

The impact of solar geometry on architectural strategies

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in partial fulfillment of the requirements for the degree of Master in Architecture**

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Abstract:

Designing architecture is related to producing vast amounts of information based on constraints, experience or common sense, and at the same time, those designs are assisted by specialized software, but, are the results of those processes giving you advantage or are they leading you in the wrong way? For example, should you include shading elements or less glazing? Should you change the shape of the building or improve envelope specifications? This research is a start to understand how to approach to design problems related to solar geometry, recognize which variables are worth modifying, reduce potential of error when iterating, and take truly advantage of the output delivered by modeling tools.

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The impact of solar geometry on architectural strategies

Introduction:

This Research & Thesis was based on the analysis of passive strategies in an early stage of the design to maximize their potential. This approach is directly related to Performance Based Design (PBD), an iterative process that allows to have control over the variables of a project from the very beginning, unlike the typical approach which validates those variables after the design is completed.

Performance-based design encompasses several factors that lead to a more realistic high-performance building, for the purpose of this research I will only focus on the first three, the rest are shown as a complement to understand what this process involves:

- Alternatives: Produce design iterations and easily find the worst case scenarios
- Ecology: Reduce the building's ecological footprint and Energy Use Index (EUI)
- Potential of Error: Recognize iterations which slow-down the process of design and improve the workflow

- Wellness: Improve the quality and experience of the space
- Financial Benefits: Design based on the goals of the stakeholders in an early stage
- Collaboration: Increase multidisciplinary communication and improve workflow
- Feedback: Performance analysis as an early stage design rather than as an end-of-process validation tool.

Focus of research:

Explore the process of designing and redesigning two buildings as they relate to solar orientation, shading, window-to-wall ratio, and solar heat gain coefficient.

Objective:

Recognize the impact of architectural strategies related to solar geometry, focusing on daylighting and solar heat gain.

Methodology:

1. Use 'Rules of Thumb' based on orientation, window-to-wall ratio and shading to design two buildings.
2. Validate or invalidate the previous 'Rules of Thumb' by testing them with a high performance building design software.
3. Iterate, compare the quantitative results of those iterations, and identify combinations of strategies that are the most impactful to balance daylighting quality and energy use.

Limitation of the research:

The quantitative data shown will only be a guide to understand the process and differences between iterations of these two buildings, and it is not intended to be used to derive universal patterns.

Chapter 1:

Rules of Thumb in architecture:

Rules of thumb¹ can be misleading because they do not account for specific variables of a project, but rather offer a more universal guideline. They do not focus on a building's context, shape, usage or plan distribution. Moreover, they cannot discriminate which strategies or architectural elements will be impactful on energy performance or daylighting. In summary, they help to design with basic parameters and general guidelines, which can be misleading, rather than allowing the professionals to recognize, combine and apply strategies on a case-by-case basis in order to meet performance goals with a technical foundation.

My research focused on the following three rules of thumb to design solar geometry in Northern Latitudes:

1.1 East-West Orientation Rule-of-Thumb

Common understanding

Ideal alignment for most buildings is east to west in its longest side or main facade (or at least within 30 degrees of south), with most glazing on the north façade for indirect daylight and south façade for passive solar gain.

The rule may be limited in its utility in specific conditions because it doesn't account for:

- Self-shading due to building geometry (e.g. 'L' shaped)
- Shading from neighbors or vegetation. (including future neighbors)
- Type of building use (e.g. internal-load vs. skin- load dominated)
- Space usage based on floor plan distribution (e.g. amount of time spent in a room and quantity of daylight needed)

1.2 Window-to-wall Ratio Rule-of-Thumb

Common understanding

Higher proportions of glazing in the south facade will benefit solar heat harvesting. To satisfy efficient daylighting, residential buildings should have an average WWR of 25% with rooms no deeper than 23ft, and office buildings an average WWR of 40% with large areas lit by skylights.

The rule may be limited in its utility in specific conditions because it doesn't account for:

- Type of building use (e.g. internal-load vs. skin-load dominated)
- Glazing allocation based on space usage or floor plan distribution
- Conditions related to climate
- Distribution of windows (few large windows or more smaller ones)
- Type and location of glazing coating⁶
- Shading elements

1.3 Shading Rule-of-Thumb

Common understanding

Shading overhangs or extensions should be 1/2 the height of the opening in northern latitudes (44°L) to block strong sun rays in the summer, and to allow solar gain in the winter.

The rule may be limited in its utility in specific conditions because it doesn't account for:

- Quantity and quality of sunlight available
- Internal-load dominated vs. skin-load dominated
- Retractable vs. static shading elements
- External vs. Internal shading elements
- Location of shading elements based on floor plan distribution

Chapter 2:

Analysis of the impact of architectural strategies

Two academic proposals were used as case studies for my Research & Thesis project. Both are located in Blacksburg, Virginia, (Northern Latitude) and were selected to compare the performance of a residential building (skin-load dominated) and an office building (internal load dominated) and understand what strategies are the most impactful related to solar orientation, shading, window-to-wall ratio, and solar heat gain coefficient.



Figure 1: Case Study #1 Residential Building



Figure 2: Case Study #2 Office Building

2.1 Case Study #1 – Residential Building

Background:

This complex was part of the Virginia Tech (VT) proposal for the Race to Zero Competition, sponsored by the U.S Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL). A multidisciplinary team formed by Building Construction and Architecture students worked on a holistic design targeting low energy consumption.



Figure 3: Case Study #1 Residential Building

Constraints:

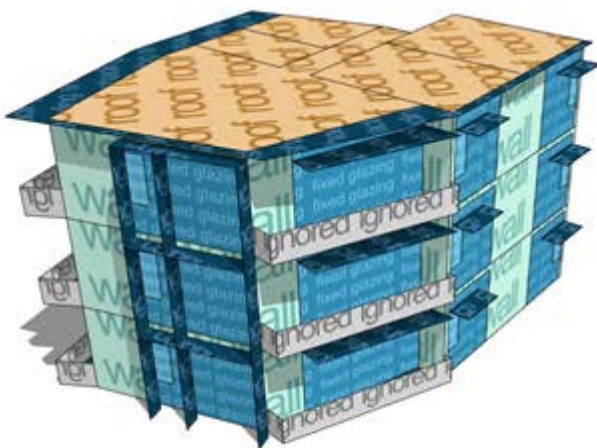
- Northern Latitude-ASHRAE Climate Zone 4
- Skin-Load Dominated
- Single family apartment (Two bedrooms, kitchen, living room, restroom, mechanical and storage rooms)
- No shade from context or neighboring buildings

Process:

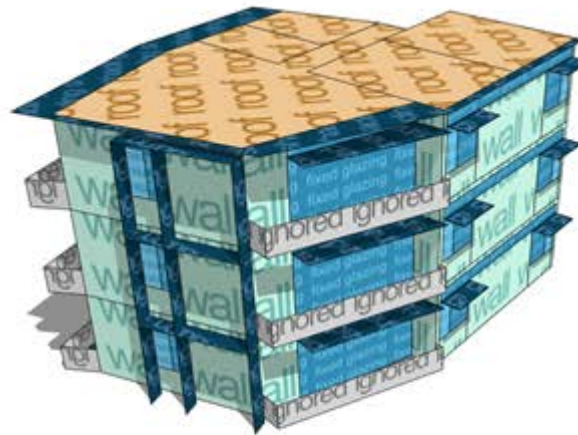
The original architectural design used Rules-of-Thumb¹ to make decisions on orientation, shading and window-to wall ratio.

For the purpose of this research, I revised only one of the eight 3-story buildings located in the complex using Sefaira-Architecture (See Appendix B) by modeling several iterations to validate and refine its original solar geometry strategies. With this, the 'worst case scenarios' were filtered to reduce potential of error and to be able to work with 'useful' iterations to analyze its energy consumption and simulate daylighting based on Spatial Daylight Autonomy (sDA)³, Annual Sun Exposure (ASE)⁴, Direct Sunlight (DS)⁴ and Daylight Factor (DF)⁵, and with this, try to achieve improved outcomes and broadly understand the tradeoffs involved in high-performance design for this specific building.

Iterations:



WWR ORIGINAL +
SHADING ORIGINAL +
ROTATION ORIGINAL



WWR REFINED +
SHADING ORIGINAL +
ROTATION ORIGINAL



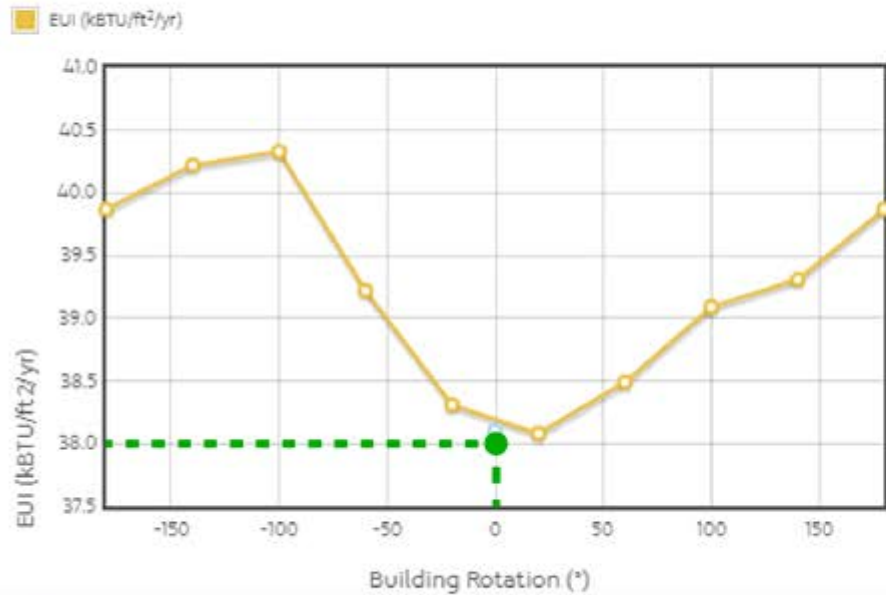
WWR REFINED +
SHADING REFINED +
ROTATION ORIGINAL



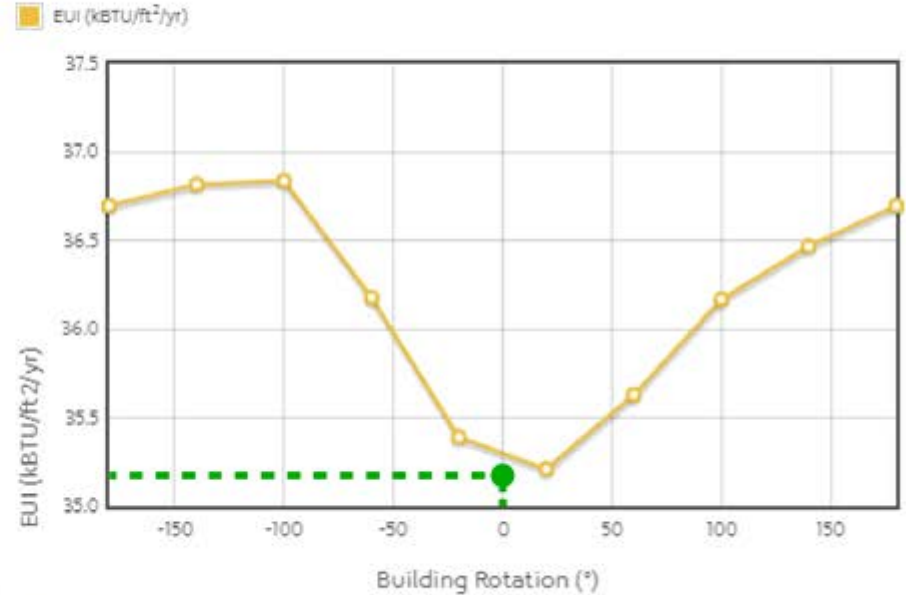
Figure 4: Examples of iterations with different variables applied

Findings:

Orientation



Original Version



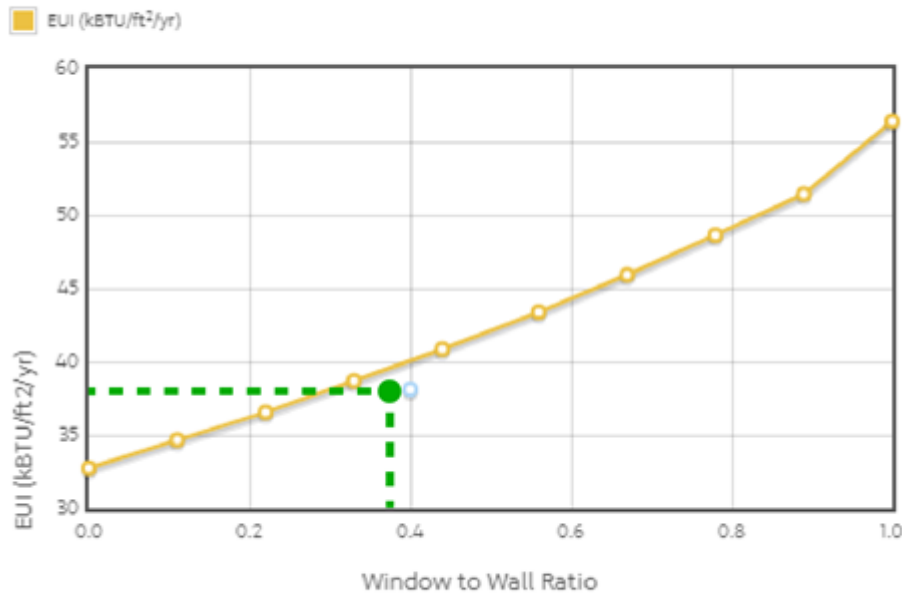
Refined Version

Figure 5: Comparison of the design refinement related to orientation

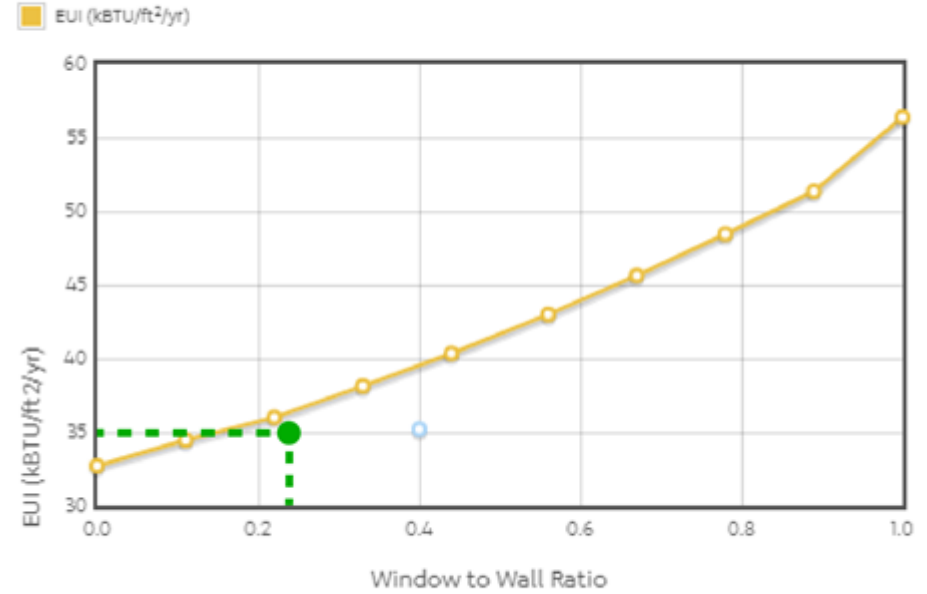
Explanation:

The original south orientation was sufficiently successful in energy use reductions, that is why this strategy was left as a constant until the end, and after combining it with other variables, the EUI² was able to be reduced by 7%. (See Appendix A)

Window-to-Wall Ratio (WWR)



Original Version



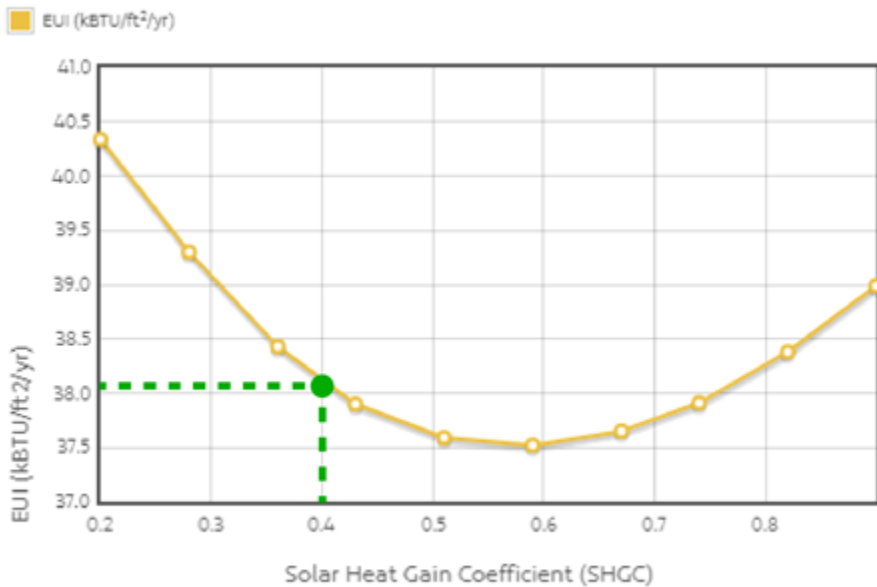
Refined Version

Figure 6: Comparison of the design refinement related to window-to-wall ratio

Explanation:

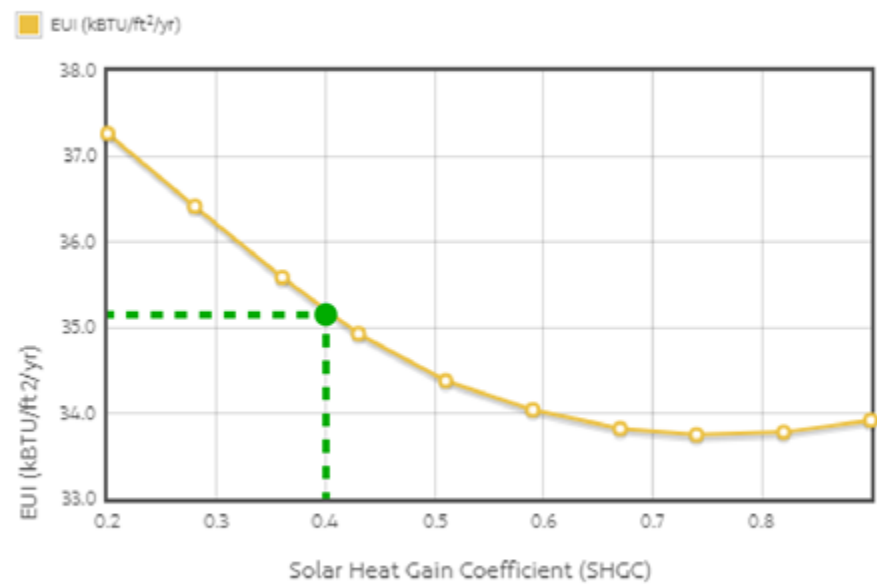
The original Window-to-wall Ratio (WWR) was too high for the recommended range for a residential building (0.2-0.3 (see appendix)) and didn't meet the basic daylight metrics, so, after the analysis of several iterations using Sefaira, the refined version included a 40% decrease to the WWR (from 0.38 to 0.23), but only a slight 8% decrease in EUI² (from 38 to 35), which seemed not impactful, but was compensated with a significant improvement on variables such as Spatial Daylight Autonomy (sDA)³, Annual Sun Exposure (ASE)⁴, Direct Sunlight (DS)⁴ and Daylight Factor (DF)⁵, confirming the importance of combining strategies to have a balanced outcome. (See Appendix D)

Solar Heat Gain Coefficient (SHGC)



Original Version

Figure 7: Comparison of the design refinement related to solar heat gain coefficient



Refined Version

Explanation:

The original curve shows that having a SHGC⁷ of 0.4 (medium-low) or 0.75 (medium-high) has the same energy consumption. The curve also confirms that medium glazing specifications (SHGC of 0.5-0.6) have even a lower energy consumption, but do not apply for a residential/single family building where the recommended coefficient is 0.4 (medium-low) (See Appendix C). In order to achieve a better performance over solar heat gains and losses during summer and winter, daylighting strategies were refined, by reducing and relocating shading elements and redistributing WWR. In other words, SHGC of 0.4 remained constant, EUI² was reduced by 15% and annual daylighting quality was improved. (Shown in the next three analyses)

Note: For the purpose of this research, the glazing U-Factor was kept constant as $U \leq 0.30$ (See Appendix C)

Daylight Factor (DF)

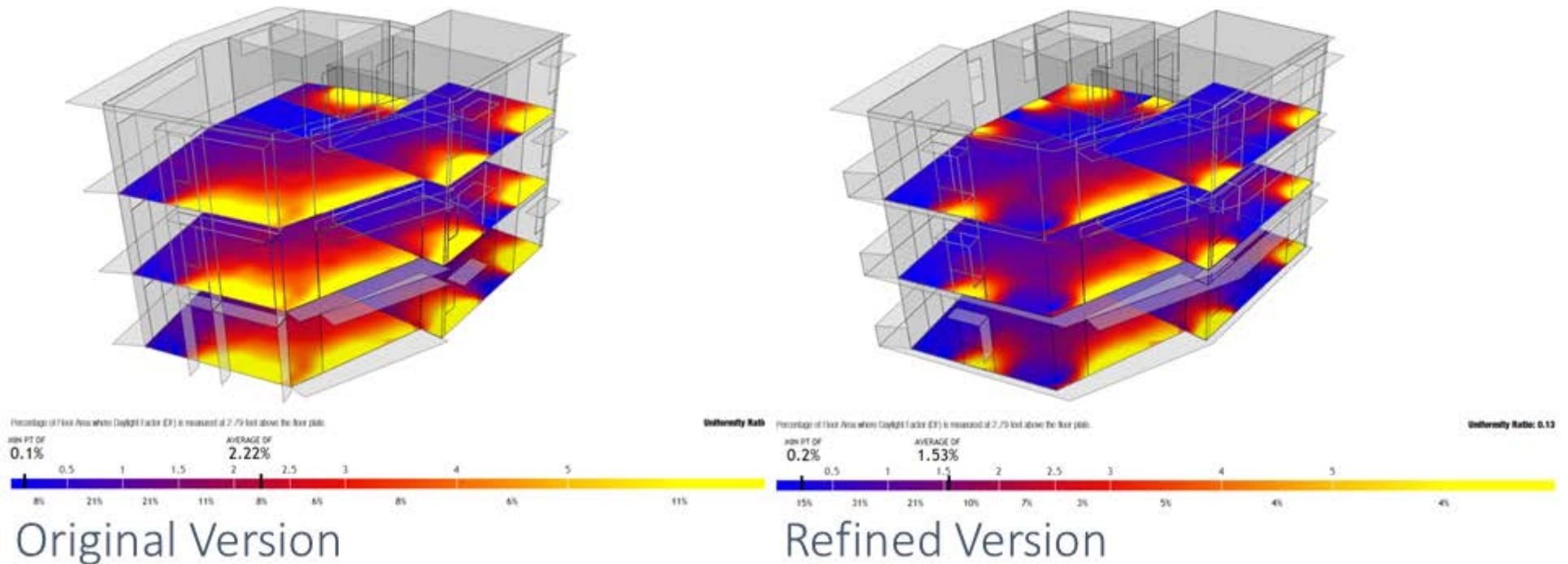


Figure 8: Comparison of the design refinement related to Daylight Factor analysis

Explanation:

This image shows the ratio of illumination levels of the interior spaces relative to the exterior. After analyzing orientation, WWR and SHGC, several iterations were tested to find the option which reduced energy consumption while improving daylighting quality.⁵

(See Appendix E)

Objective:

Reduce large yellow areas (glare), increase purple areas (indirect or ambient light), and redistribute large lit areas into several small ones.

Direct Sunlight (DS)

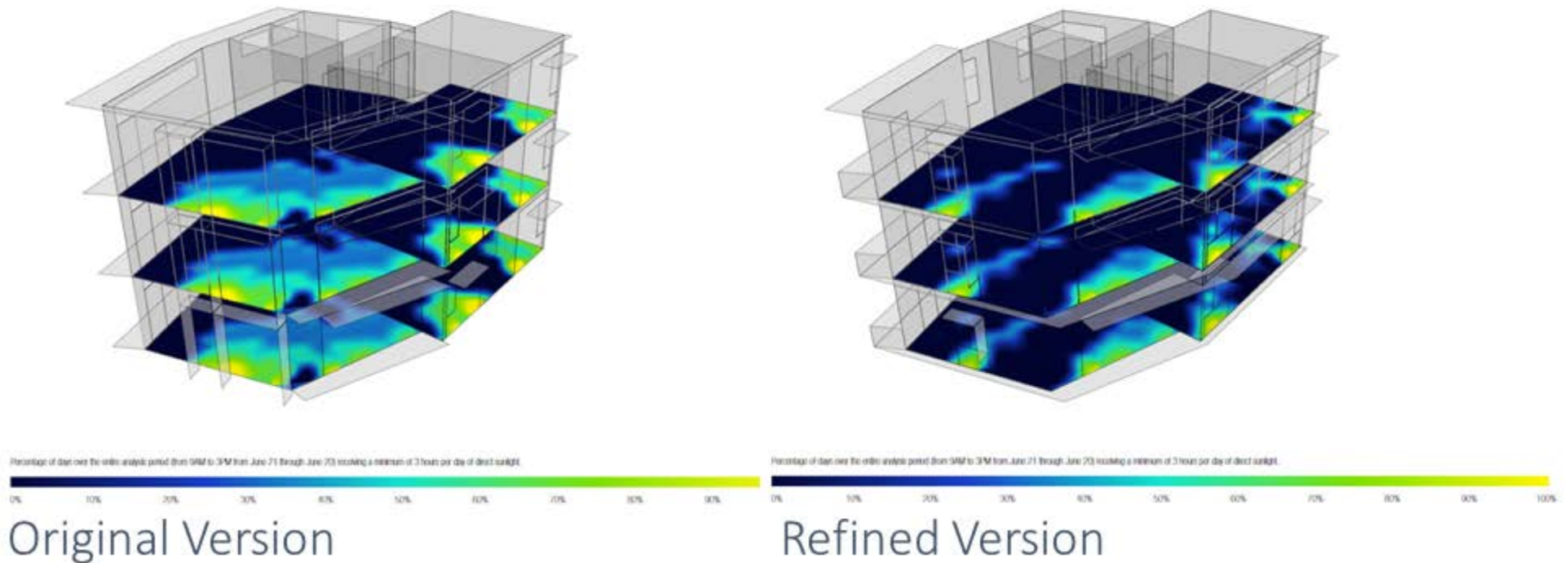


Figure 9: Comparison of the design refinement related to Direct Sunlight analysis

Explanation:

This image shows the percentage of days (from 9am to 4pm from June 21 through June 20 next year) receiving a minimum of 3 hours per day of direct sunlight.⁴

Objective:

Reduce large yellow and green areas (too much exposure) and redistribute them to get more area of indirect/ambient light.

Overlit Underlit (sDA – ASE)

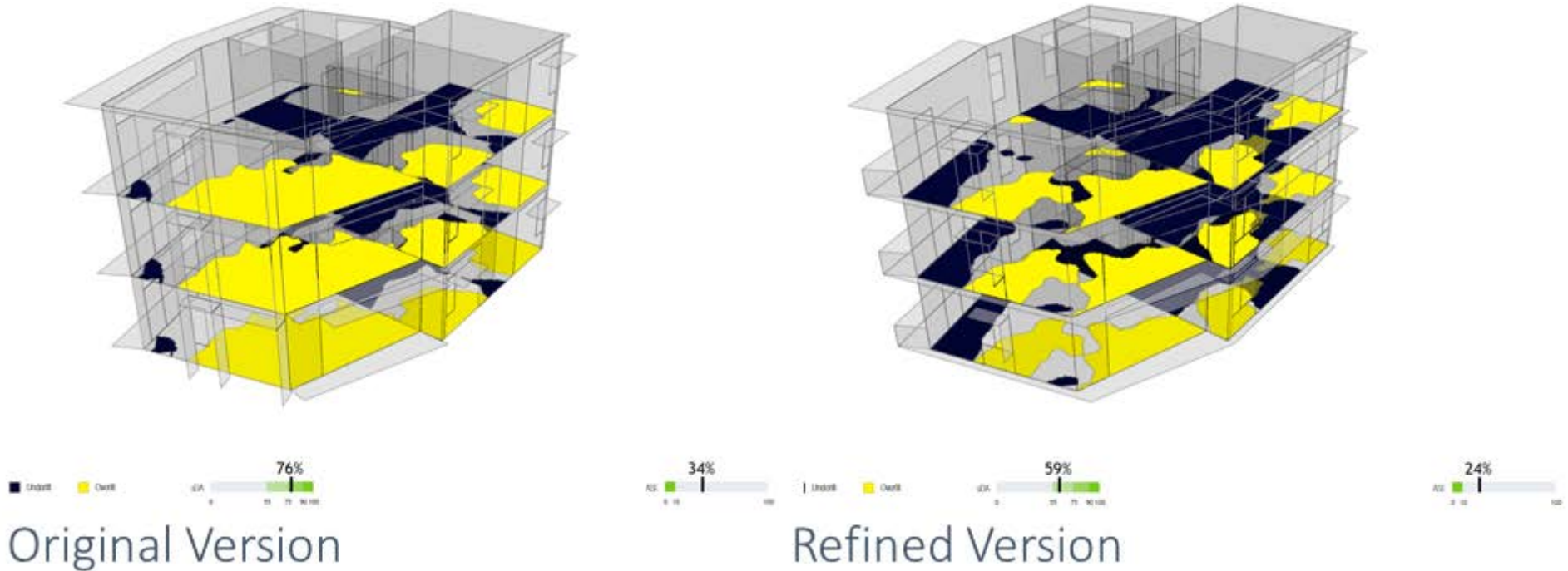


Figure 10: Comparison of the design refinement related to Overlit Underlit analysis

Explanation:

The combination of Spatial Daylight Autonomy (sDA)³ and Annual Sunlight Exposure (ASE)⁴ allows a balanced illumination (depending on space requirements), visual comfort (less glare), thermal comfort (less radiation) during occupied hours.⁶

Objective:

Balance yellow areas (overlit) with black areas (underlit), and redistribute large lit areas into several small ones.

Iteration comparison chart - Residential Building

Criteria							
Solar Geometry Strategies	Iteration #	EUI (Energy Use Intensity) (kBTU/ft ² /yr)	WWR (Window-to-wall ratio)	DF (Daylight Factor) (Average)	sDA (Spatial Daylight Autonomy)	ASE (Annual Sun Exposure)	SHGC (Solar Heat Gain Coefficient)
		Lower=Better	0.20 to 0.30	1-5%	Higher%=Better	Lower%=Better	Lower Coeff.=Better
WWR ORIGINAL + SHADING ORIGINAL + ROTATION ORIGINAL	Re1	38	0.38	2.22	76	34	0.4
WWR REFINED + SHADING ORIGINAL + ROTATION ORIGINAL	Re2	35	0.23	1.67	63	30	0.4
WWR REFINED + SHADING REFINED + ROTATION ORIGINAL	Re3	35	0.23	1.53	59	24	0.4

Figure 11: Comparison chart of variables applied to iterations

Explanation:

This chart shows the most efficient iterations after combining six variables to get the lowest EUI² after eliminating the “worst case scenarios”. These are not results to be used as rules, but are guides to understand the impact of each variable.

Note: An important aspect for the accuracy of the results was to analyze each iteration by modifying *WWR by façade* based on floor plan distribution and daylighting requirements, to then, get an average ratio. Generally, the average ratio assumes that all the facades have the same glazing area. (See Appendix D)

WWR by façade			
A	B	C (South)	D
0.24	0.56	0.6	0.12
0.13	0.34	0.38	0.08
0.13	0.34	0.38	0.08

Figure 12: WWR by facade based on the different variables

2.2 Case Study #2 – Office Building

Background:

This was a proposal for the new College of Sciences building at Virginia Tech campus, as part of the Economical and Sustainable Materials Strategic Growth Area Master Plan. This building was designed to function as a "showcase" where visitors can see students and faculty working at their laboratories and desks. For the purpose of this research, this project was analyzed solely as an office building with a central public atrium, not taking into account special rooms or areas required by a College of Sciences.



Figure 13: Case Study #2 Office Building

Constraints:

- Northern Latitude-ASHRAE Climate Zone 4
- Internal Load Dominated
- Office building
- No shade from context
- Original site orientation: -40 degrees SW

Process:

The original architectural design used Rules-of-Thumb¹ to make decisions on orientation, shading and window-to wall ratio. I revised the entire building using Sefaira-Architecture (See Appendix B) by modeling several iterations to validate and refine its original solar geometry strategies. With this, the 'worst case scenarios' were filtered to reduce potential of error and to be able to work with 'useful' iterations to analyze its energy consumption and simulate daylighting based on Spatial Daylight Autonomy (sDA)³, Annual Sun Exposure (ASE)⁴, Direct Sunlight (DS)⁴ and Daylight Factor (DF)⁵, and with this, try to achieve improved outcomes and broadly understand the tradeoffs involved in high-performance design for this specific building.

Iterations:

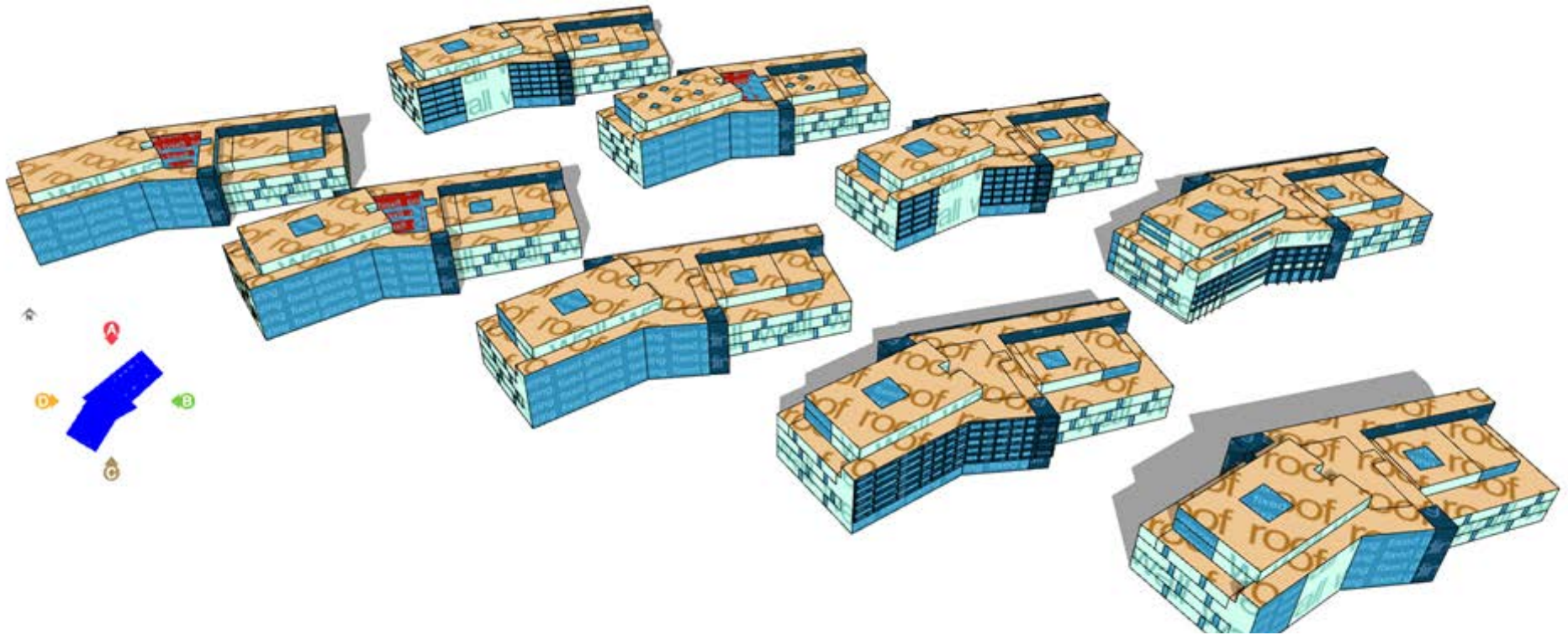
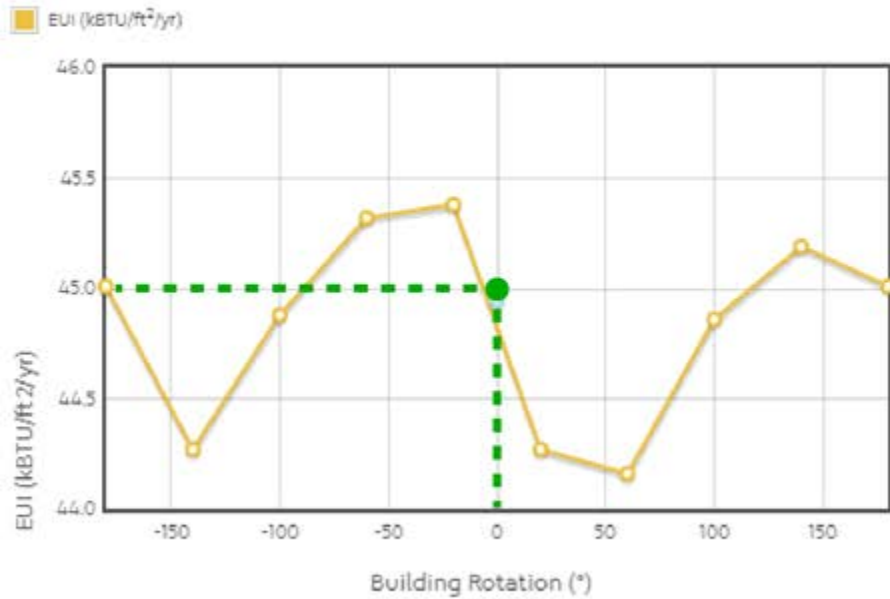


Figure 14: Examples of iterations with different variables applied

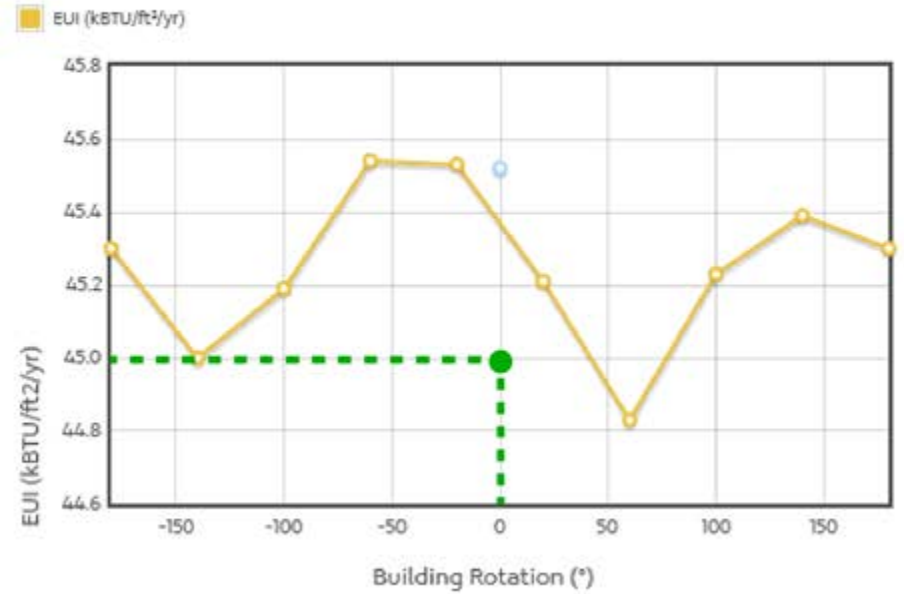
Findings:

Orientation



Original Version

Figure 15: Comparison of the design refinement related to orientation

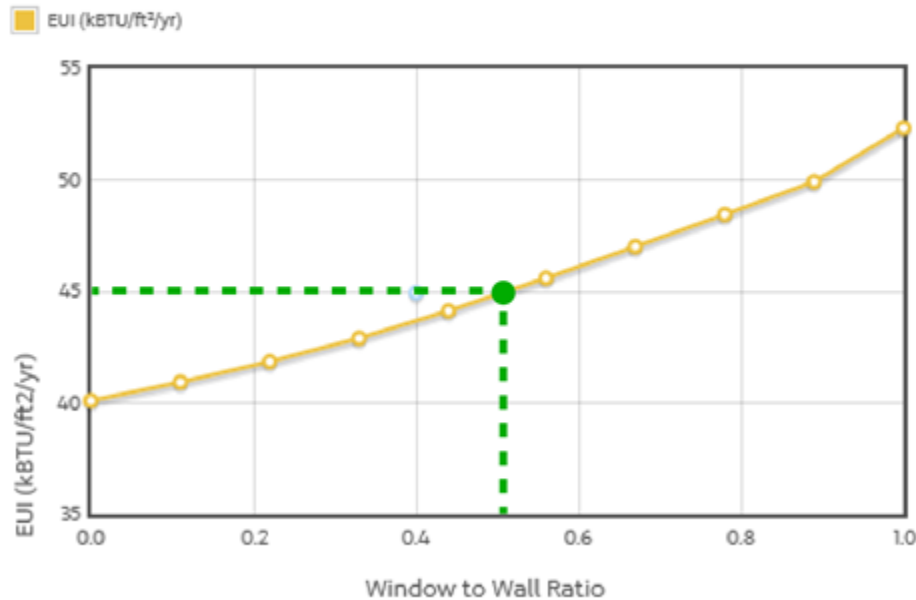


Refined Version

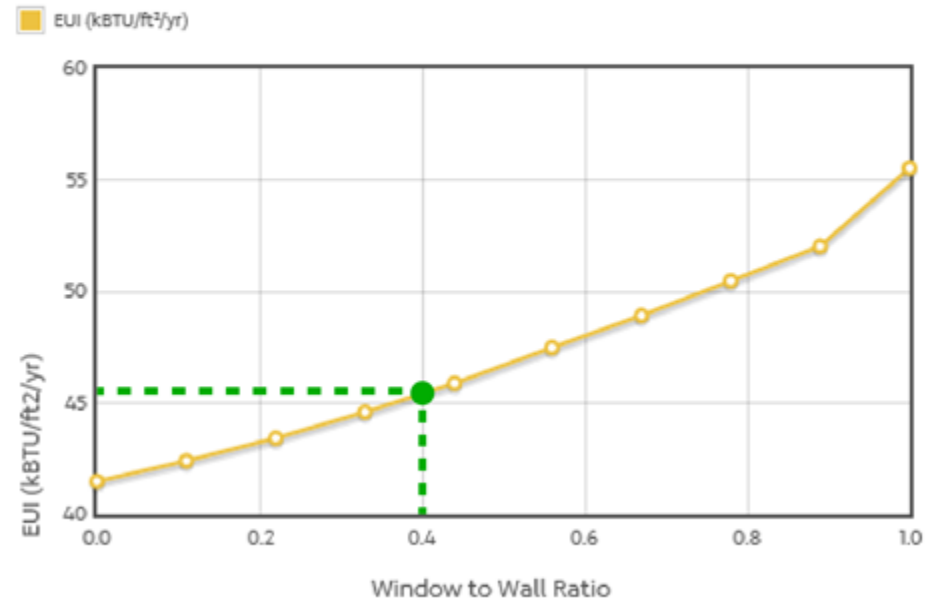
Explanation:

The original -40° SW orientation (based on site position) was successful enough on using the least energy, because any other rotation will only have a maximum change of $\pm 2\%$ in EUI², that is why this strategy was left as a constant until the end, and after modifying other variables, the EUI was not able to be reduced and it was confirmed that the original Rule-of-Thumb¹ of the East-West orientation, was invalid for this case study. (See Appendix A)

Window-to-Wall Ratio (WWR)



Original Version



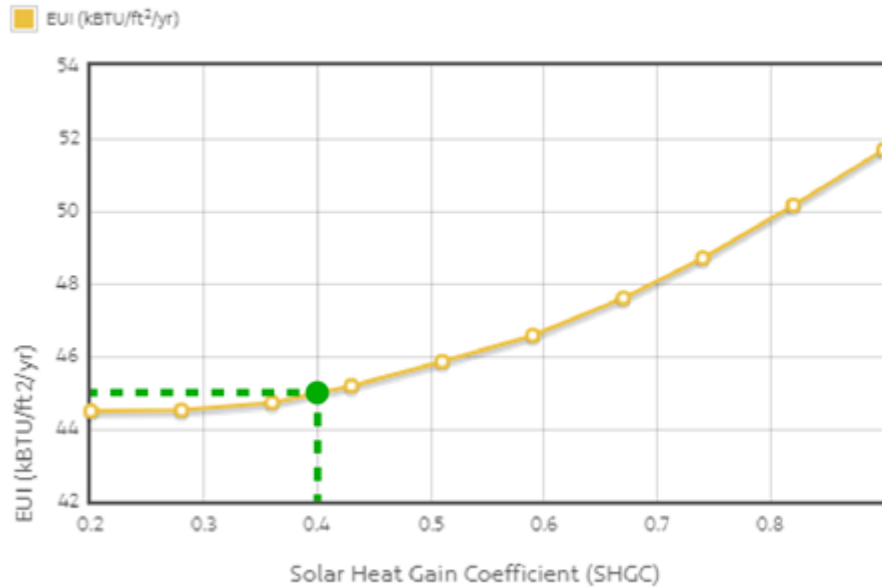
Refined Version

Figure 16: Comparison of the design refinement related to window-to-wall ratio

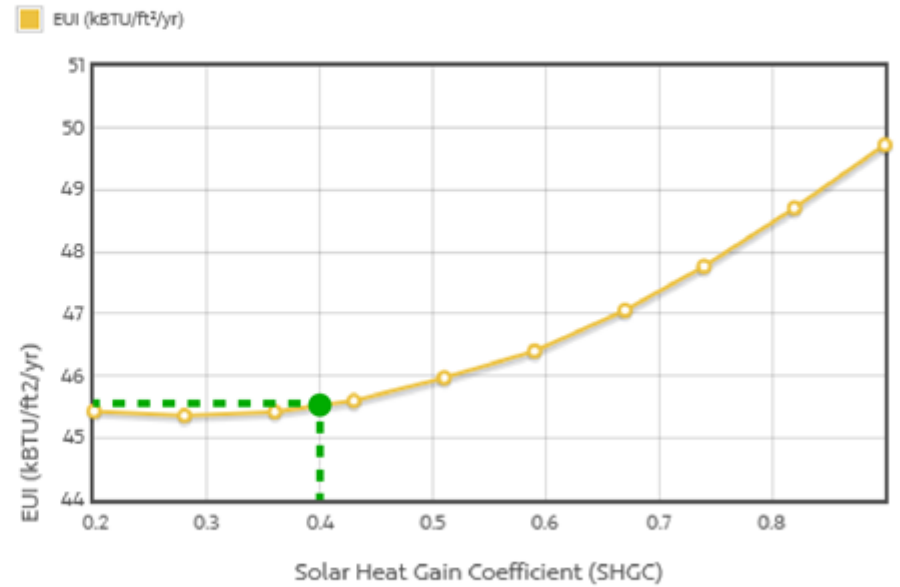
Explanation:

The curves show that even though the Original WWR was reduced by 20% (From 0.5 to 0.4) the energy consumption remained the same. This confirms that glazing ratio is not impactful on reducing EUI² for internal load dominated buildings that have high-performance specifications. But, this modifications have a high impact on daylight metrics such as Spatial Daylight Autonomy (sDA)³, Annual Sun Exposure (ASE)⁴, Direct Sunlight (DS)⁴ and Daylight Factor (DF)⁵. (Shown in the next three analyses) (See Appendix D)

Solar Heat Gain Coefficient (SHGC)



Original Version



Refined Version

Figure 17: Comparison of the design refinement related to solar heat gain coefficient

Explanation:

Because it is an internal load dominated building, the iterations showed that regardless the glazing properties, shading elements, WWR, or orientation, the SHGC⁷ (solar heat transmittance) and energy consumption are directly proportional, and the difference between the original and refined versions is minimum, confirming that other variables or strategies will be more impactful.

Note: For the purpose of this research, the glazing and skylight U-Factor were kept constant as $U \leq 0.30$ and $U \leq 0.53$ respectively. As well as the SHGC with a value of 0.4. (See Appendix C)

Daylight Factor (DF)

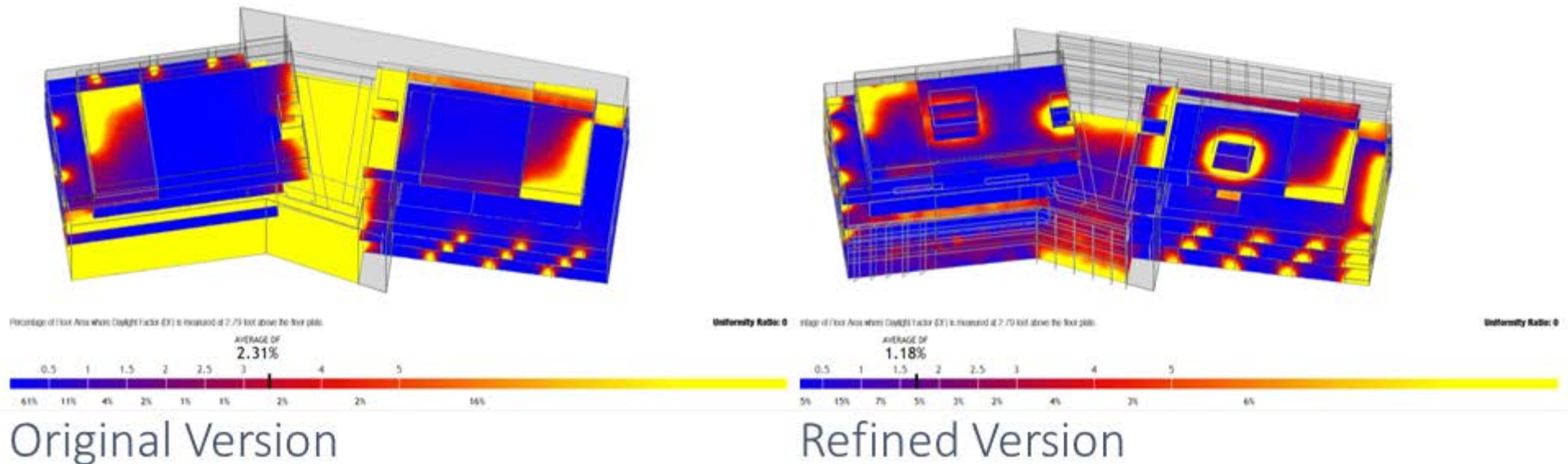


Figure 18: Comparison of the design refinement related to Daylight Factor analysis

Explanation:

This image shows the ratio of illumination levels of the interior spaces relative to the exterior. After analyzing orientation, WWR and SHGC, several iterations were tested to find the option which reduced energy consumption while improving daylighting quality.⁵ (See Appendix E)

Objective:

Reduce large yellow areas (glare), increase purple areas (indirect or ambient light), and redistribute large lit areas into several small ones.

Direct Sunlight (DS)

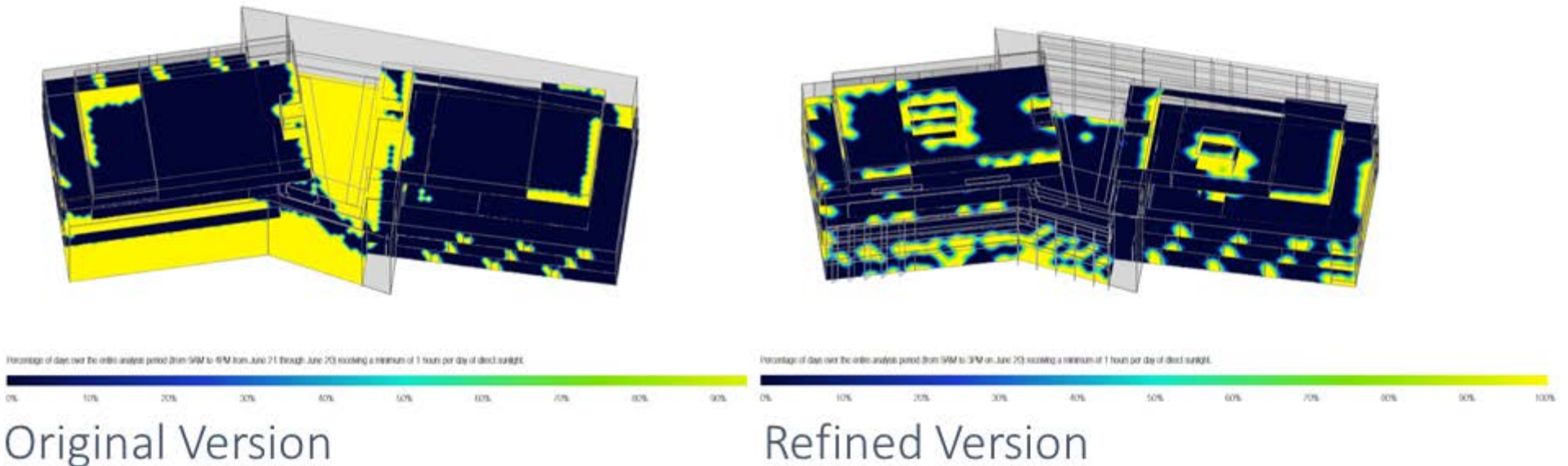


Figure 19: Comparison of the design refinement related to Direct Sunlight analysis

Explanation:

This image shows the percentage of days (from 9am to 4pm from June 21 through June 20 next year) receiving a minimum of 3 hours per day of direct sunlight.⁴

Objective:

Reduce large yellow and green areas (too much exposure) and redistribute them to get more area of indirect/ambient light.

Overlit Underlit (sDA – ASE)

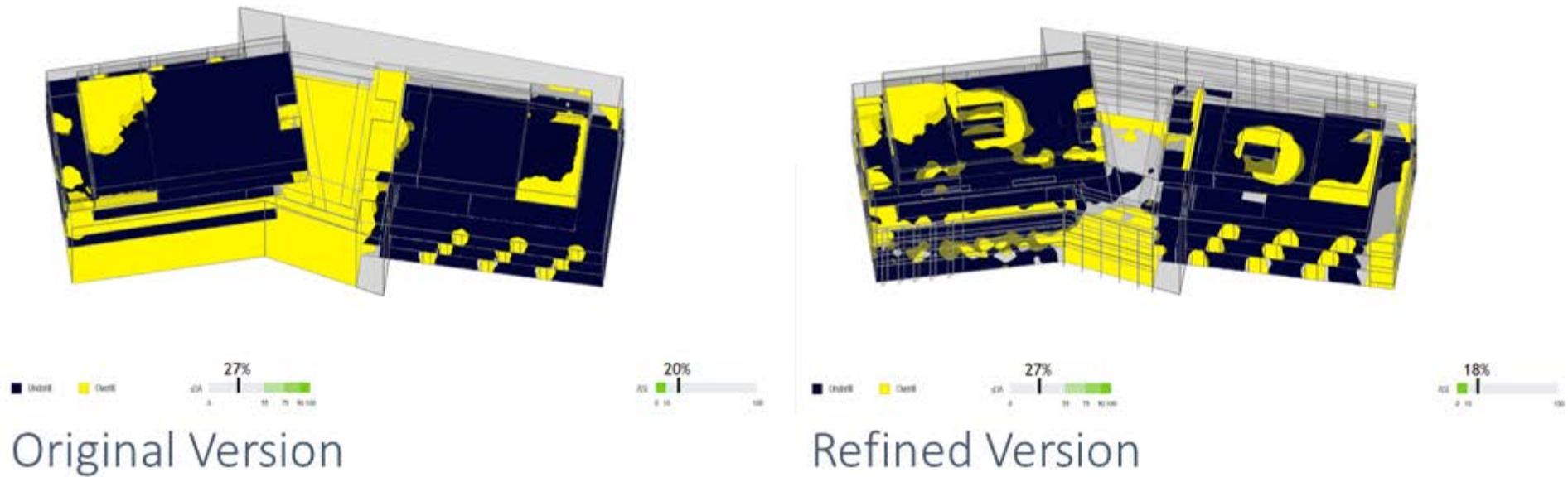


Figure 20: Comparison of the design refinement related to Overlit Underlit analysis

Explanation:

The combination of Spatial Daylight Autonomy (sDA)³ and Annual Sunlight Exposure (ASE)⁴ allows a balanced illumination (depending on space requirements), visual comfort (less glare), thermal comfort (less radiation) during occupied hours.⁶

Objective:

Balance yellow areas (overlit) with black areas (underlit), and redistribute large lit areas into several small ones.

Iteration comparison chart - Office Building

		Criteria					
Solar Geometry Strategies	Iteration #	EUI (Energy Use Intensity) (kBTU/ft ² /yr)	WWR (Window-to-wall ratio)	DF (Daylight Factor) (Average)	sDA (Spatial Daylight Autonomy)	ASE (Annual Sun Exposure)	SHGC (Solar Heat Gain Coefficient)
		Lower=Better	0.40 to 0.60	1-5%	Higher%=Better	Lower%=Better	Lower Coeff.=Better
Atrium + No Skylights + Original WWR + No Shading	Of1	45	0.54	1.96	24	20	0.4
Atrium + Few Skylights + Original WWR + No Shading	Of2	47	0.54	2.26	29	25	0.4
No Atrium + Few Skylights + Original WWR + No Shading	Of3	47	0.54	1.76	27	21	0.4
No Atrium + Few Skylights + Original WWR + Shading	Of4	47	0.54	1.22	27	19	0.4
No Atrium + Few Skylights + Reduced WWR + No Shading	Of5	45	0.40	1.37	24	19	0.4
No Atrium + Few Skylights + Reduced WWR + No Shading	Of6	45	0.40	1.08	23	16	0.4
Atrium + Multiple Skylights + Original WWR + No Shading	Of7	50	0.54	2.41	31	25	0.4
No Atrium + Few Skylights + Reduced WWR + Shading	Of8	45	0.40	1.09	23	16	0.4
Combination of most impactful strategies No Atrium + Few Skylights + Reduced WWR and redistributed glazing location in Facades A and B + Relocated Shading in Facades A and B + Original Orientation	Of9	45	0.40	1.18	27	18	0.4

Figure 21: Comparison chart of variables applied to iterations

WWR by façade			
A	B (South)	C (South)	D

Explanation:

This chart shows the most efficient iterations after combining six variables to get the lowest EUI² after eliminating the “worst case scenarios”. These are not results to be used as rules, but are guides to understand the impact of each variable.

Note: An important aspect for the accuracy of the results was to analyze each iteration by modifying *WWR by façade* based on floor plan distribution and daylighting requirements, to then, get an average ratio. Generally, the average ratio assumes that all the facades have the same glazing area. (See Appendix D)

0.93	0.64	0.34	0.24
0.93	0.64	0.34	0.24
0.93	0.64	0.34	0.24
0.93	0.64	0.34	0.24
0.64	0.37	0.34	0.24
0.64	0.37	0.34	0.24
0.93	0.64	0.34	0.24
0.64	0.37	0.34	0.24
0.46	0.46	0.29	0.39

Figure 22: WWR by facade based on the different variables

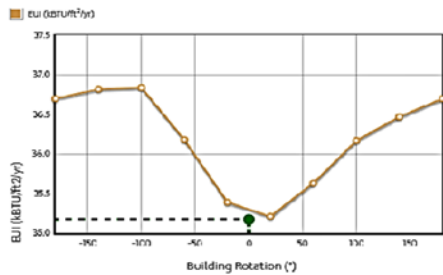
General Findings:

This research has allowed me to understand how to approach early-stage design and has helped me identify what to focus on as a start to achieving a high performance building. Mainly, by being conscious of the dozens of variables a project has and be able to discriminate from them based on the requirements, to reduce the potential of error, to foresee future problems, reduce energy consumption and provide better daylighting. In the following Response Curve comparison, it can be seen how the different variables or strategies make an impact only under certain conditions and should not be generalized.

Case Study #1 - Residential Building

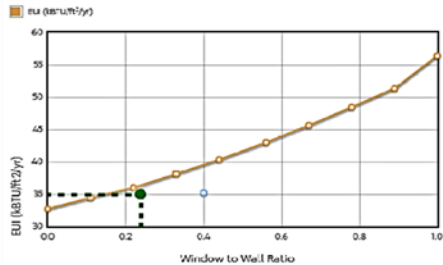
Case Study #2 - Office Building

Orientation



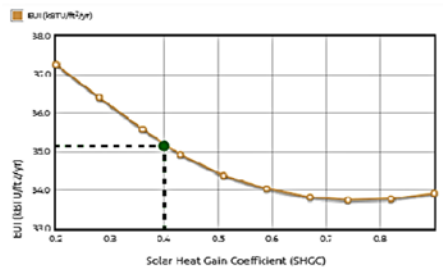
The Rule of Thumb is valid, because the main facade is oriented to the south and uses the least EUI. The Response curve confirms that any other rotation will only have a maximum change of 5% in EUI, in other words, it is not highly impactful and other variables should be taken into consideration.

WWR



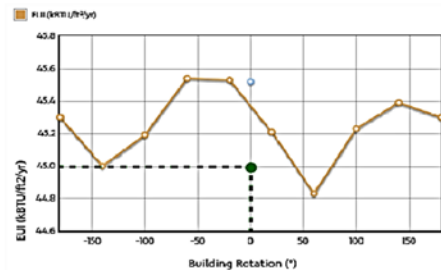
The Response curve shows the results of the lowest recommended WWR with the lowest possible EUI after combining the most impactful architectural strategies. But, despite EUI and WWR are directly proportional, for this type of building, increasing WWR increases EUI and also negatively affects daylighting quality.

SHGC

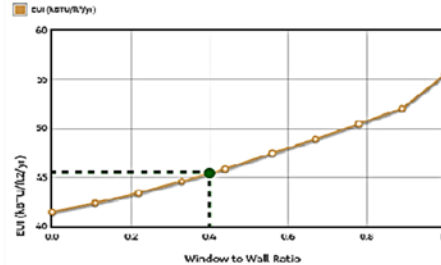


The Response curve shows that this type of building performs better (less energy use) if it includes medium to low glazing specifications or a high SHGC.

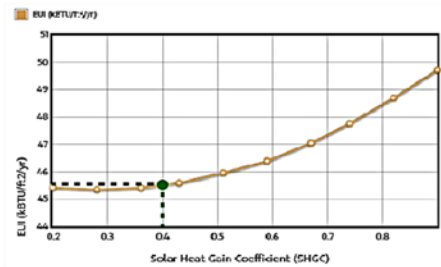
- Advantages:
- More heat gain in winter day
- Disadvantages:
- More heat gain in summer
 - More heat loss in winter night



The Rule of Thumb is not valid, because the main facade is not oriented to the south, but instead, -40° SW. The Response curve confirms that any other rotation will only have a maximum change of 2% in EUI, in other words, it is not highly impactful and other variables should be taken into consideration.



The Response curve shows the results of the lowest recommended WWR with the lowest possible EUI after combining the most impactful architectural strategies. But, despite EUI and WWR are directly proportional, for this type of building, increasing WWR doesn't necessarily increase the EUI but improves daylighting quality when correctly distributed.



The Response curve shows that this type of building performs better (less energy use) if it includes high performance glazing specifications or a low SHGC.

- Advantages:
- Less heat gain in summer
 - Less heat loss in winter night
- Disadvantage:
- Less heat gain in winter day

General Conclusions:

It is important to stress that this research only focuses on solar geometry, related to daylighting and solar heat gain, being these only a part of all the different components that involve designing a high-performance building.¹¹

Early stage design:

- An integral or holistic design allows a more accurate architectural decision making, and therefore, reduces the potential of future problems. For example, it helps to recognize the negative impact of including high-performance glazing in facades that will not receive direct sunlight during most of the year, or not allocating glazing ratios based on the floor plan distribution or space usage.
- Early stage analysis and design helps to have a more accurate model to work between the different professional fields.

Rules-of-Thumb:

- Use rules-of-thumb as a general guideline to create iterations which can later be tested with a modeling tool (Sefaira) and drive your design to the right direction.¹ (See Appendix B)

Iterations and Variables:

- Recognize which iterations are worth analyzing and which might be useless by watching tendencies in the response curves. For example, in some cases what might seem an obvious building orientation to the south, could be leading to the worst case scenario in energy performance and/or daylighting quality.
- Combine architectural strategies to find the balance between cost and benefit. For example: to reduce the shading overhang length, include brise soleils or improve glass specifications (number of glazing surfaces or low-e coating location^{8,9,10}).

Envelope:

- Recognize that higher-performance envelope specifications are not necessarily beneficial to a project. Response curves show that depending on the constraints, there is a high-return range or point of diminishing returns¹² where a variable reaches its peak of performance, and after that, loses value. For example, increasing the quantity of glazing panels or shading elements is NOT directly proportional to the benefits to reduce energy use. It gets to a point where they have a negative impact and should be compensated with other variables as adding low-e coating⁶ or increasing shading length, but again, a new analysis should be done to be aware of the points of diminishing returns¹².
- Target to achieve a balance between heating and cooling throughout the year, in other words, it is the better to focus on average envelope specifications in combination with other mitigating strategies (point of diminishing returns) to achieve efficiency over the annual energy use.

Glazing and Window-to-Wall Ratio (WWR):

- Carefully allocate glazing ratios based on the floor plan distribution and space usage, to avoid glare, heat loss or heat gain, visual obstruction and to get a more accurate daylighting analysis. For example, it can be negative to have a floor-to-ceiling window in a bedroom (in 60%of the facade) as to have a high window in the living room (10% of the facade). (See Appendix D)
- Recognize that less glazing means less energy use, but a good daylighting is not guaranteed, so it is important to consider the combination of strategies, like improving shading or modifying envelope specifications to find the right balance over heat losses and gains.

Shading:

- Use external, not internal shading devices as this prevents the sun's rays from entering the most of the buildings.
- Shade walls based on energy and daylighting analysis, this strategy can be very beneficial to reduce heat gain.

References:

- Heywood, Huw. *"101 Rules of Thumb for low energy architecture"*. RIBA, 2012
- Grant, Elizabeth. *"Integrating Building Performance with Design"*. Routledge, 2017
- Dekay & Brown. *"Sun wind and light"*. Wiley, 2014
- Baker, Nick & Steemers, Koen. *"Energy and Environment in Architecture: A Technical Design Guide."* Routledge, 2000

- "Rule of thumb". <https://www.merriam-webster.com> (12 Dec 2017)
- "PBD." <http://learn.sefaira.com/architecture/what-is-pbd/> (12 Dec 2017)
- "Low-e glass". http://glassed.vitroglazings.com/glassttopics/how_lowe_works.aspx (12 Dec 2017)
- "Point of diminishing returns". <http://hipcrime.blogspot.com/2013/07/an-architect-explains-diminishing.html> (12 Dec 2017)
- "Solar heat gain coefficient" <http://www.efficientwindows.org/energystar.php> (12 Dec 2017)
- "Sun Path". <http://andrewmarsh.com/apps/releases/sunpath3d.html> (12 Dec 2017)
- "Sefaira". <http://sefaira.com/sefaira-architecture/> (12 Dec 2017)
- "2030 Challenge". http://www.architecture2030.org/files/2030_Challenge_Targets_National.pdf (12 Dec 2017)
- "Rules Of Thumb That Could Lead You Astray". <http://sefaira.com/wp-content/uploads/2013/12/4-Architectural-Rules-of-Thumb-that-could-You-Astray.pdf> (12 Dec 2017)

Literature Appendix:

1. Rules of Thumb

("Rule of thumb." Merriam-Webster.com. 2017. <https://www.merriam-webster.com> (12 Dec 2017))

Definition:

- 1: a method of procedure based on experience and common sense
- 2: a general principle regarded as roughly correct but not intended to be scientifically accurate

'Six Metrics Every Architect Should Know'

(Carl Sterner, written for Sefaira's White Papers – Jul 3 2014 –

<http://sefaira.com/resources/six-metrics-every-architect-should-know-and-how-to-use-them/>)

2. EUI (Energy Use Intensity)

Definition:

Energy Use Intensity is a building's annual energy use per unit area. It is typically measured in thousands of BTU per square foot per year (kBTU/ft²/yr) or kWh/m²/yr. EUI can measure "site" energy use (what the building consumes) or "source" energy use (the amount of fuel the power plant burns to produce that much energy). Unless otherwise specified, EUI typically refers to "site" energy use.

Why it's important:

EUI is useful for comparing performance of buildings across sizes, types, and locations. It can help you design buildings with low energy use, and, as a likely result, lower operating costs. It is used by programs like ENERGY STAR and the 2030 Challenge, which have specific EUI goals for different building types. It is also being used to benchmark buildings for public reporting in many cities.

3. Spatial Daylight Autonomy (sDA)

Definition:

Spatial Daylight Autonomy (sDA) describes how much of a space receives sufficient daylight. Specifically, it describes the percentage of floor area that receives a minimum illumination level for a minimum percentage of annual occupied hours — for instance, the area that receives at least 300 lux for at least 50% of occupied hours (which would be notated as sDA300/50%). It is a climate-based daylighting metric, meaning that it is simulated using a location-specific weather file (similar to an energy model).

Why it's important:

Simulated sDA can help you design buildings that have good daylighting, as sDA has been shown to be a good predictor of actual as-built daylight performance. It is used in one of the compliance pathways for daylight credits in LEED v4.

4. Annual Sunlight Exposure (ASE)

Definition:

Annual Sun Exposure (ASE) describes how much of space receives too much direct sunlight, which can cause visual discomfort (glare) or thermal discomfort. Specifically, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year (ASE1000,250).

Why it's important: ASE is an indicator of possible glare or thermal comfort issues. However, it doesn't directly measure glare or thermal comfort, but rather direct sunlight. ASE is used alongside sDA in LEED v4.

5. Daylight Factor

Average Daylight Factor provides an overall daylighting score for the space. For example, this feature can be used to assess minimum Average Daylight Factor levels for rooms, per the BRE daylight and sunlight assessment in the UK.

Minimum Daylight Factor shows the lowest value of Daylight Factor in the area, excluding a perimeter zone around the walls. This is the “worst case” value within the area.

6. Underlit & Overlit

Spatial Daylight Autonomy (sDA) is used to evaluate whether a space receives enough usable daylight throughout the year.

Annual Sunlight Exposure (ASE) helps to identify whether a space is subject to overlighting. Sefaira already computed these two metrics, but we now display the values on our “Underlit and Overlit” visualization, along with green benchmark zones to help evaluate your design. To improve (increase) sDA, consider providing more light to the “underlit” areas in the visual. To improve (decrease) ASE, address the “overlit” areas in the visual. Keeping sDA and ASE on track is especially important for projects aiming for LEEDv4 daylighting credit.

7. Solar Heat Gain Coefficient (SHGC)

(<http://www.efficientwindows.org/shgc.php>)

The SHGC is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward. SHGC is expressed as a number between 0 and 1. The lower a window's solar heat gain coefficient; the less solar heat it transmits.

Why is SHGC important?

Solar heat gain can provide free heat in the winter but can also lead to overheating in the summer. How to best balance solar heat gain with an appropriate SHGC depends upon the climate, orientation, shading conditions and other factors.

8. Low-e Glass/Coating

(http://glassed.vitroglazings.com/glassttopics/how_lowe_works.aspx)

Low-E coatings have been developed to minimize the amount of ultraviolet and infrared light that can pass through glass without compromising the amount of visible light that is transmitted.

When heat or light energy is absorbed by glass, it is either shifted away by moving air or re-radiated by the glass surface. The ability of a material to radiate energy is known as emissivity. In general, highly reflective materials have a low emissivity and dull darker colored materials have a high emissivity. All materials, including windows, radiate heat in the form of long-wave, infrared energy depending on the emissivity and temperature of their surfaces. Radiant energy is one of the important ways heat transfer occurs with windows. Reducing the emissivity of one or more of the window glass surfaces improves a window's insulating properties. For example, uncoated glass has an emissivity of .84, while Vitro Architectural Glass' (formerly PPG glass) solar control *Solarban*[®] 70XL glass has an emissivity of .02.

This is where low emissivity (or low-e glass) coatings come into play. Low-E glass has a microscopically thin, transparent coating—it is much thinner than a human hair—that reflects long-wave infrared energy (or heat). Some low-e's also reflect significant amounts of short-wave solar infrared energy. When the interior heat energy tries to escape to the colder outside during the winter, the low-e coating reflects the heat back to the inside, reducing the radiant heat loss through the glass. The reverse happens during the summer. To use a simple analogy, low-e glass works the same way as a thermos. A thermos has a silver lining, which reflects the temperature of the drink it contains. The temperature is maintained because of the constant reflection that occurs, as well as the insulating benefits that the air space provides between the inner and outer shells of the thermos, similar to an insulating glass unit. Since low-e glass is comprised of extremely thin layers of silver or other low emissivity materials, the same theory applies. The silver low-e coating reflects the interior temperatures back inside, keeping the room warm or cold.

9. Low-e Coating Performance Measures

(http://glassed.vitroglazings.com/glassttopics/how_lowe_works.aspx)

Low-e coatings are applied to the various surfaces of insulating glass units. Whether a low-e coating is considered passive or solar control, they offer improvements in performance values. The following are used to measure the effectiveness of glass with low-e coatings:

- **U-Value** is the rating given to a window based on how much heat loss it allows.
- **Visible Light Transmittance** is a measure of how much light passes through a window.
- **Solar Heat Gain Coefficient** is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed & re-radiated inward. The lower a window's solar heat gain coefficient, the less solar heat it transmits.
- **Light to Solar Gain** is the ratio between the window's Solar Heat Gain Coefficient (SHGC) and its visible light transmittance (VLT) rating.

10. Glazing Coating Location

(http://glassed.vitroglazings.com/glassttopics/how_lowe_works.aspx)

In a standard double panel IG there are four potential surfaces to which coatings can be applied: the first (#1) surface faces outdoors, the second (#2) and third (#3) surfaces face each other inside the insulating glass unit and are separated by a peripheral spacer which creates an insulating air space, while the fourth (#4) surface faces directly indoors. Passive low-e coatings function best when on the third or fourth surface (furthest away from the sun), while solar control low-e coatings function best when on the lite closest to the sun, typically the second surface.

11. Solar Geometry

(<http://www.tboake.com/carbon-aia/strategies1a.html>)

“Solar geometry is the determining factor of heat gain, shading and the potential of daylight penetration...”

12. Point of diminishing returns

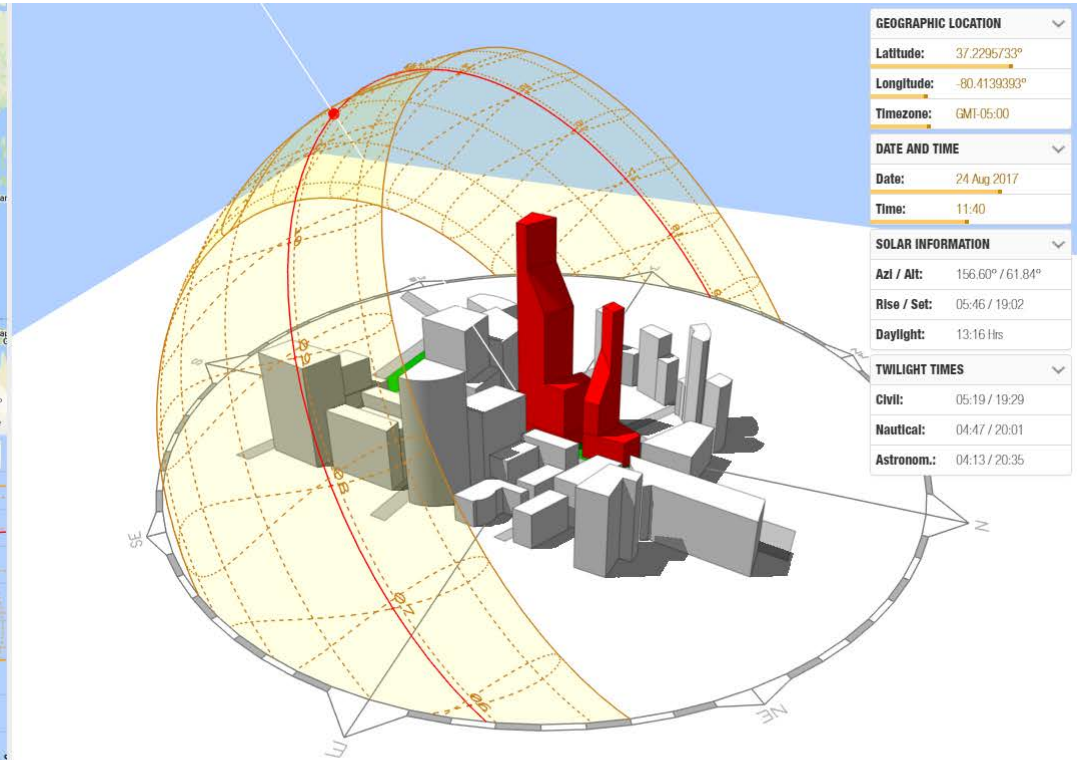
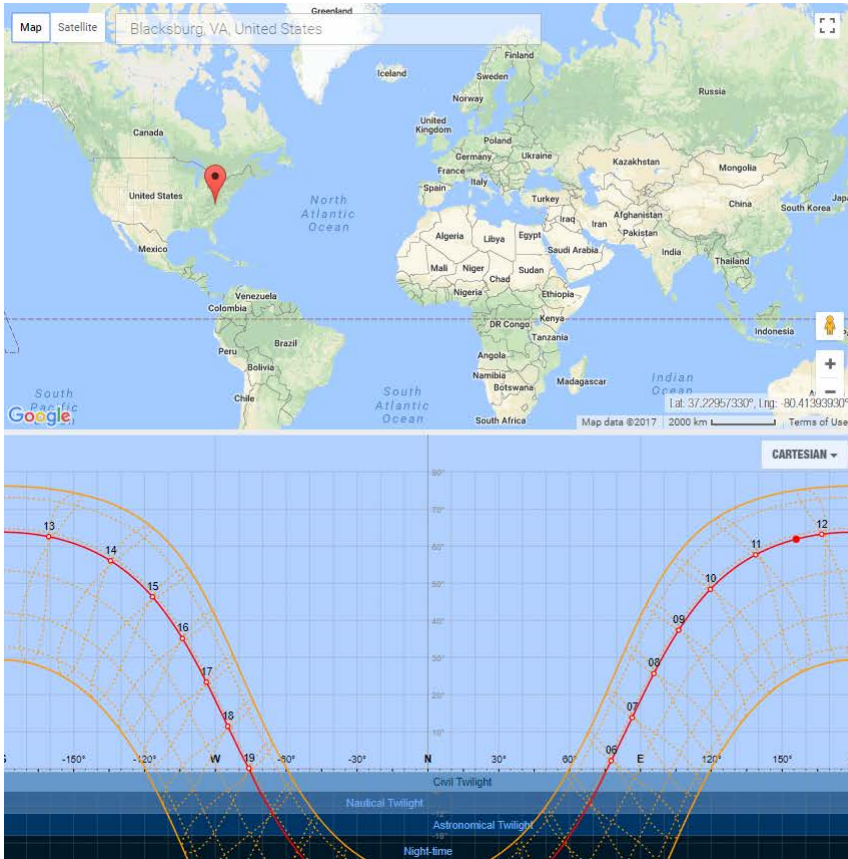
(<http://hipcrime.blogspot.com/2013/07/an-architect-explains-diminishing.html>)

So this is the critical takeaway: diminishing returns applies to everything, including technology, innovation, society, and economic growth. There is a point at which more is not better, yet we are unable to recognize this. More is not always better, and the benefits decline over time. As certain forward-thinking economists have pointed out, economic growth has consequences, and the consequences can potentially outweigh the benefits, in pollution, inequality, fragility, quality of life, etc.

Image Appendix:

A: Sun Path 3D visualization

(<http://andrewmarsh.com/apps/releases/sunpath3d.html>)



B: Sefaira Architecture Analysis Platform

(<https://apps.sefaira.com/page/projects/>)

Baseline Concept
138,531 ft²

Clone Del Export Idf

HVAC System Type ?
VAV - Return Air Package (System)

45 kBtu/ft²/yr 45 kBtu/ft²/yr 45 kBtu/ft²/yr 45 kBtu/ft²/yr

+ Copy your active concept, then add design changes to compare performance X

Envelope Shading Space Use Nat Vent PV Zoning !

Peak Loads Energy Breakdown Free Area Comfort

Custom Inputs Residential Non-residential

Use Cost CO_{2e} Energy & CO_{2e} Tariffs Area weighted

Facade Glazing

Assembly U-Value: 0.35 BTU/h-ft²-°F

Solar Heat Gain Coefficient (SHGC): 0.4

Walls

Assembly Type: Concrete Block

Assembly R-Value: 9.62 ft²-h-°F/BTU

Floors

Floor Finish: Carpet

Ground Floor R-Value: 17.69 ft²-h-°F/BTU

Infiltration

Infiltration Type: Facade Area

Design Infiltration Rate: 0.394 cfm/ft²

Override Window to Wall Ratio

Window to Wall Ratio: 0.64

Turn off

While this override is applied, the fixed glazing on your 3D model for this facade is considered operable.

Building Orientation

End Use / Energy Mix Annual / Monthly Compare Concepts Download

Total Energy
1,836,642
kWh per year

Heating	Cooling	Fans
■ AHU	■ AHU	■ AHU
■ Zones	■ Heat Rejection	■ Zones
■ Humidification	■ Zones	■ Zones
Interior	■ Pumps	■ Other Gas

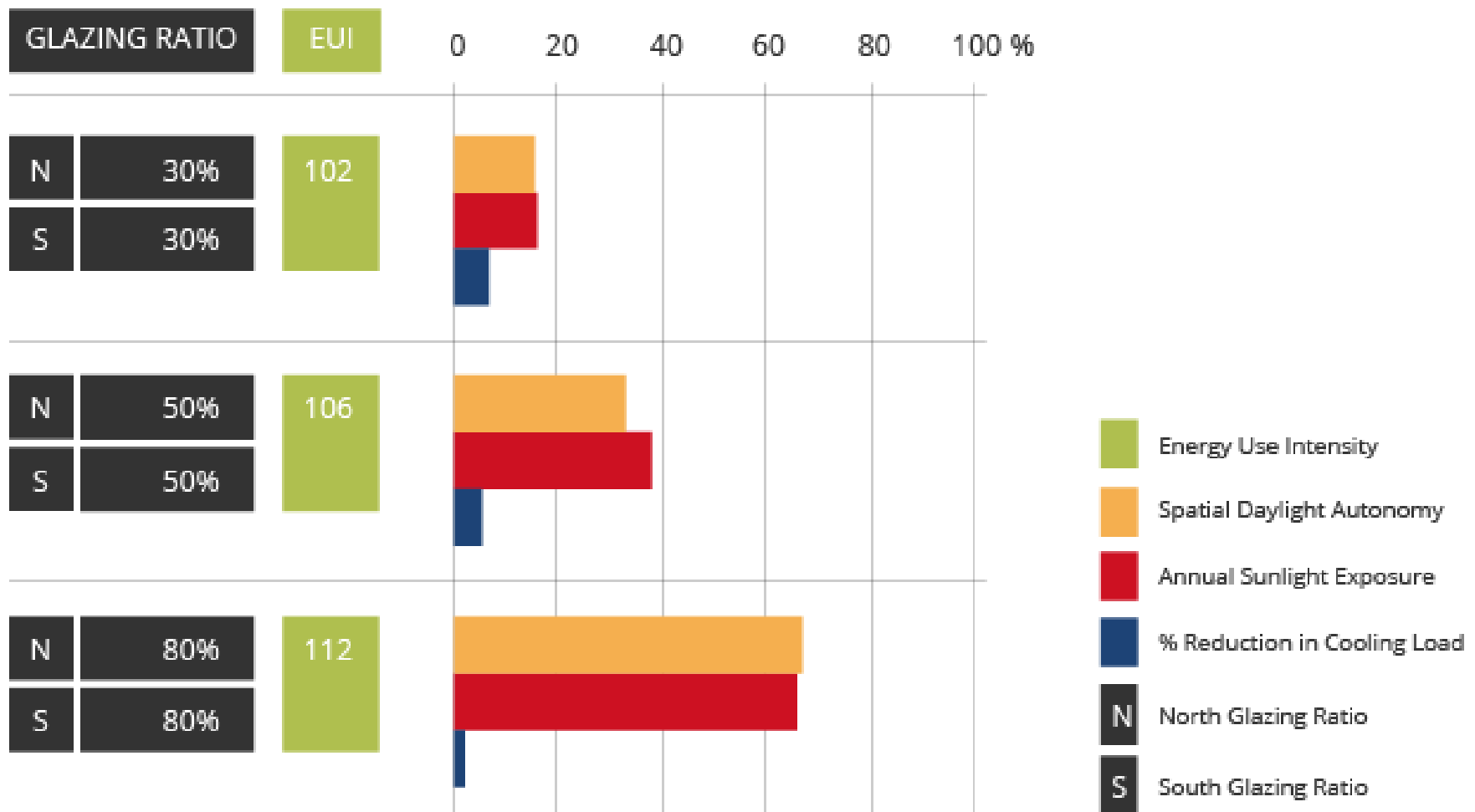
C: Recommended SHGC on Northern latitudes (Climate Zones 4 and 5)

(<http://www.efficientwindows.org/energystar.php>)

North/Central Zone Required Properties (heating & cooling)			
U-factor	Solar Heat Gain Coefficient (SHGC)	Visible Transmittance (VT)	Air Leakage (AL)
Windows: $U \leq 0.30$ Skylights: $U \leq 0.53$ <i>EWC Recommendation:</i> The larger your heating bill, the more important a low U-factor becomes. For superior energy performance, use windows with a U-factor of 0.25 or less.	Windows: $SHGC \leq 0.40$ Skylights: $SHGC \leq 0.35$ <i>EWC Recommendation:</i> A low SHGC value reduces summer cooling demand, but also reduces free winter solar heat gain. If you have significant air conditioning costs or summer overheating problems, look for SHGC values of 0.25 or less. If you have moderate air conditioning requirements, select windows with a SHGC of 0.40 or less.	Windows: VT=No Requirement Skylights: VT=No Requirement <i>EWC Recommendation:</i> Select windows with a higher VT to maximize daylight and view.	Windows: $AL \leq 0.30$ Skylights: $AL \leq 0.30$ <i>EWC Recommendation:</i> Select windows with an AL of 0.30 or less.

D: Glazing ratios and EUI comparison

(<http://sefaira.com/resources/the-balancing-act-of-facade-design-glazing-ratios/>)



E: Suggested Daylight Factor criteria (under overcast skies)

(<http://slideplayer.com/slide/1717156/>)

SPACE	AVERAGE DF	MINIMUM DF
Commercial/Institutional		
Corridor	2	0.6
General Office	5	2
Classroom	5	2
Library	5	1.5
Gymnasium	5	3.5
Residential		
Dining Room/Studio	5	2.5
Kitchen	2	0.6
Living Room	1.5	0.5
Bedroom	1.0	0.3

F: Comparison of Source EUI, Site EUI and targeted EUI for the 2030 Challenge

(http://www.architecture2030.org/files/2030_Challenge_Targets_National.pdf)

	Source EUI (power plant's energy consumption)	Site EUI (building energy consumption)	2030 Challenge target (60% reduction, site EUI)
Office	148 kBTU/ft2/yr 467 kWh/m2/yr	67 kBTU/ft2/yr 211 kWh/m2/yr	27 kBTU/ft2/yr 85 kWh/m2/yr
K-12 Education	141 kBTU/ft2/yr 445 kWh/m2/yr	58 kBTU/ft2/yr 183 kWh/m2/yr	23 kBTU/ft2/yr 73 kWh/m2/yr
Single-family residence	68 kBTU/ft2/yr 215 kWh/m2/yr	46 kBTU/ft2/yr 145 kWh/m2/yr	18 kBTU/ft2/yr 57 kWh/m2/yr