite uses the ‘BS ISO 15469-1997 Spatial distribution of Daylight – International Commission on Illumination (CIE) Standard Overcast Sky and Clear Sky’ for its illumination distribution model (Autodesk 2010). The Ecotect analysis then uses these radiance values, calculated using the above standard methods, as the model for a detailed radiant-exchange analysis. All the solar position and solar radiation calculations conform with the standards outlined in ‘CIBSE TM33 (2006) Tests for Software Verification and Accreditation’ (Autodesk 2010). Solar access and rights-to-light calculations conform to the building research establishment site planning handbook.

Vangimall et al. (2011) compared the accuracy of Ecotect estimates with actual field measurements, and concluded that Ecotect overestimated the illuminance levels by approximately 15% in the majority of cases. However, the study acknowledges that time and date inputs were lacking in the model for the weather data that was used. The newest version of Ecotect allows times and dates to be manipulated to account for both local and global conditions, therefore solving this problem.

The Lewis Hall case study evaluated here used both of these factors as inputs into the model. The close proximity of the weather station to the building site provides additional confidence that the model would have performed better in the work at hand than was the case in the study by Vangimall et al. (2011).

5.3 Study Limitations

Due to the limitations of the Ecotect software, trees and external foliage were not included in this study model. The majority of the tress and landscaping that could have a significant impact on the results presented in this thesis are located on the north side of the building along the pathway, thereby minimizing this possibility because the northern exposure has the least sunlight. The small bushes located directly adjacent to the building would also have negligible effects on the solar radiation and/or overshadowing values. However, the landscaping might be considered in future studies exploring ways to reduce energy costs given that one study, by Santamouris (2011), showed that strategically placed landscaping can reduce building energy costs by up to 10%.

5.4 Opportunities for Future Research

The simulations performed for this thesis could be taken further by including material properties and insulation and thermal resistance of insulation and the reflectivity and efficiency of the windows. With this information, detailed analysis can be conducted to determine the heat flow from the outside environment to the interior spaces.

This study has focused on radiation values and the heat energy received from the Sun which may have a large impact on building energy systems. The impacts of natural sunlight or illuminance values on the building's lighting systems were not considered. With advances in light systems and energy efficient lighting, lighting has a relatively low impact on energy costs compared to HVAC systems. However, illuminance values should not be ignored, because natural sunlight plays an important role in the behavior and satisfaction of a building's occupants. In Phase 03 of this study, the construction of the Verna and Peter Dauterive Hall was shown to have a large impact on the predicted solar radiation values.

Direct and diffuse radiation values can also be considered separately by the Ecotect software. Direct radiation can be shielded using either interior or exterior window shading devices. Windows that were predicted to receive the highest amount of radiation should be considered as high priority candidates for window treatments.

The temporal aspect of this study explored seasonal changes through four different compilations of average daily values. The Ecotect software also allows analysis at hourly increments and this would allow the comparison and analysis of how a building is heated throughout the day by the Sun. Systems might be adjusted to compensate for higher temperatures in spaces with eastern exposures in the morning and spaces with western exposures late in the afternoon following this kind of detailed analysis for example.

With the information gained from this study, temporary and permanent building designs may be taken into consideration. Non-permanent changes such as the addition of insulated window coverings may be considered for zones receiving high amounts of solar radiation. Permanent considerations would include the addition of glazing or film to windows which have been proven to transmit a high amount of radiation during the warmer summer months. Increasing thermal mass or improving insulation in areas susceptible to high radiation would also be desirable.

There have been many studies that have focused on improving energy efficiency in buildings. Engineers and researchers have developed complex methods to improve energy efficiency, but the buildings are often managed by non- specialized technicians who need understandable and cost-effective methods to achieve the desired results in their buildings. The results of this study can be exported directly from the Ecotect model into other Building energy management programs such as Green Building Studio or Energy Plus. The solar radiation values predicted in this study are directly proportional to heat gain; however, further evaluation of exact heat gain calculations and resulting energy flows within the building may be helpful for further understanding of the solar heat flux and its implications.

This investigation has demonstrated the temporal variability of solar radiation impacts on a building surface as well as how these impacts change based on the context surrounding a building. In urban planning it is ideal to examine how future developments impact the solar access to existing buildings. As building energy management systems become more sophisticated, the acknowledgment of the dynamic exterior environment should be considered for improved energy efficiency. The effects of solar radiation will impact a building throughout its existence and should be evaluated at various levels, not just during the design phase. This study has proven how the effects of solar radiation can be considered at a more intricate level after the building has been occupied. Future sustainable building designs need to have an intimate connection with their location as well as the natural environment. As urban density increases the influences from natural sources, such as the Sun, decreases and buildings will need to compensate for this impact. The need to find a balance between these two phenomena will be beneficial for future generations.

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APPENDIX A: CHARTS AND FLOOR PLANS

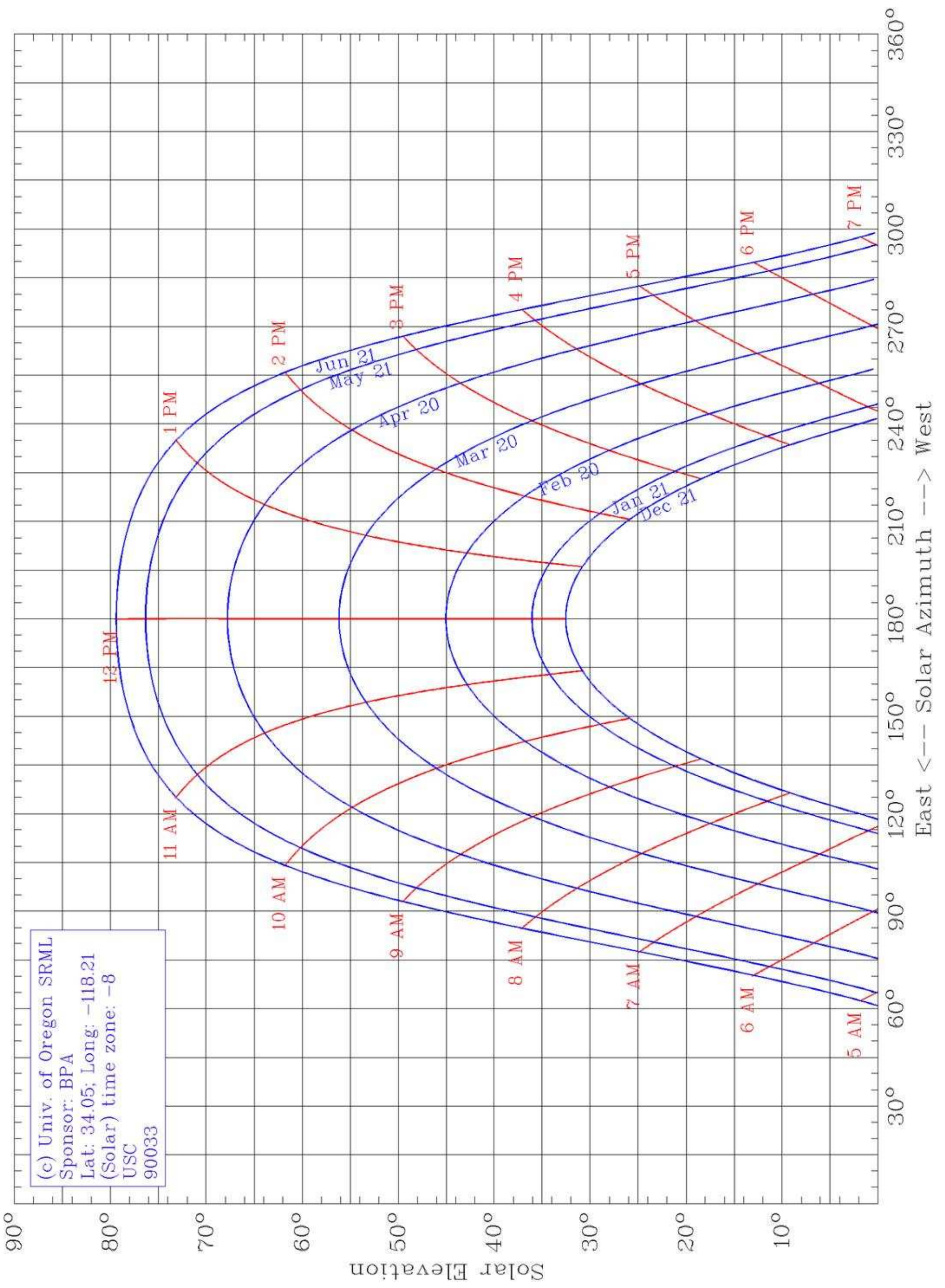


Figure 23 Sunpath chart for Los Angeles, CA (UO 2007)

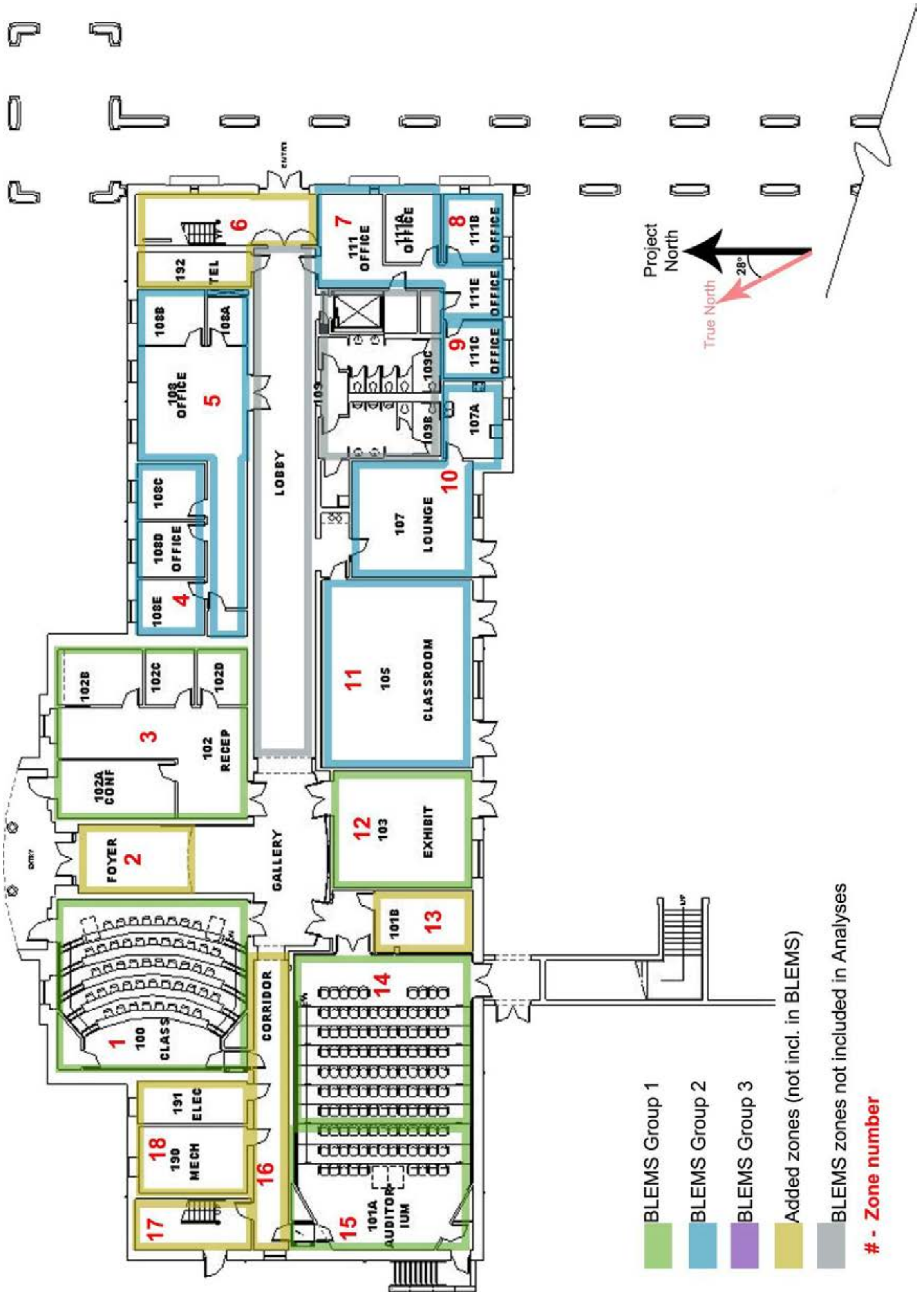


Figure 24 Lewis hall floor plan with BLEMS zones: First Floor

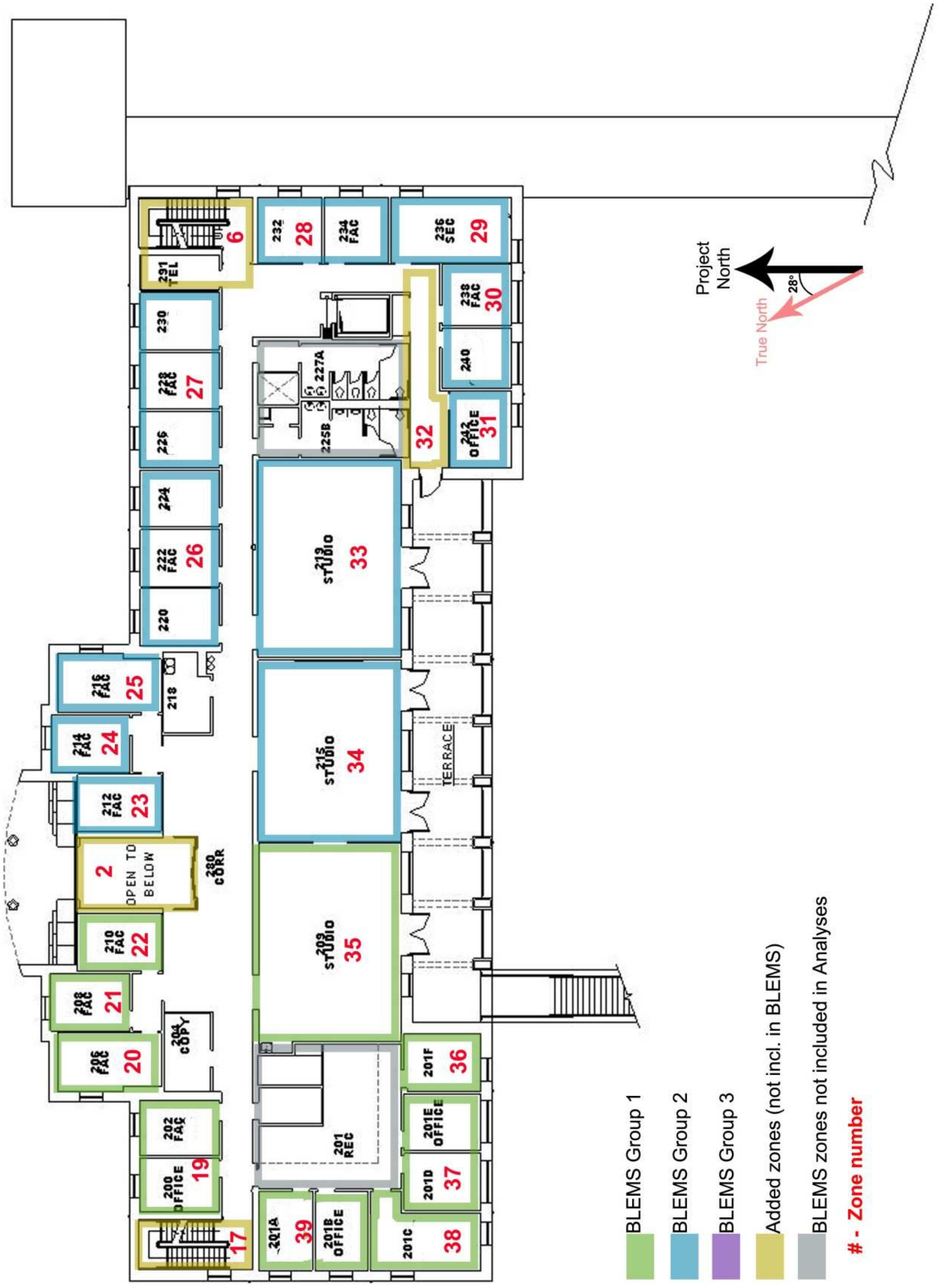


Figure 25 Lewis hall floor plan with BLEMS zones: Second Floor

Figure 26 Lewis hall floor plan with BLEMS zones: Third Floor

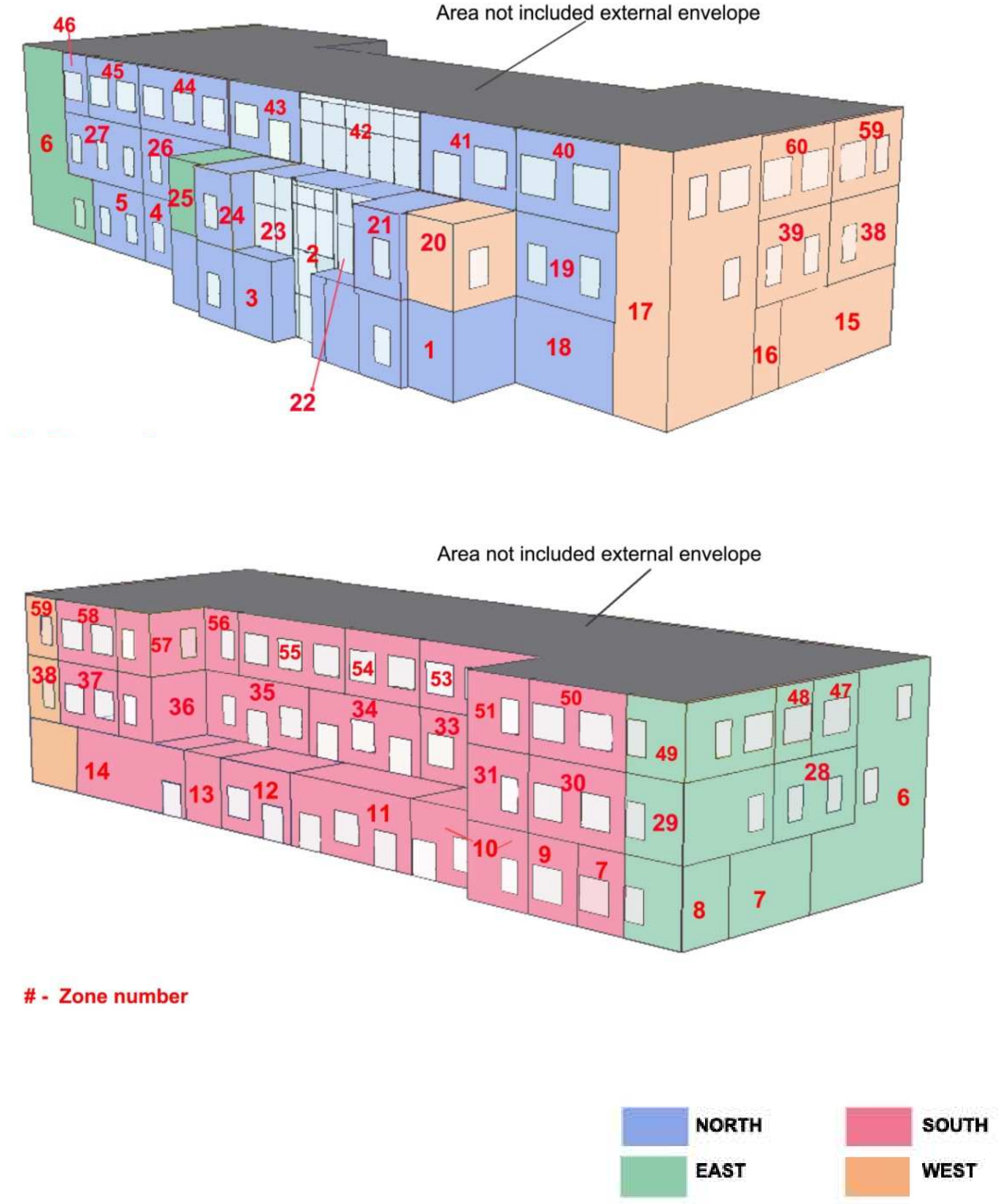


Figure 27 Three dimensional view of building envelope with orientations

APPENDIX B: GRAPHIC RESULTS

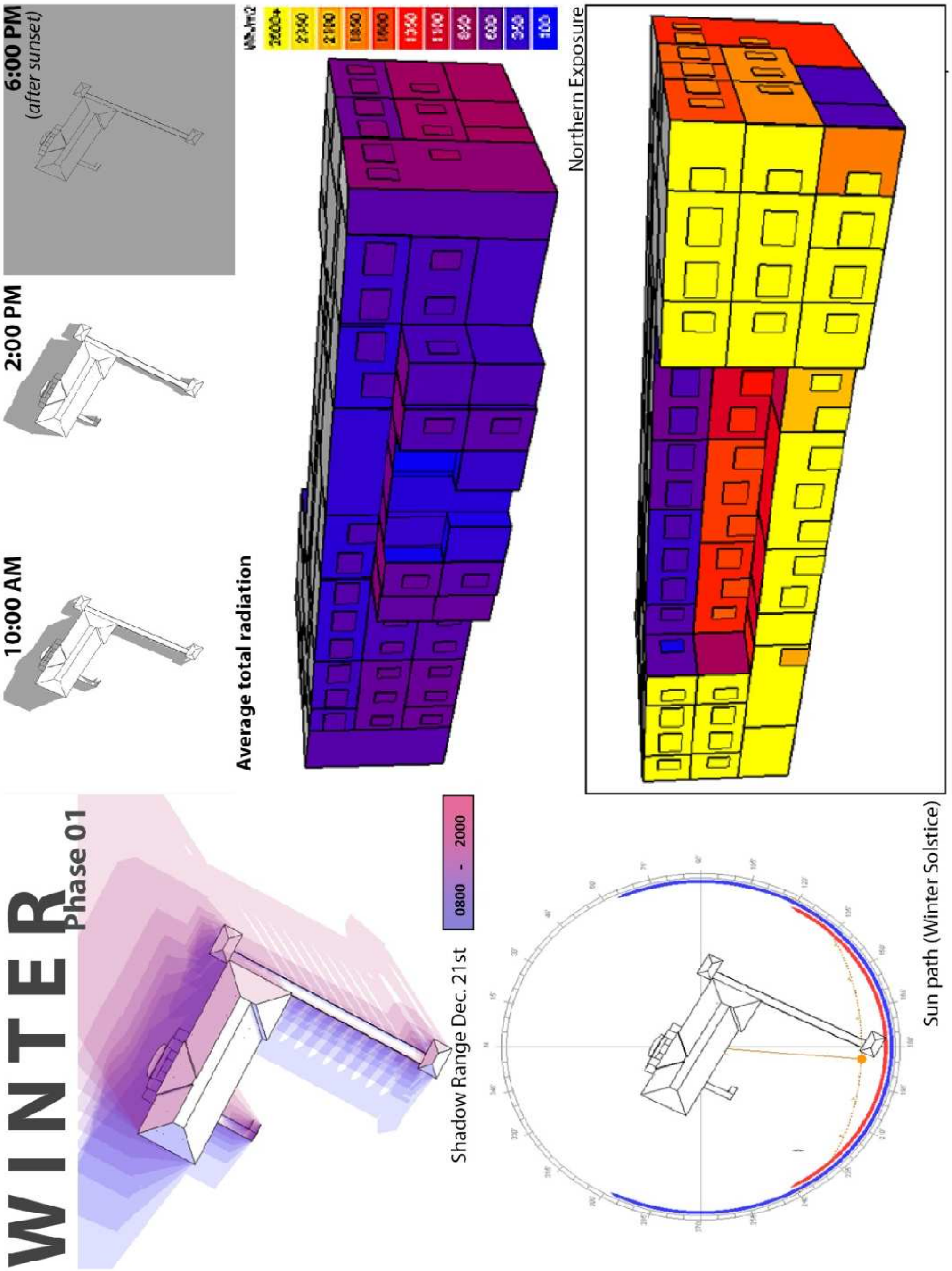


Figure 28 Phase 01 results

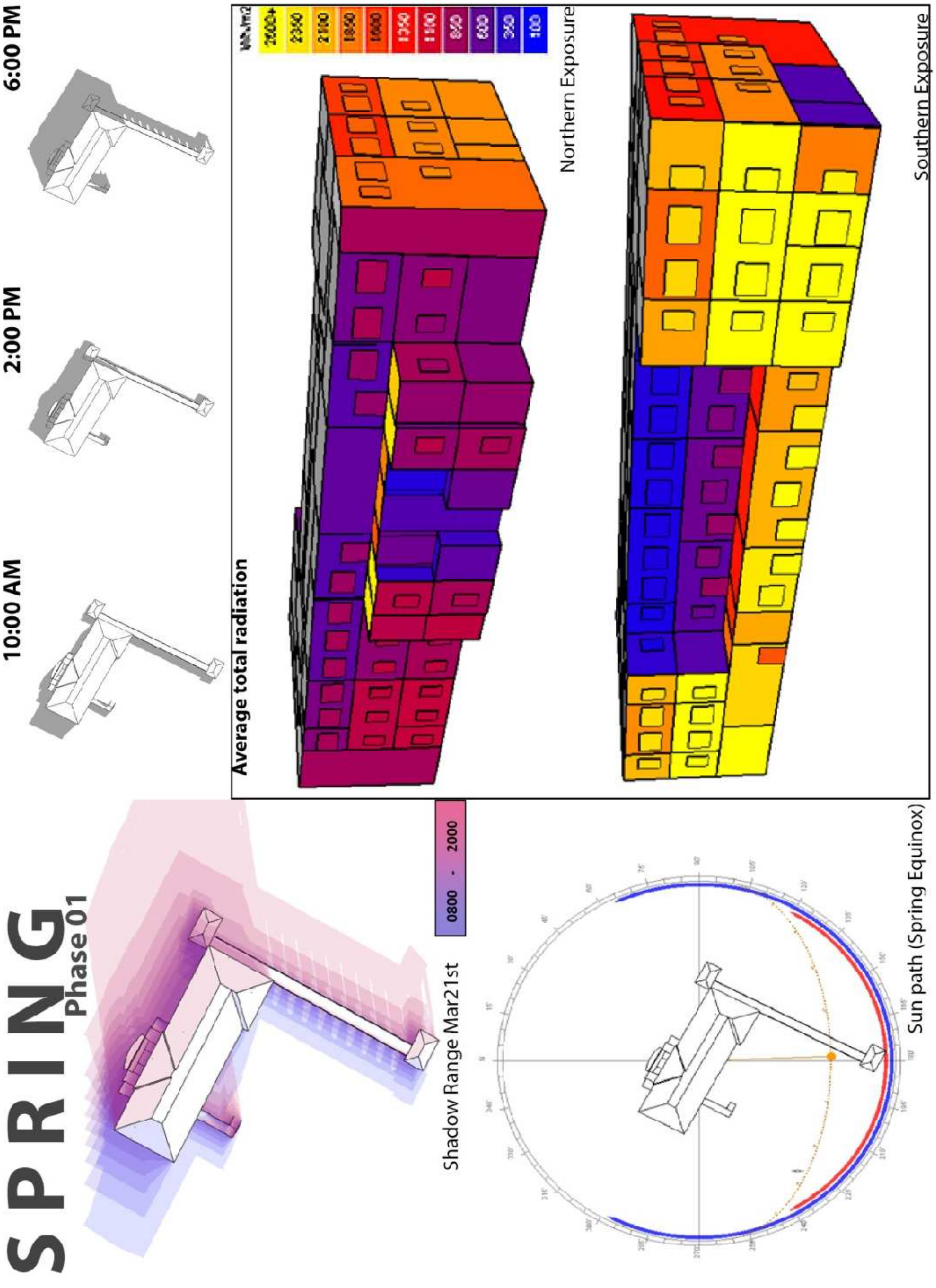


Figure 28 Phase 01 results (Continued)

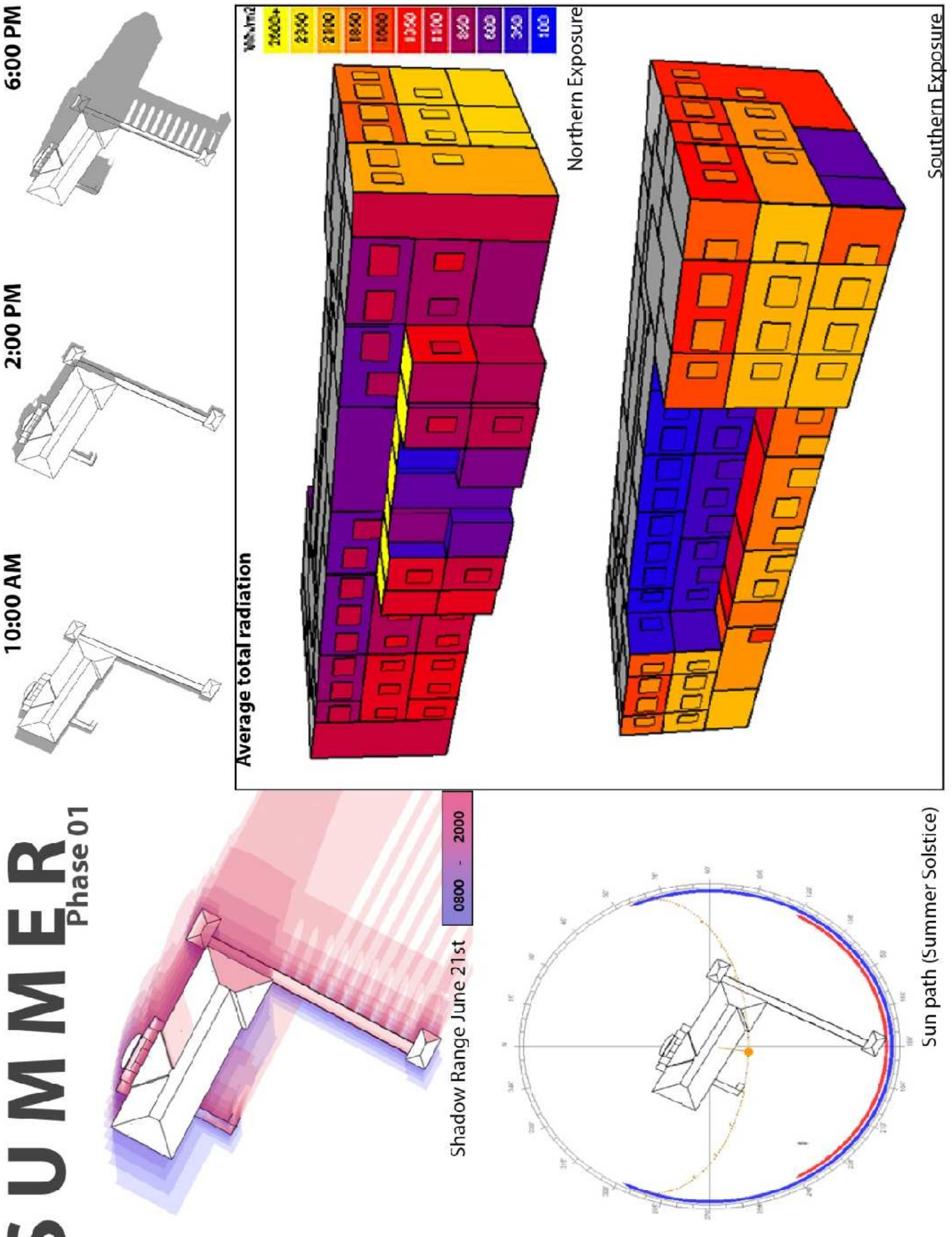
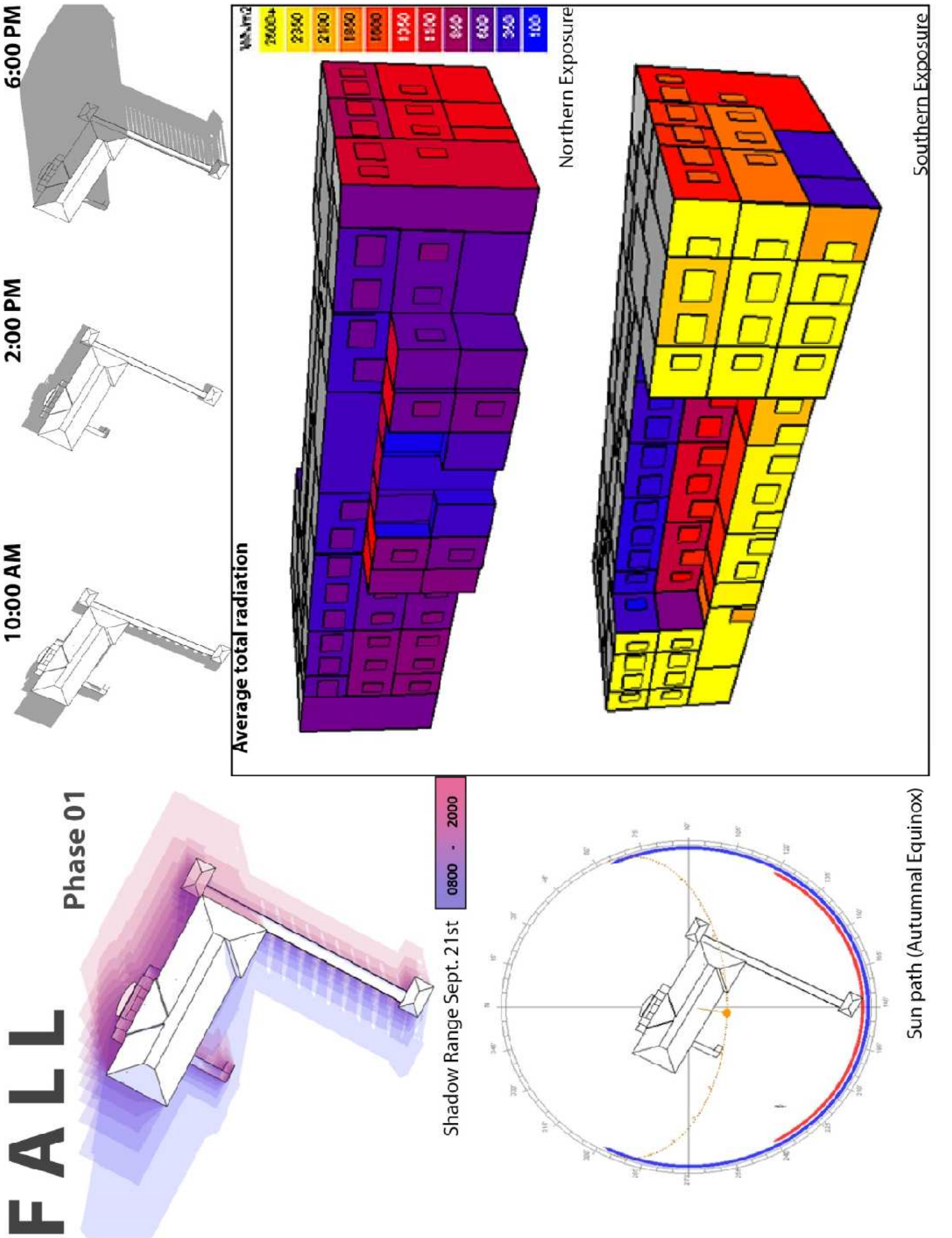


Figure 28 Phase 01 results (Continued)



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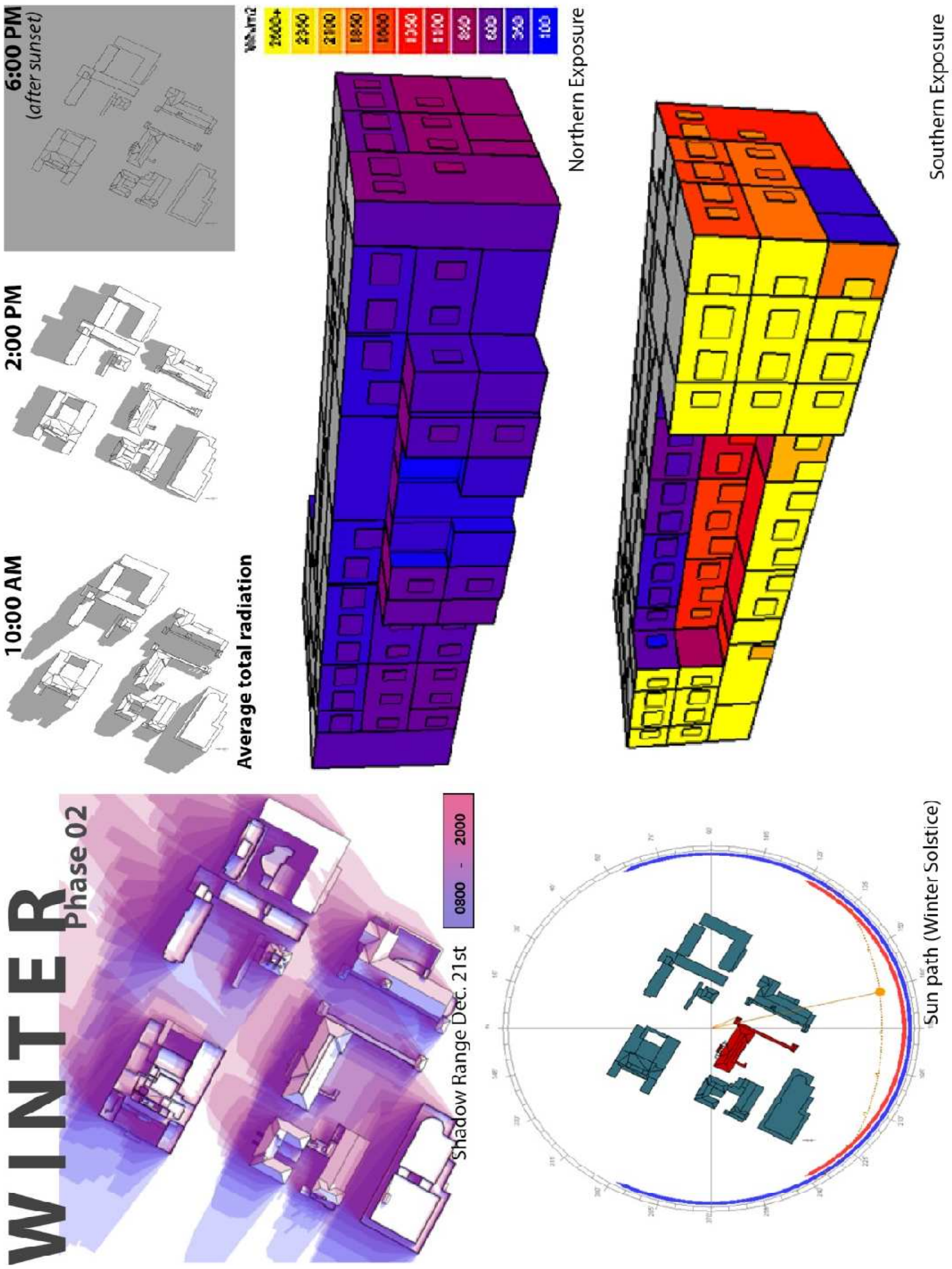
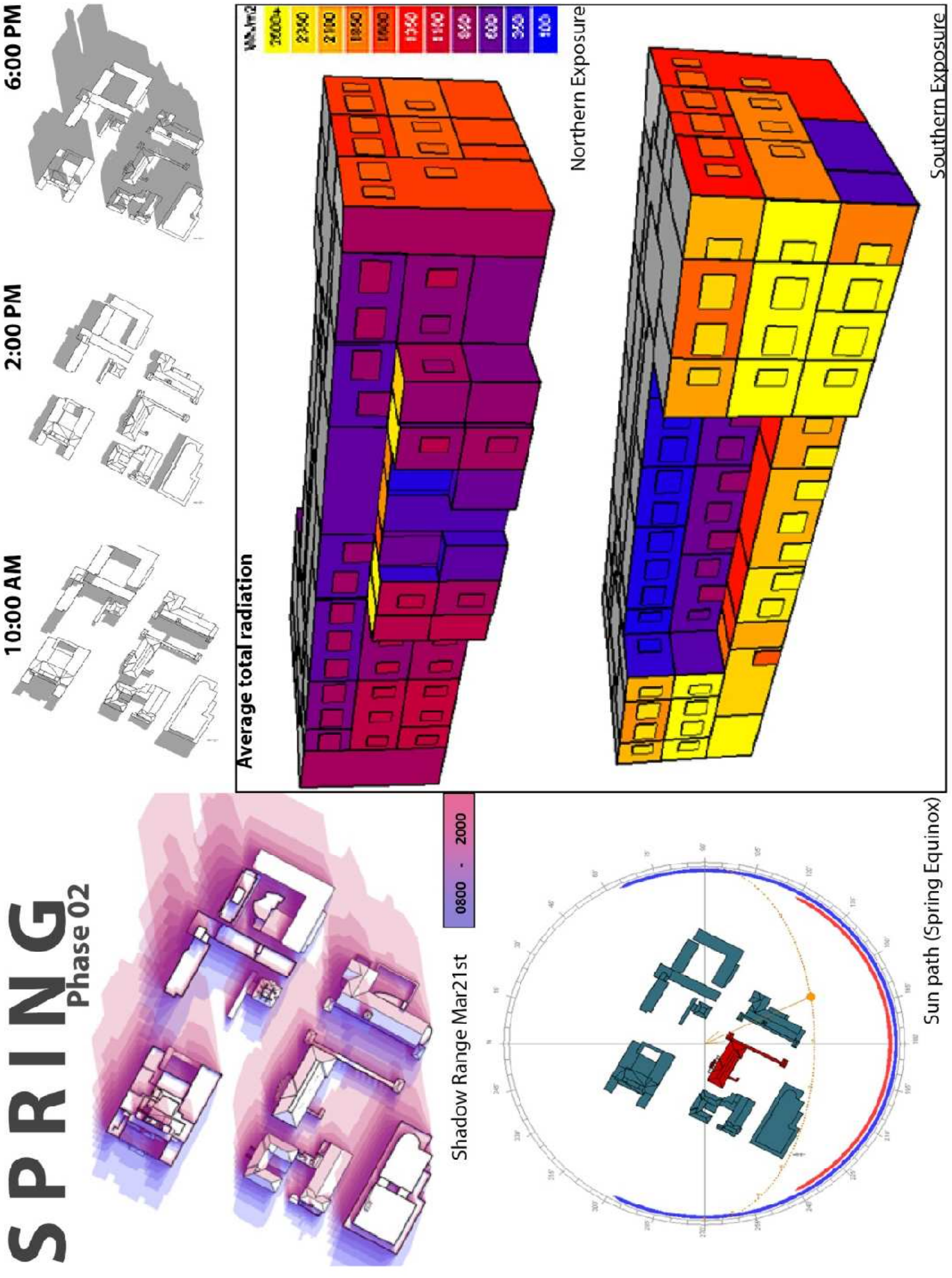


Figure 29 Phase 02 results



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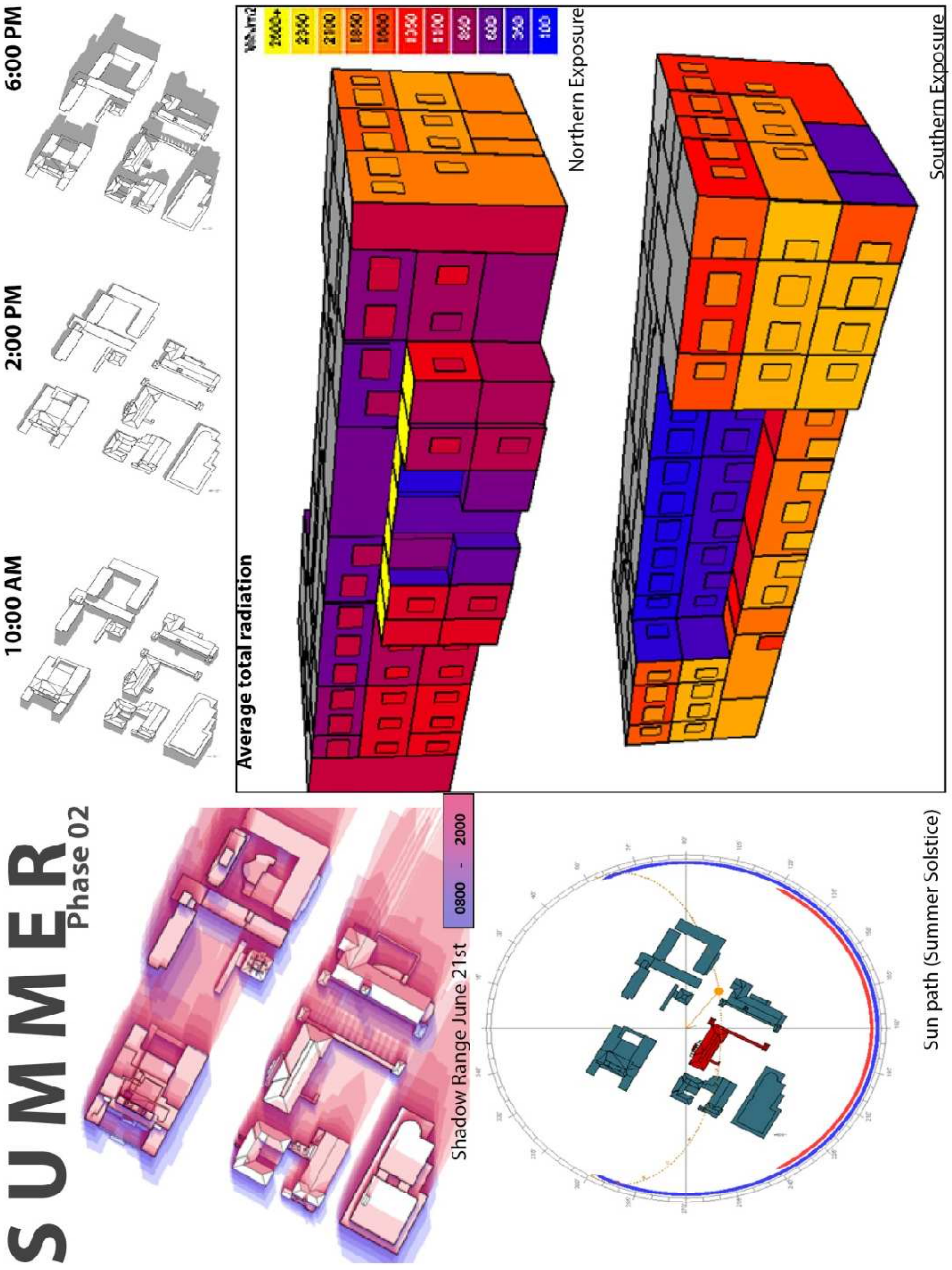

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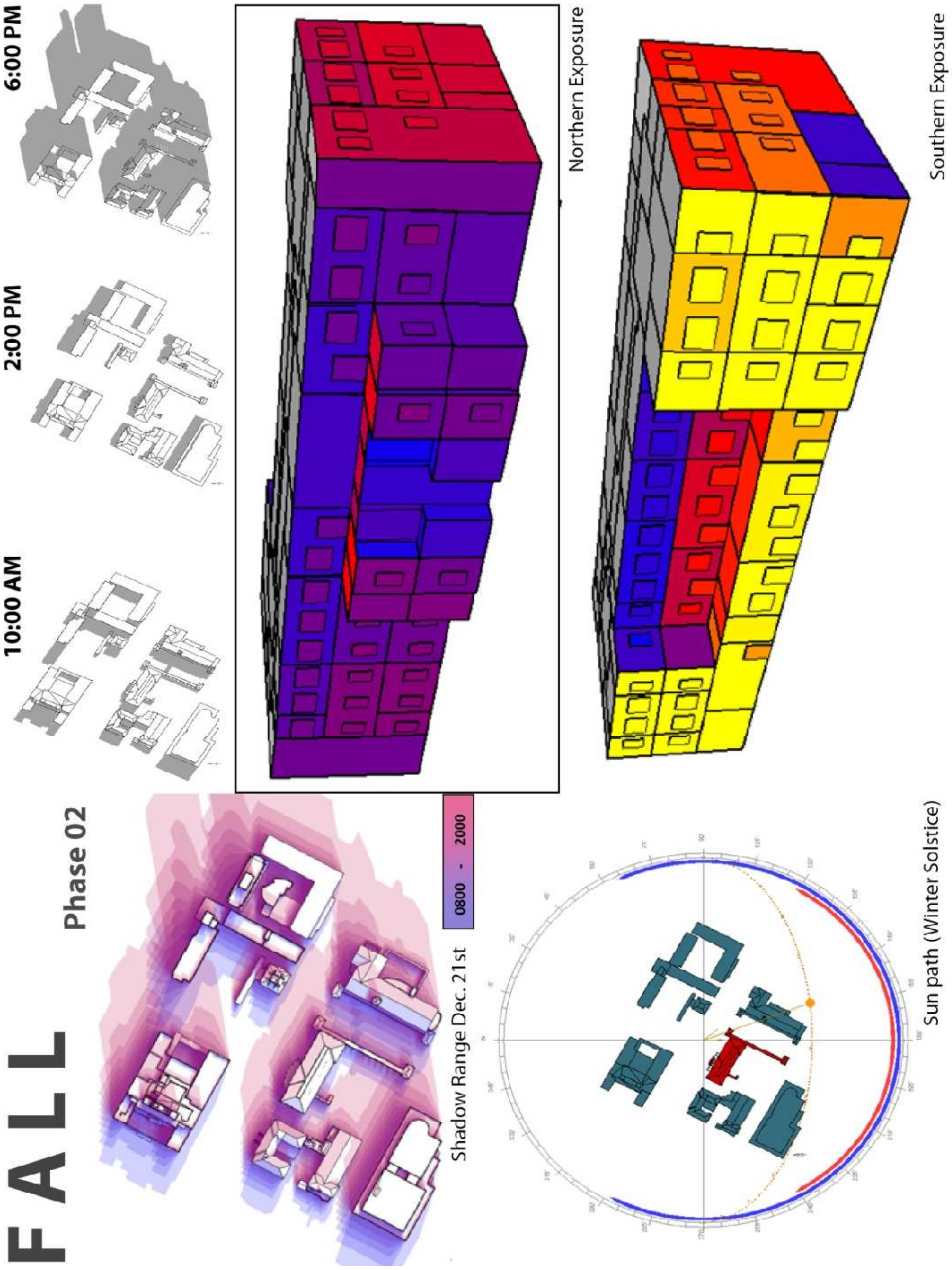

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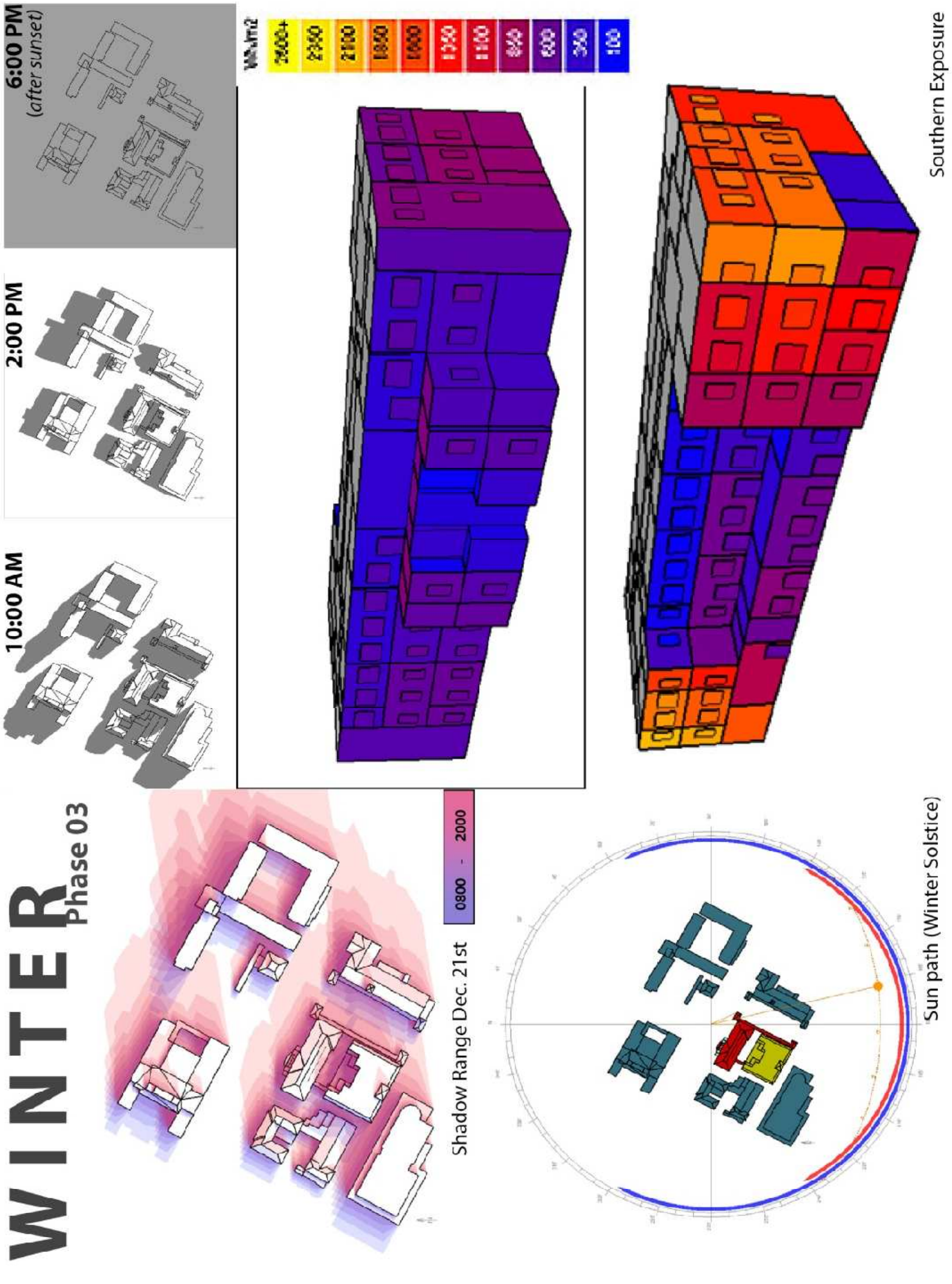


Figure 30 Phase 03 results

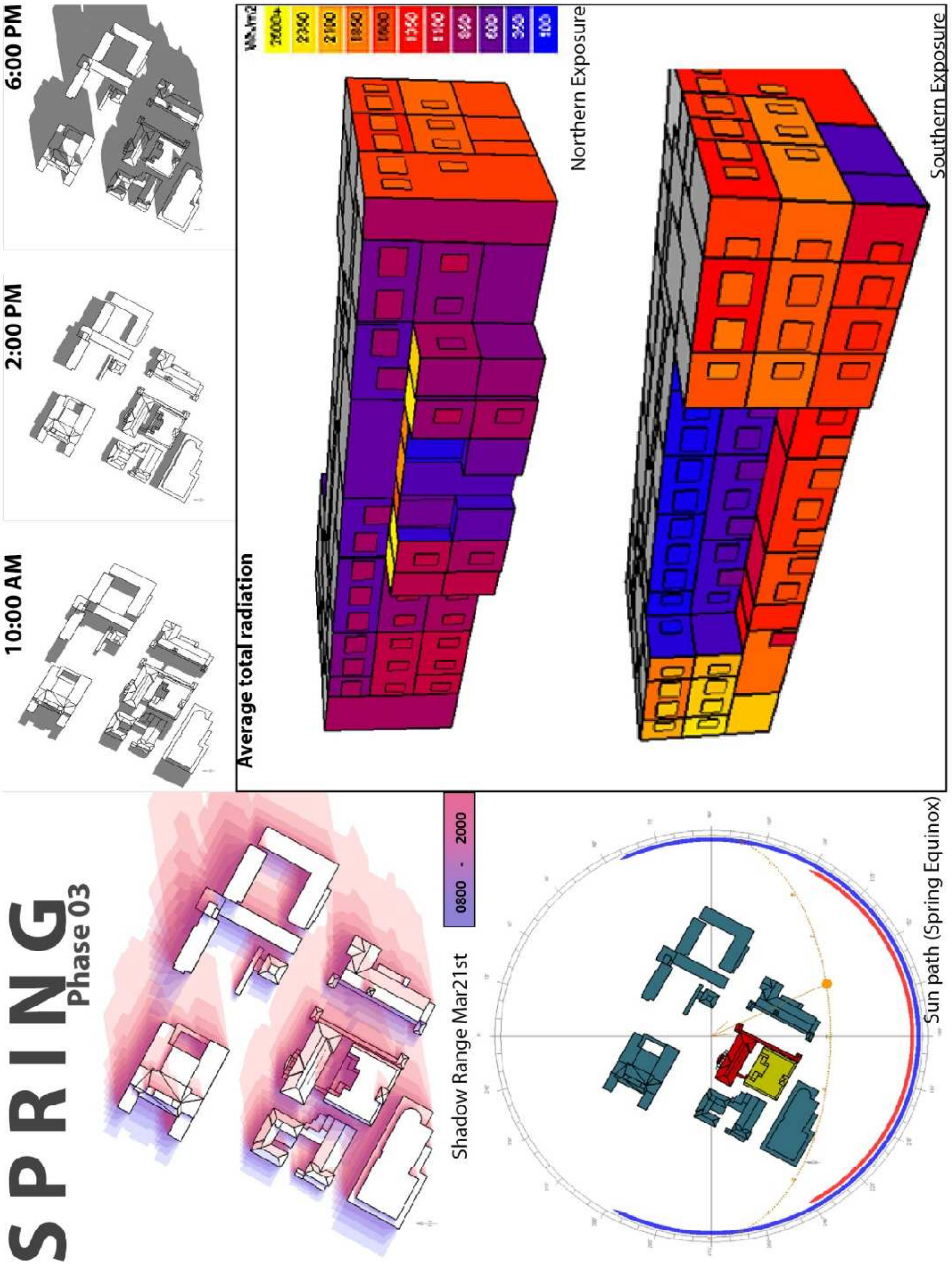
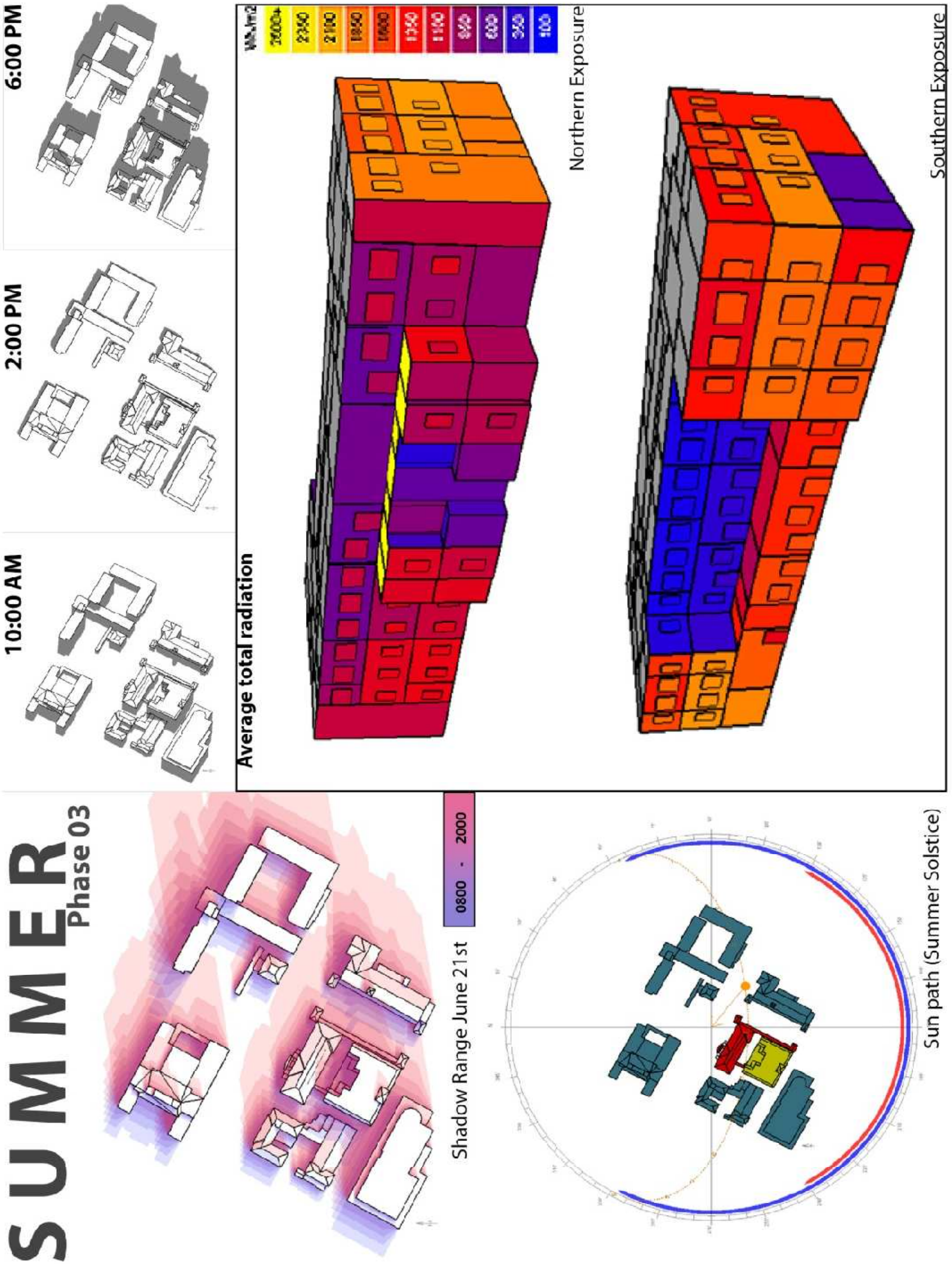


Figure 30 Phase 03 results (Continued)



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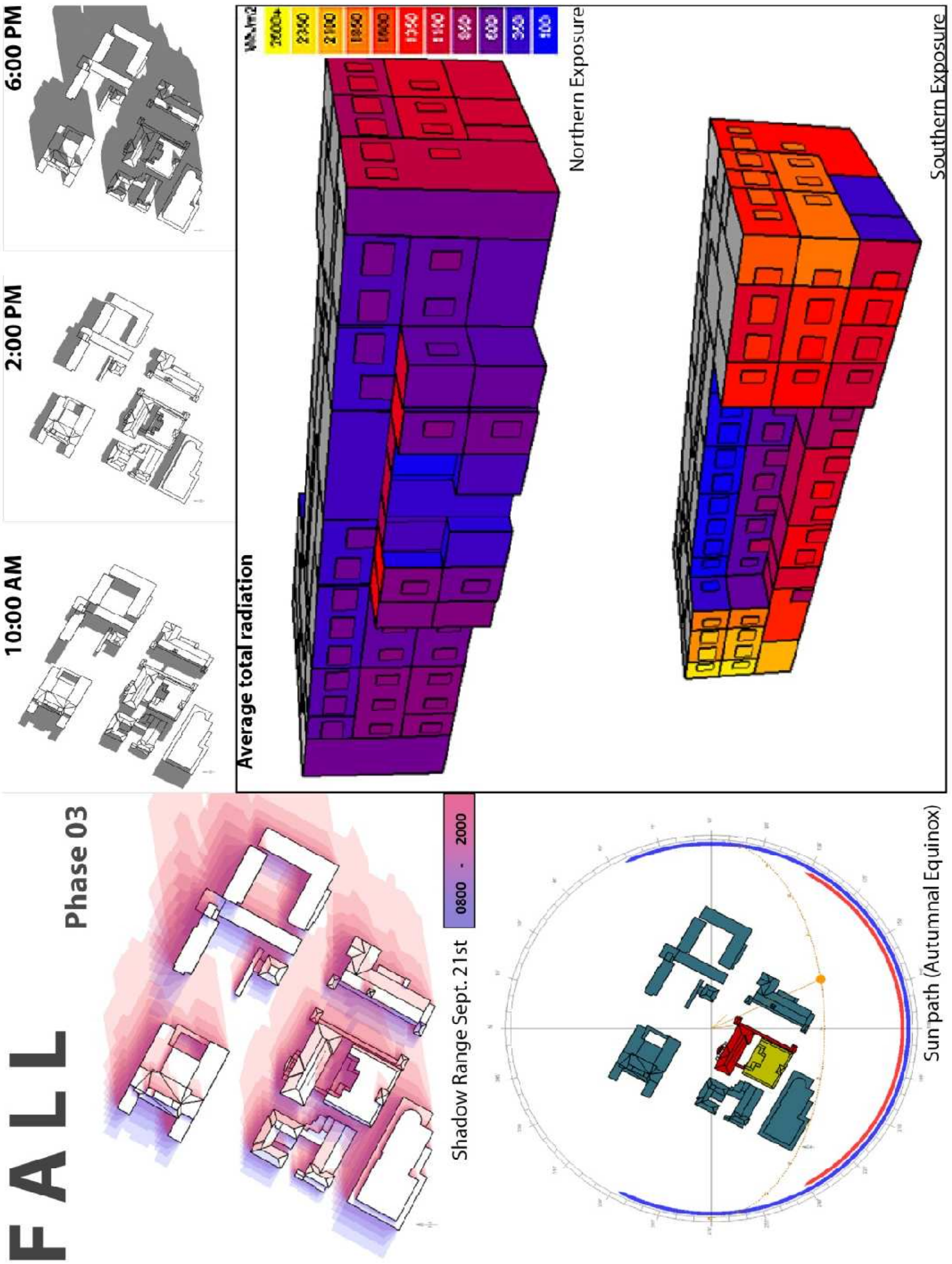

Figure 30 Phase 03 results (Continued)

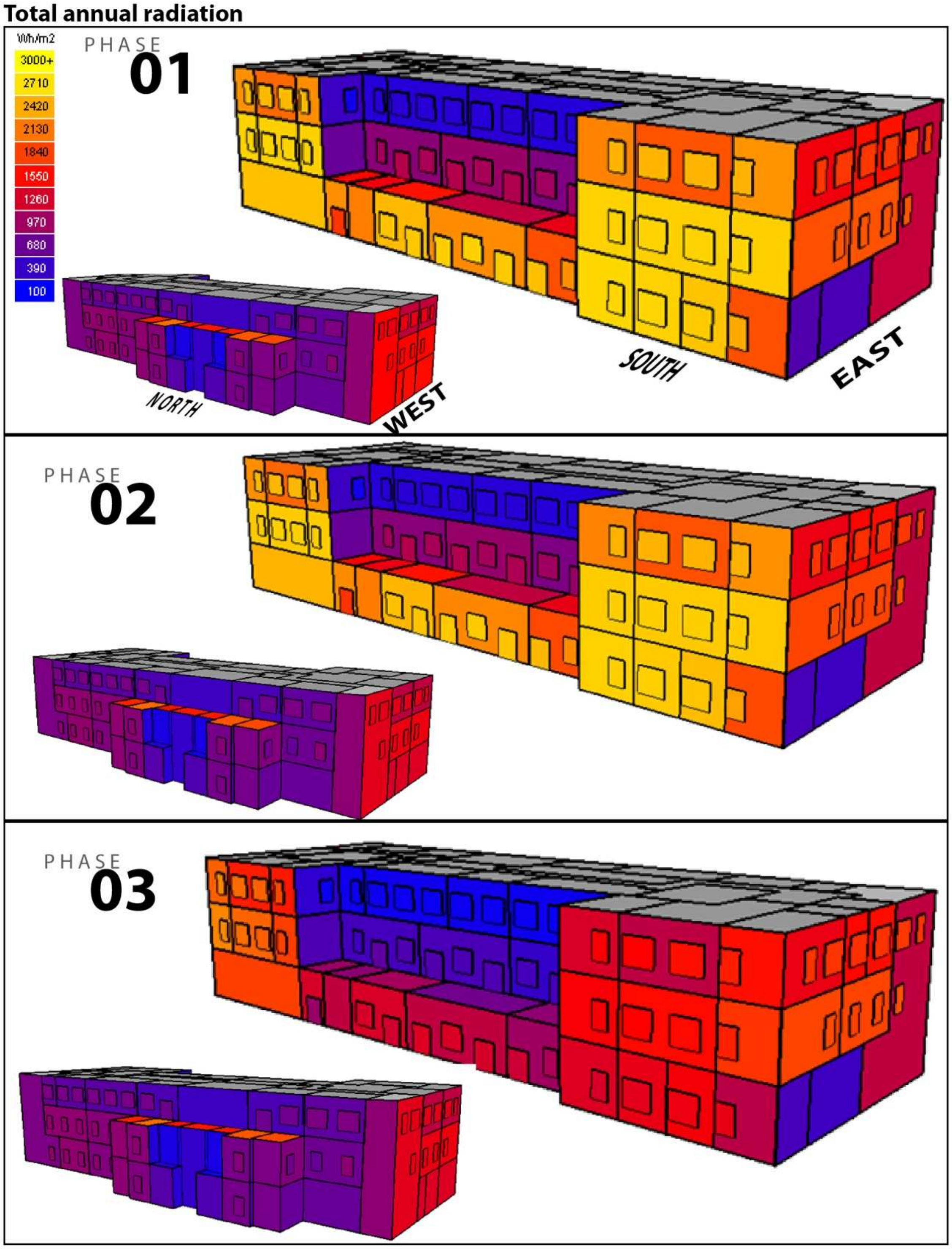

Figure 31 Annual comparisons of all three phases

APPENDIX C- RESULT CHARTS BY BLEMS ZONE

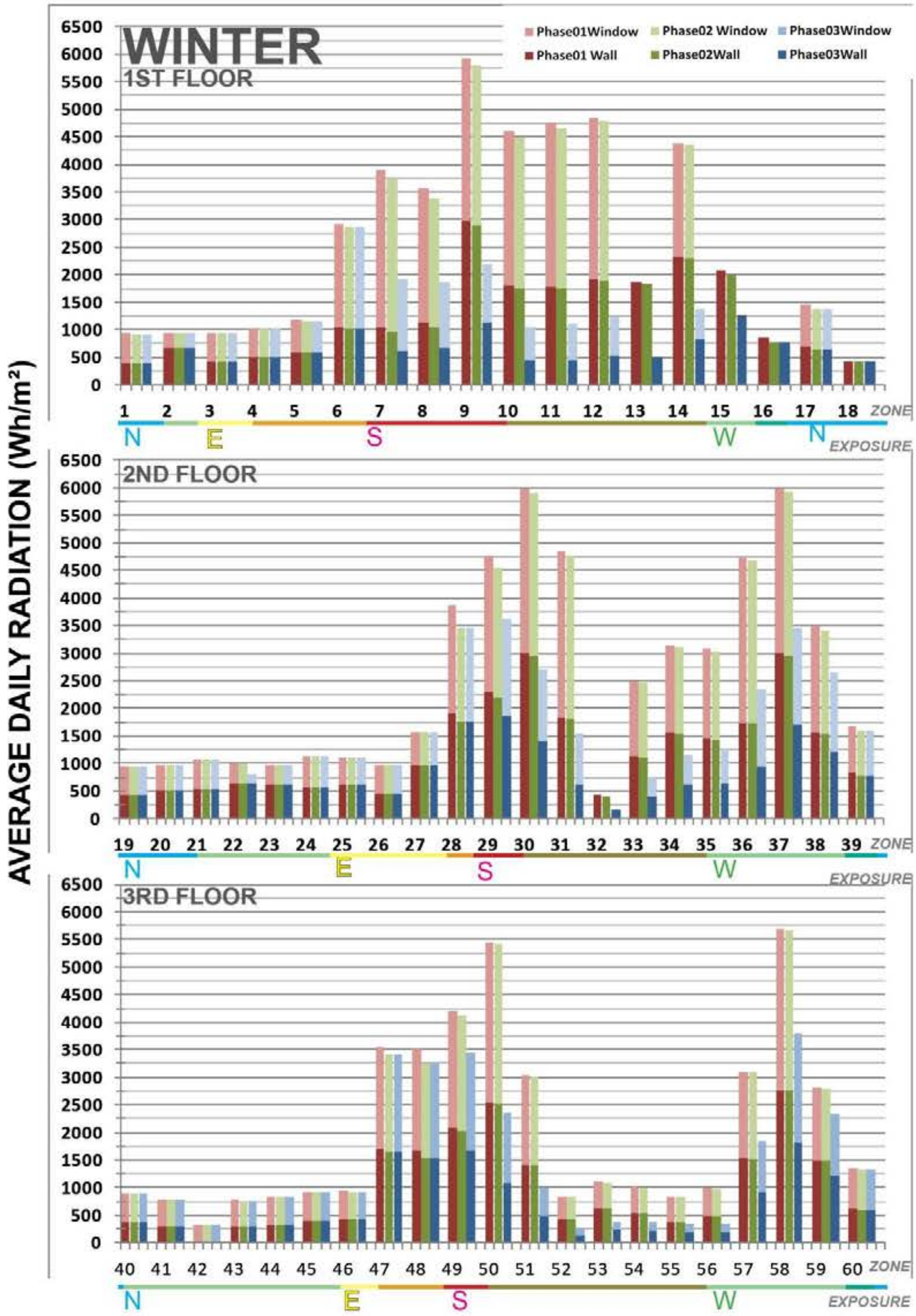

Figure 32 Comparison of each phase by BLEMS zone

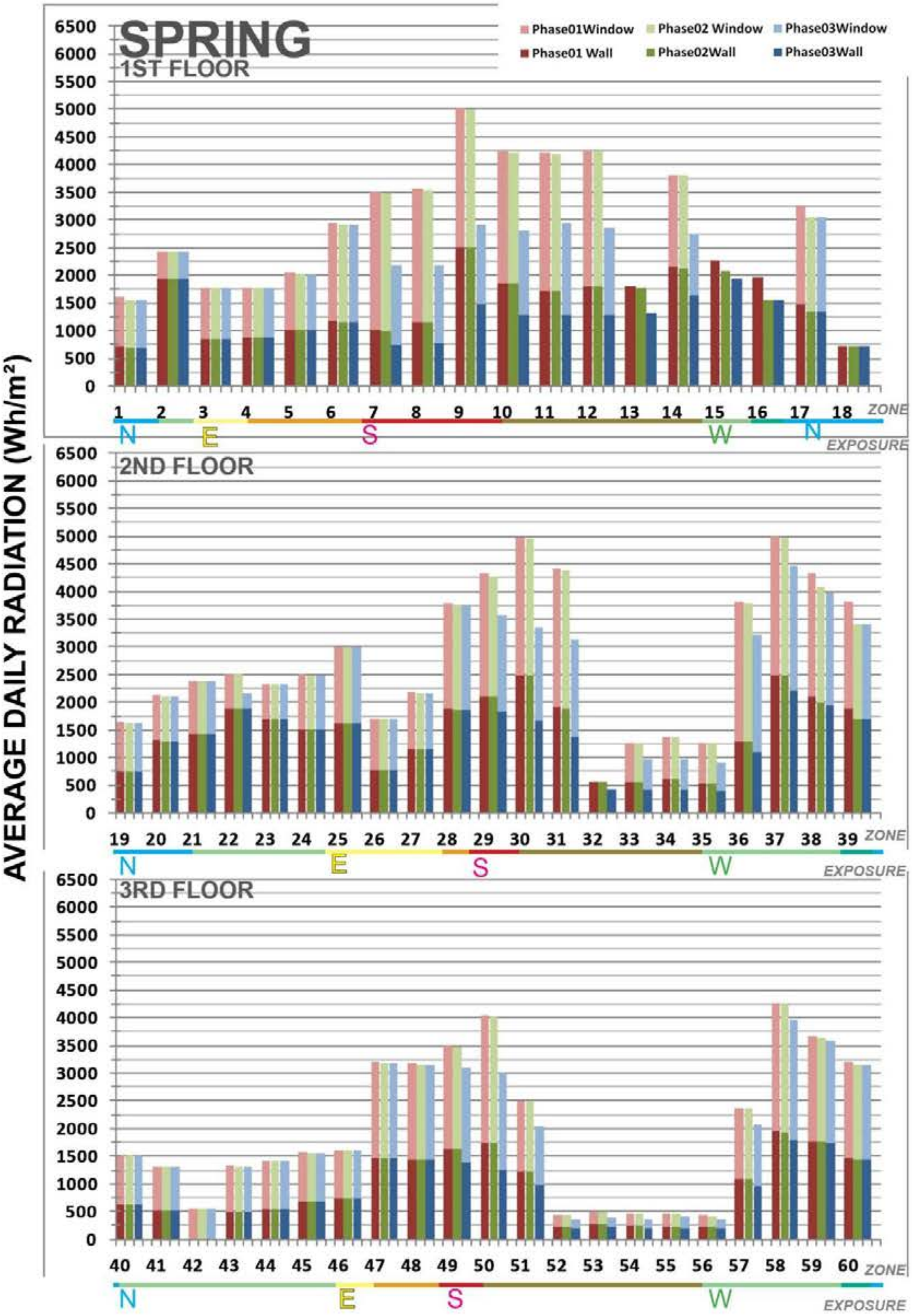

Figure 32 Comparison of each phases by BLEMS zone (Continued)

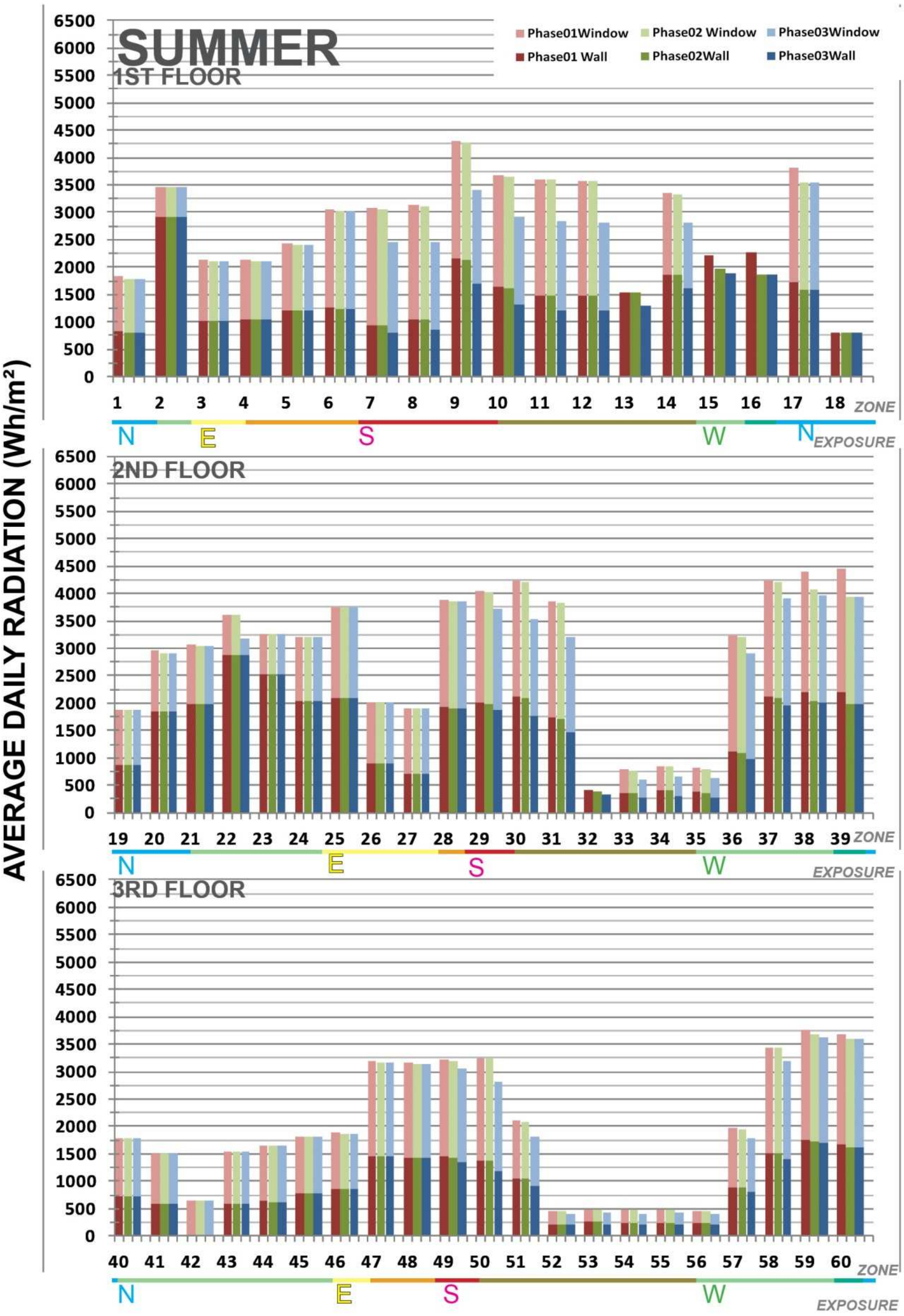

Figure 32 Comparison of each phases by BLEMS zone (Continued)

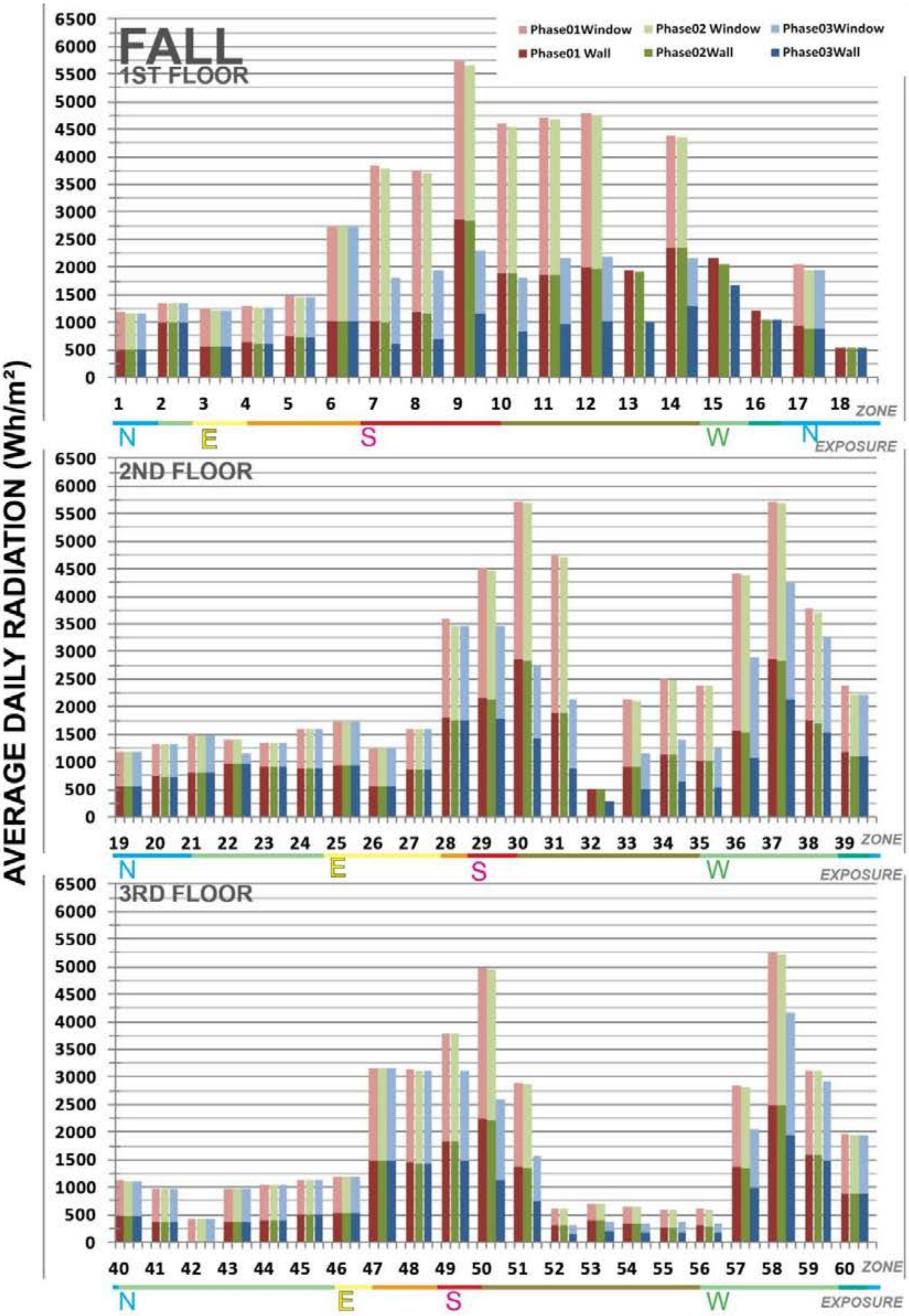

Figure 32 Comparison of each phases by BLEMS zone (Continued)

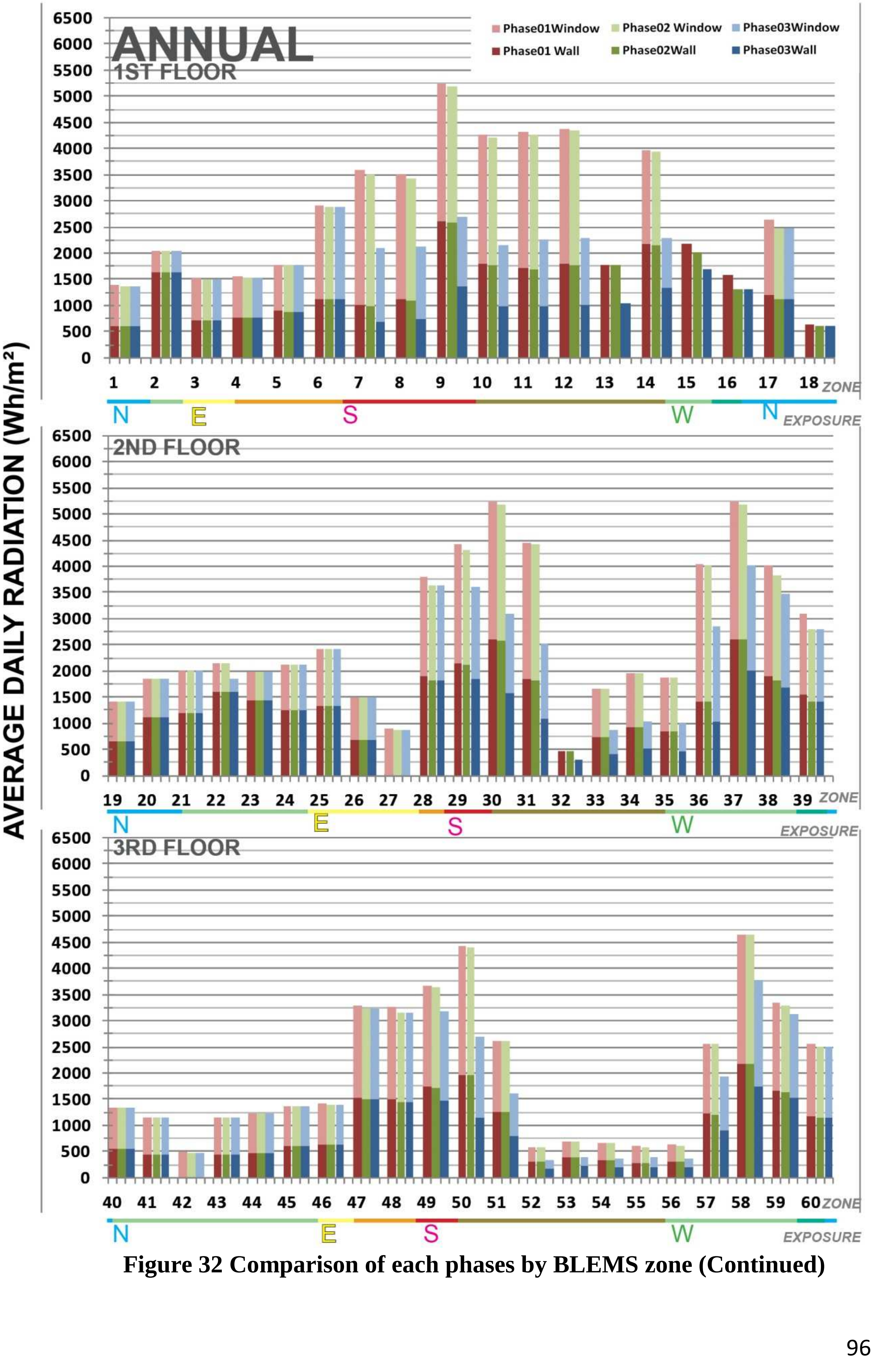

Figure 32 Comparison of each phases by BLEMS zone (Continued)

APPENDIX D: IMPACT CHARTS BY BLEMS ZONE

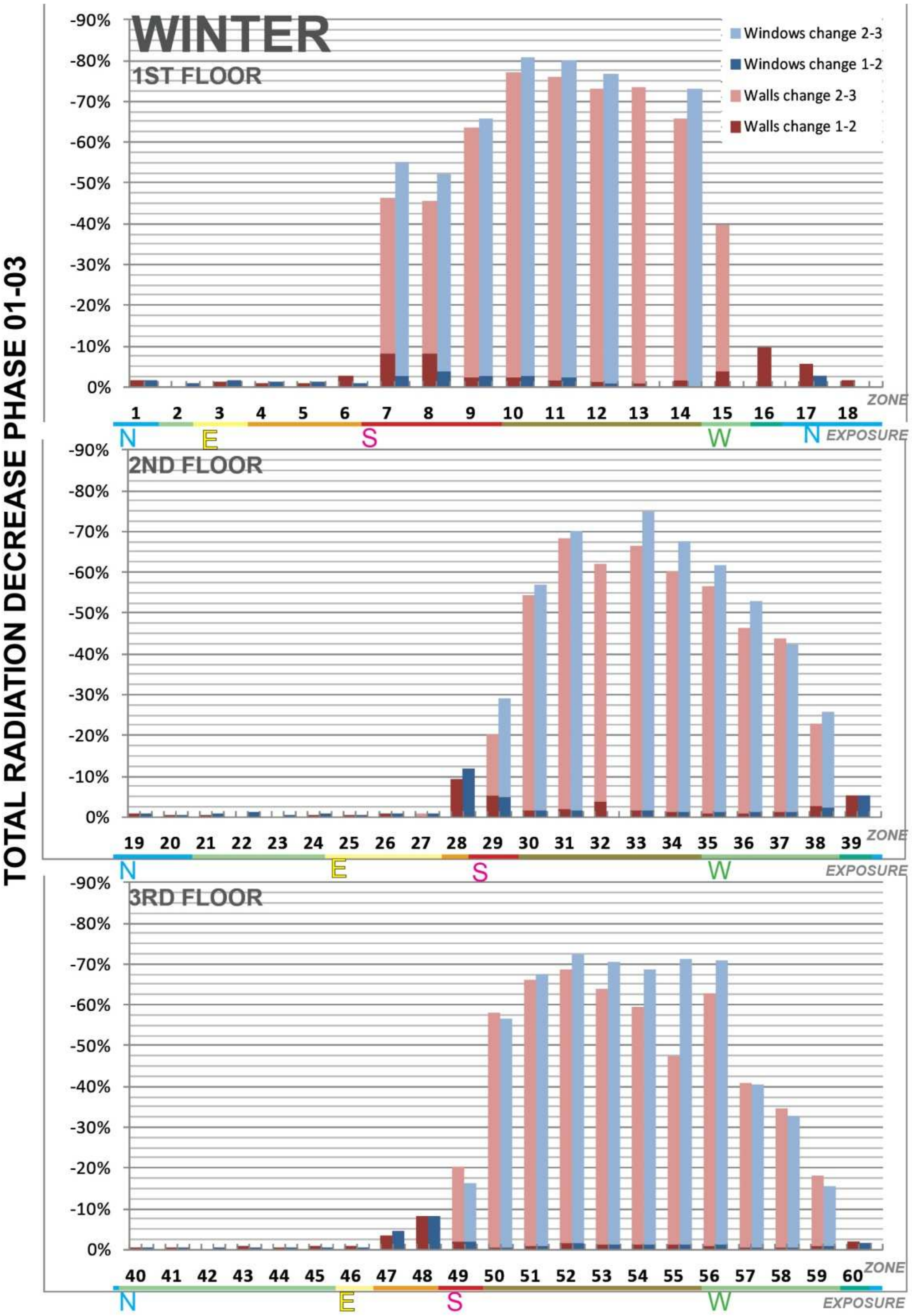

Figure 33 Comparison of total impact by BLEMS zone

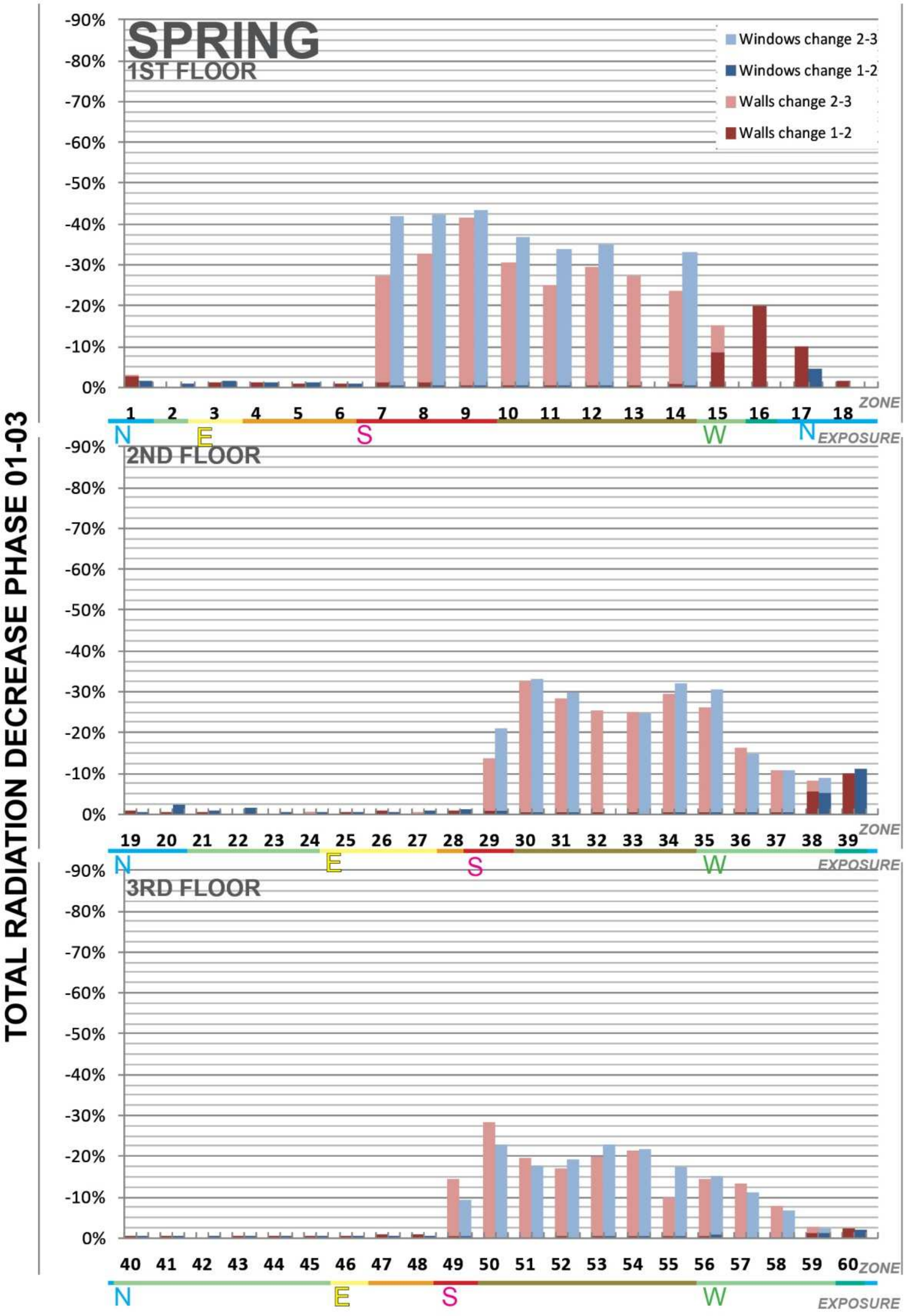

Figure 33 Comparison of total impact by BLEMS zone (Continued)

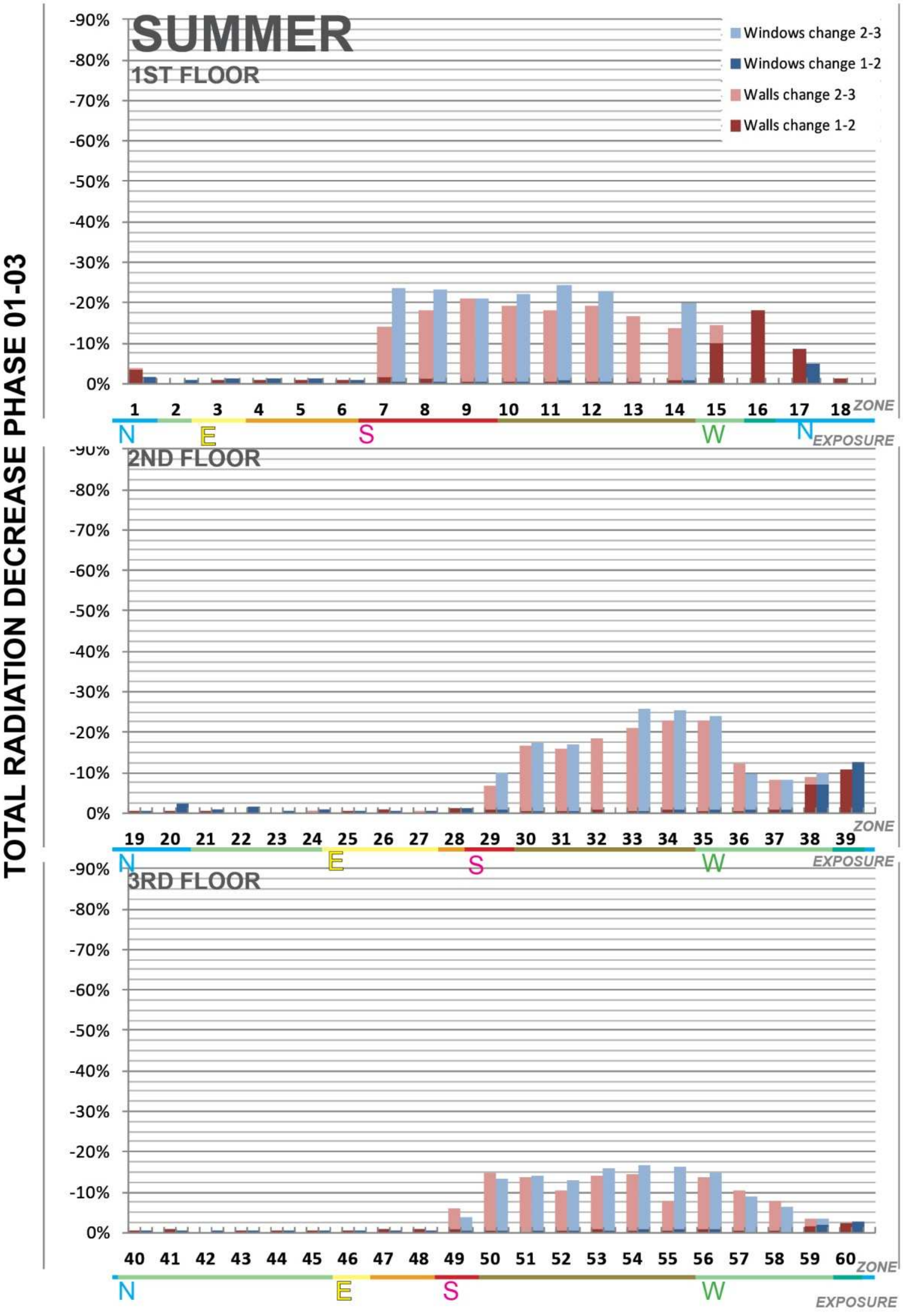

Figure 33 Comparison of total impact by BLEMS zone (Continued)

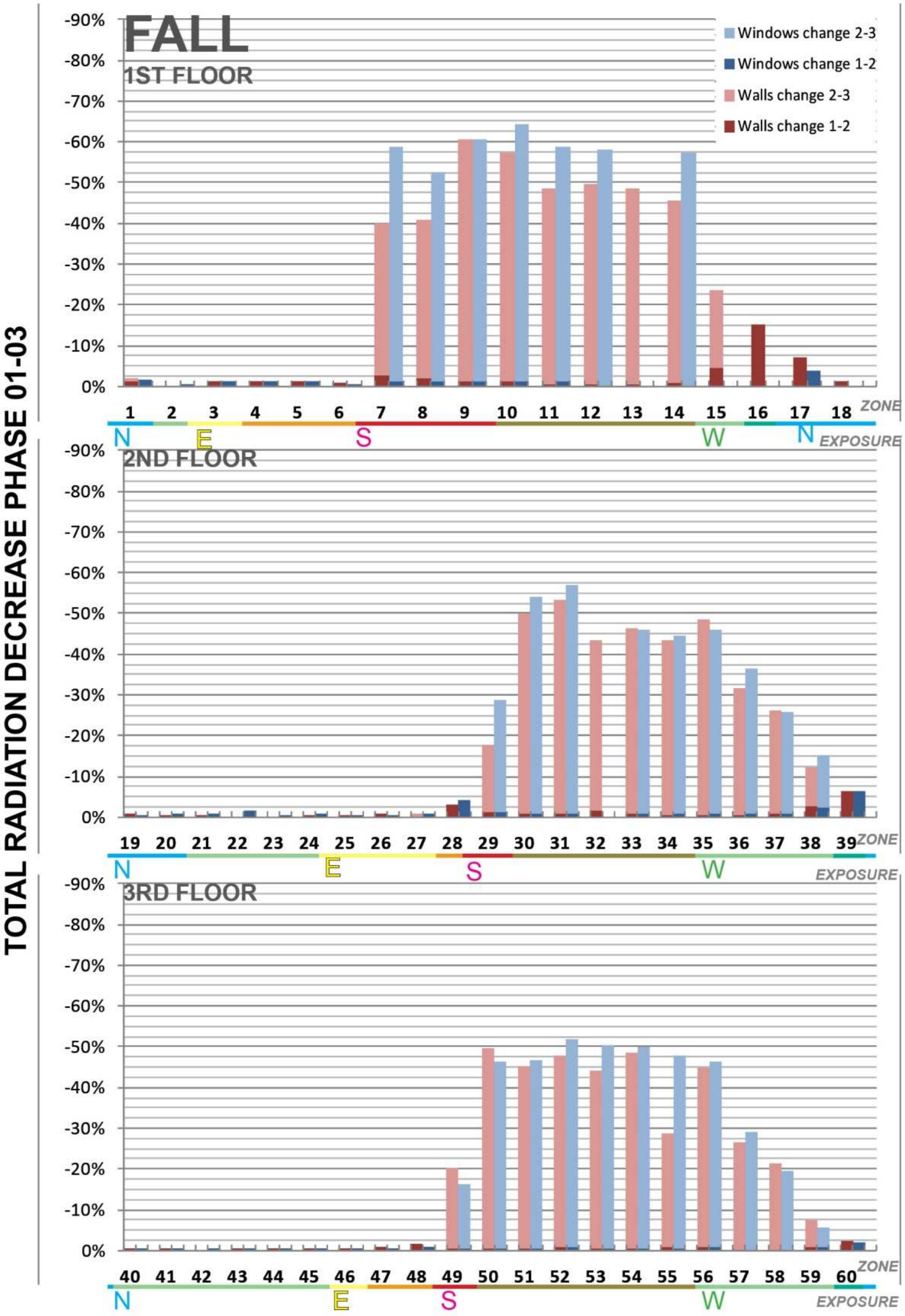

Figure 33 Comparison of total impact by BLEMS zone (Continued)

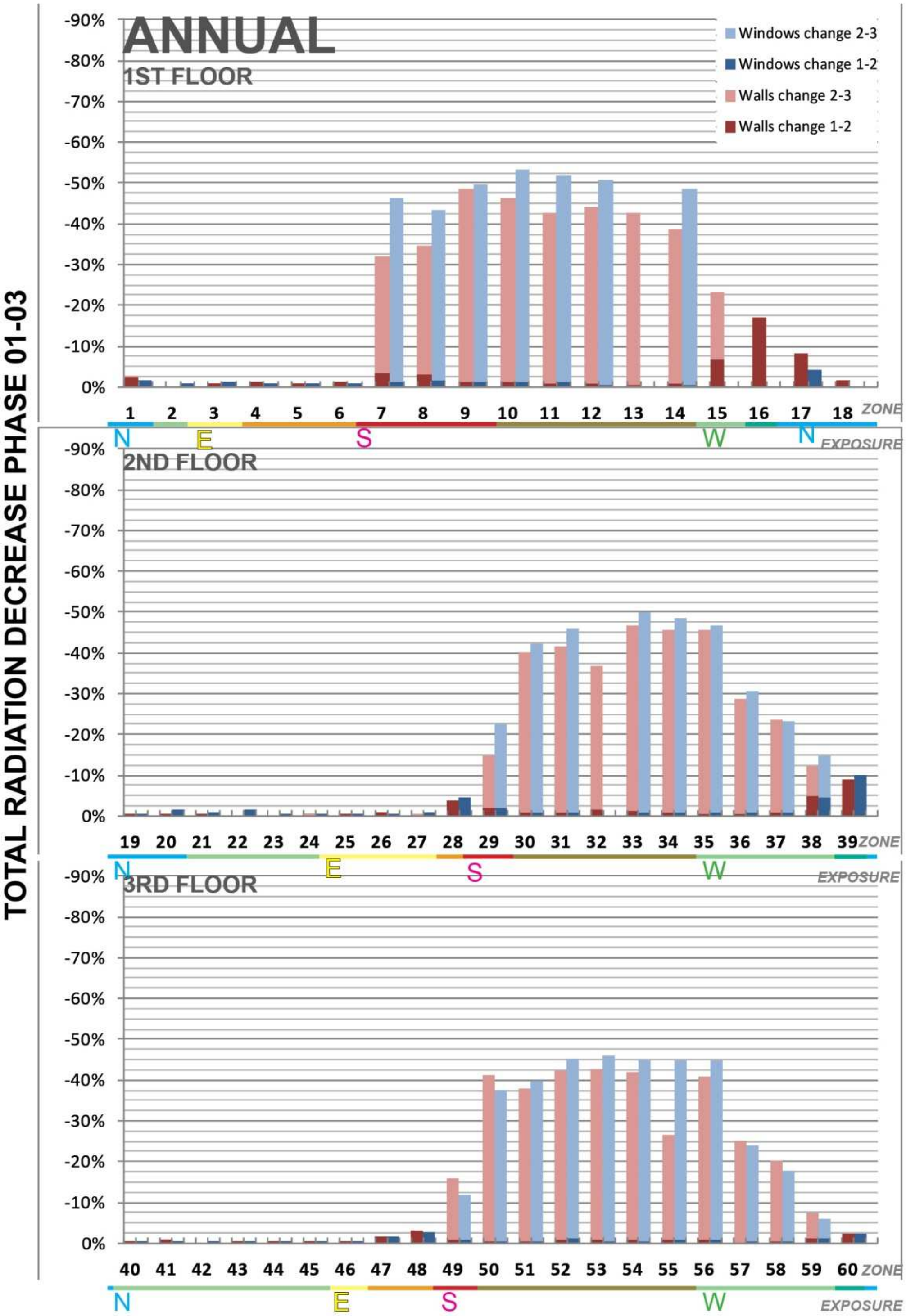

Figure 33 Comparison of total impact by BLEMS zone (Continued)