The Impact of Material Lifespan on Carbon Analysis

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Abstract

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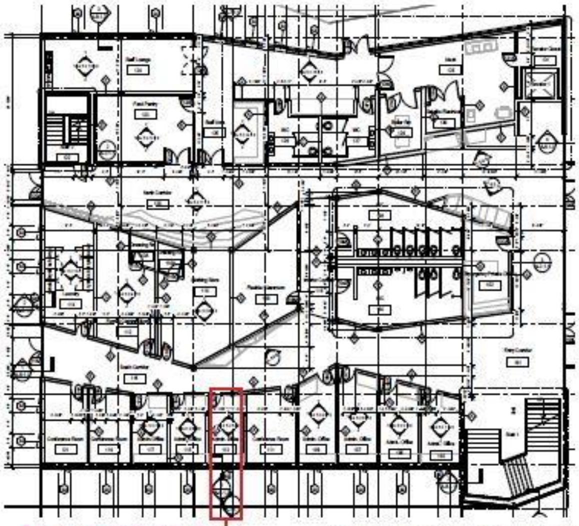
Introduction

The study focused on evaluating the carbon contributions of a proposed envelope design using the idea that each assembly must be evaluated on the assumption that the life expectancy of each material's useful life expectancy is based on manufacturer data and instead of assuming that each assembly will last the building's lifespan, while also taking into account other factors in order to determine an optimal design. While most exterior building assemblies have similar contributions to initial and in-use carbon, the roofing system was chosen for evaluation due to the large difference in the lifespan of different roofing products. The lifespan between different roofing materials varies so greatly that it creates a challenge in determining what material choice offers the most benefits. For example, the lifespan of an asphalt shingle roof can be estimated as only 20 years before needing replacement, while the concrete tile and standing seam metal roofs last 3 times as long that is to say, roughly for the duration of the building's useful life. While many factors were taken into account including energy, carbon, and cost performance, the materials' lifespan performance largely controlled the outcomes of the aforementioned evaluation criteria. When including lifespan as an evaluation criterion for design, the intuitive choice can easily become the wrong choice. The study primarily focused on standard roofing material performance, by comparing three common roof systems; standing seam metal, high quality asphalt shingles, and a concrete tile roofing system. The systems were



Location of Figure 2, Figure 3, Figure 4. Wall section of focus space.

Figure 1: Ground floor plan of subject building

evaluated based on a series of criteria with the effects of material lifespan on carbon impact taking priority, while holding such other factors in carbon emissions, such as insulation value, as constant in all three assemblies. The study used the results taken from standard carbon analysis software, Tally and the Athena Impact Estimator, in order to gain an accurate understanding of the carbon effects of each building assembly as well as what aspect of the assembly generates the most carbon impacts. The paper will discuss the research into each software, and how they were adapted in order to provide a more accurate comparison of the carbon performance for roof assemblies when the maintenance and lifespan of the roofing components are taken into consideration.

The Alternative Assemblies

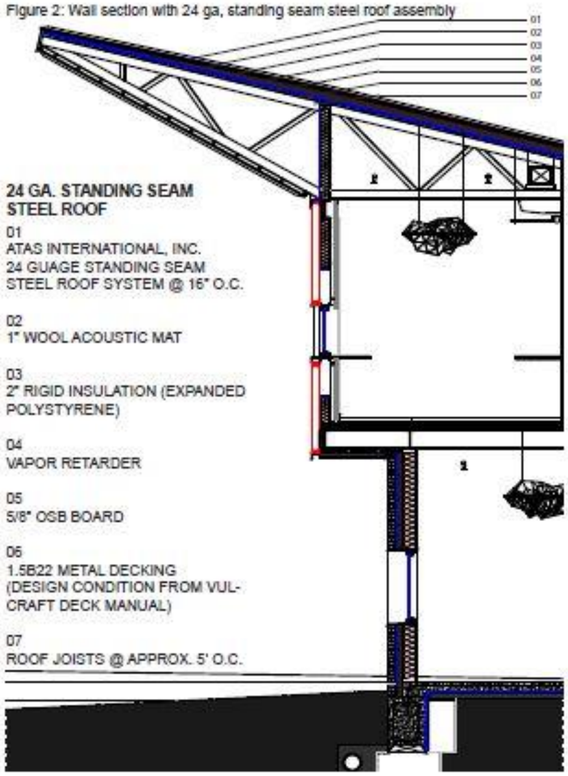
The design was to be developed through the schematic phase for the entire complex, while fully developing an important portion of the building called the focus space, through the development phase. The building envelope of the counseling spaces that acted as the focus space will provide a basis for this study. The wall section was adapted for three common roof systems with the standing seam steel roof acting as the baseline, and the asphalt shingle and concrete tile roof systems are common alternative roofing systems with largely differing material properties and lifespans. The three assemblies studied were:

24 ga. Standing Seam Steel Roof
-ATAS International, Inc. 24 Ga. Standing Seam Steel Roof System (Cold-formed Steel with included insulation)
-1” Wool Acoustic Mat
- 2” Rigid Insulation (Expanded Polystyrene)

Asphalt Shingle Roof
-Certainteed | McRoof Architectural Asphalt Shingle
-Roofing Paper
-5/8” OSB board
- 5” Rigid Insulation (Expanded Polystyrene)

Concrete Tile Roof
-Eagle Roofing Concrete Roof Tiles
- 1” x 2” Wood Batten
- Roofing Paper
- 5” Rigid Insulation (Expanded Polystyrene)
-Due to increased weight of the concrete tiles -
A 25% increase in structure was required.

Figure 2: Wall section with 24 ga, standing seam steel roof assembly



In order to maintain a consistent thermal value of the roof systems, the thickness of rigid insulation was adjusted. All other components remained the same to ensure that the results were limited to as few variables as possible. The roofing assemblies in the following section diagrams illustrate these differences. (figures 2, 3 and 4)

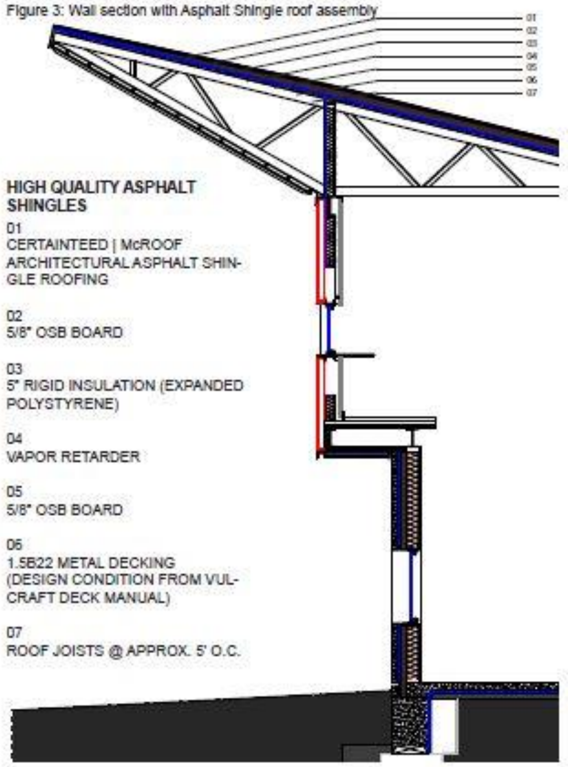


Figure 3: Wall section with Asphalt Shingle roof assembly

Comparison Material Performance Data

The space used for this study is located in Oklahoma City on the South facade of the building. Figure 2 shows the coordinated systems that comprise the wall section.

Control Components:

The second floor facade employs a 4" high performing translucent fiberglass insulated sandwich wall panel. The translucent wall system allows for daylight without compromising the thermal performance of the envelope. This is paired with a Alpen Tyrol 6 Series True Triple PH+ operable window system, a high performing triple pane window unit. The first floor facade employs a stack bond brick veneer and the same operable window unit.

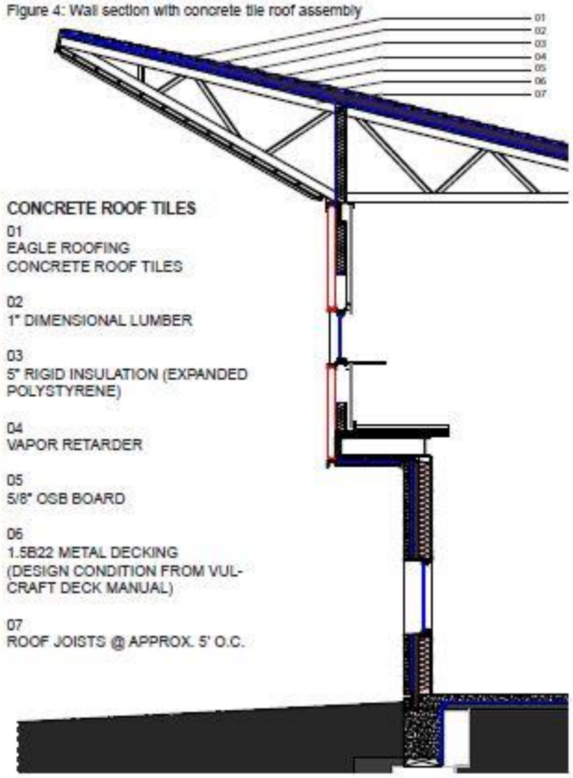


Figure 4: Wall section with concrete tile roof assembly

The wall section is metal stud construction with steel framing. The roof framing consists of joists comprised of steel angles spaced roughly 5' on center which structures the 14' overhang that protects the southern facade from solar heat gain between the months of April and September as well as protects from rain water. Much of the roof envelope will remain consistent. 1.5B22 metal decking was used over the steel joists along with a 5/8" oriented strand board, vapor retarder, and 4-5 inches of rigid insulation. The amount of insulation in the 3 wall sections is used to keep a consistent u-value of insulating properties, which was based on energy codes as not to skew the performance results of the exterior roof membrane.

Comparison Components:

A 24 gauge standing seam steel roof panels along with a 1" wool acoustic mat were specified in the original project submission. The system was chosen for its energy efficiency, durability to weather Oklahoma's harsh climate, as well as its aesthetic value.

Alternative Component 1 [Asphalt Shingles]:
High quality asphalt shingles along with roofing paper and 5/8” oriented strand board were specified as a second alternative. This is a common and cost-effective roofing system for commercial and residential applications.

Alternative Component 2 [Concrete Tiles]:
Concrete tiles along with tile battens, an underlay radiant barrier, and an 5/8” oriented strand board sheathing were specified as a third alternative. Concrete tiles are heavier than its other roofing alternatives which affects the structure of the wall section. The system has a high energy performance as well as being resistant to fire and harsh weather.

Following are performance data sheets of the three roofing material alternatives that were used as a guide for the study, along with the performance data of the main control components.

eQuest Peak Load Data

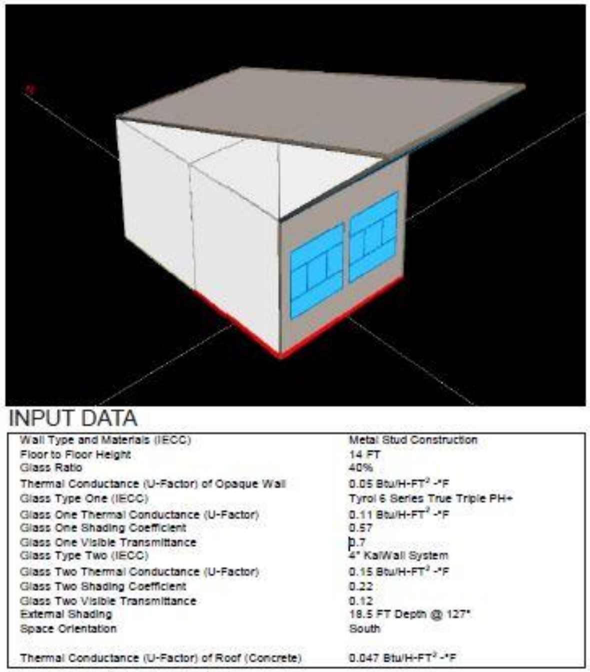
Four different building performance analysis software programs were used in this study to evaluate the building’s performance with two different objectives in mind. EQUEST and Therm were both used to ensure that each roof variation maintained uniform peak loads and heat transfer effects. Both of these program evaluations are used to measure that the differences in energy use of each roof assembly are negligible. Tally and Athena estimate the potential impact of the life cycle carbon impacts of a building based on each material used. While they are both comprehensive programs that measure a variety of environmental impacts, Athena has the unique capability of comparing variations side-by-side, which proved to provide clear results that could easily be further compared to the results from Tally.

EQuest energy modeling was used to calculate the peak loads of the focus space as well as its energy use index. Energy modeling is a simulation of a building that focuses on energy consumption, utility bills, and life cycle costs of energy related items such as air conditioning, lights, and hot water. This simulation is constructed in the program based on its corresponding building components using its U-value. In this way, the program can quantitatively predict future performance and thus has considerable value. In order to maintain consistency, the rigid insulation of each roof variation was adjusted to maintain a consistent U-value, limiting the number of variables used in the study. The following data demonstrates the cooling capacity of the control components. Each wall assembly remained the same as to not skew any of the results with the rigid insulation adjusted to ensure that the roofing system maintained the same cooling capacity for all three roofing variations. The results are as follows:

PERIMETER THERMAL ZONE:
Maximum Cooling Load
7.481 KBTU
Maximum Cooling Load Per Square Foot
24.9 BTUH/SQFT
Required Air Supply Per Square Foot
1.15 CFM/SQFT
INTERIOR THERMAL ZONE:
Maximum Cooling Load
3.805 KBTU
Maximum Cooling Load Per Square Foot
12.68 BTUH/SQFT
Required Air Supply Per Square Foot
0.59 CFM/SQFT
(see figure 5)

Therm Heat Transfer Data

Thermal data for each roof variation was then calculated using Therm. Therm is a computer program developed at Lawrence Berkeley National Laboratory used to model two-dimensional heat transfer effects in building components where thermal bridging can be a problem. A heat transfer analysis allows for the evaluation of a product’s energy efficiency and local temperature



INPUT DATA

Wall Type and Materials (IECC)	Metal Stud Construction
Floor to Floor Height	14 FT
Glass Ratio	40%
Thermal Conductance (U-Factor) of Opaque Wall	0.05 Btu/H-FT^2 -°F
Glass Type One (IECC)	Tyrol 6 Series True Triple PH+
Glass One Thermal Conductance (U-Factor)	0.11 Btu/H-FT^2 -°F
Glass One Shading Coefficient	0.57
Glass One Visible Transmittance	0.7
Glass Type Two (IECC)	4" KalWall System
Glass Two Thermal Conductance (U-Factor)	0.15 Btu/H-FT^2 -°F
Glass Two Shading Coefficient	0.22
Glass Two Visible Transmittance	0.12
External Shading	18.5 FT Depth @ 127°
Space Orientation	South
Thermal Conductance (U-Factor) of Roof (Concrete)	0.047 Btu/H-FT^2 -°F

patterns, which may relate directly to problems with condensation, moisture damage, and structural integrity.

Figure 5: input data

Therm uses a two-dimensional conduction and radiation heat-transfer analysis based on the finite-element method, which can model complicated geometries of building elements. The building elements are defined by each material's conductivity and emissivity, as well as its boundary conditions. (figure 6)

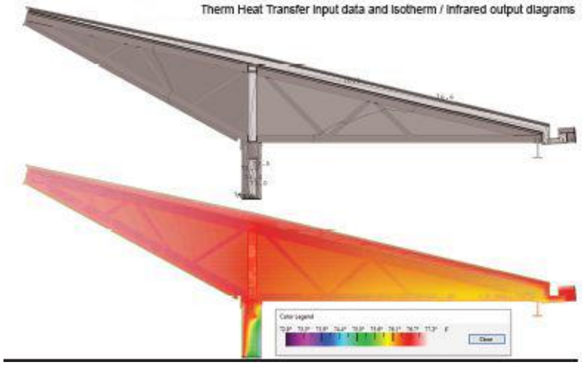


Figure 6: Therm's isothermal representation

The material input values are listed along with the boundary conditions used in determining the heat transfer analysis. The input information was taken from material databases and the boundary condition was calculated using the peak load information from eQuest. Since the insulation of each rood variation was adjusted so that U-factor between the roofs would remain consistent, the heat transfer data between the roof systems were negligible. The results of the heat transfer data demonstrates that the building's efficiency is not effected by the exterior roofing material. The values below show input values used in the program, as well as the Error Energy Norm, and the amount of thermal stress applied to each roof type. The data collected from Therm further demonstrated that the building performance variations between each alteration is negligible. material conductivity (W/m-k) emissivity % Error Energy Norm KalWall (4" Translucent Insulated Fiberglass Sandwich Wall Panel) 0.032 0.9 Gypsum Board 0.17 0.85 Aluminum Stud Wall 160 0.2 Cavity Insulation (Polyurethane Foam) 0.05 0.9 30mm Polycarbonate 0.2 0.9 Steel Framing 50 0.6 Particleboard, Plywood 0.24 0.9 Rigid Insulation (Polystyrene) 0.16 0.9 Standing Seam Metal Roofing 62 0.2 7.79 Asphalt shingles 0.75 0.93 8.04 Concrete Roof Tiles 1.1 0.95 9.49 Boundary Conditions Temperature (F) Film Coefficient (Btu/h-ft2-F) Reactive Humidity Peak Load Condition 77 8.237 50%

Tally Environmental Impact Estimator

Tally is a Revit plugin that takes advantage of BIM modeling software to calculate the environmental impacts of the material selections with a life cycle assessment. The assessment created by Tally represents the complete architectural, structural, and finish systems. This is beneficial when comparing relative environmental impacts associated with building components or when comparing a variety of design options. In order to provide accurate information, generalized functional inputs are required, which are listed below.

Project Location: Atlanta (closest climate zone to Oklahoma within the Tally program)

Building Type: Office Owner - Occupied

Building Life Expectancy: 60 years
Building Operating Energy Consumption:
Electricity - 229,471 kWh per year
Natural Gas - 1,126,770 ft3 per year

Tally utilizes a custom database that combines material attributes, assembly details, and architectural specifications with environmental impact data to analyze the full cradle to grave life cycle of the design options including, material manufacturing, maintenance and replacement, and eventual end of life.

Many criteria are considered while defining the material and its life cycle stages, which are listed and explained below.

Product

This encompasses the full manufacturing stage which includes the raw material extraction and processing, intermediate transportation, and final manufacturing and assembly.

Transportation

This accounts for the transportation from the manufacturer to the building site during the construction stage.

Maintenance and Replacement

This encompasses the placement of materials in accordance with their expected service life. This also includes the end of life treatment of the existing products as well as the cradle to gate manufacturing and transportation to the site of the replacement products. The service life is specified separately for each product. There is also an option for materials to be marked as existing or salvaged if that is the case. However, the maintenance and replacement section is based on a series of manual inputs. All inputs were based on the manufacturing data. If the lifespan and maintenance data was unable to be found using manufacturer data, Tally makes the assumption that all materials will last the building's life expectancy, which in this case was assumed to be 60 years. This assumption, if not changed for each material can cause large miscalculations in the environmental and life cycle assessment, which can lead to a misleading design assumption.

Operational Energy

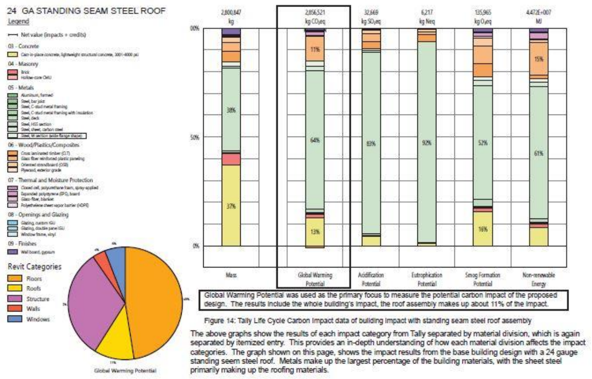
This is based on the anticipated or measured energy and natural gas consumed at the building site over the lifetime of the building. The energy use index for the building was found using EQuest.

End of Life

This includes the relevant material collection rates for recycling, processing requirements for recycled materials, incineration rates, and landfilling rates. The impacts associated with landfilling are based on average material properties, such as plastic waste, biodegradable waste, or inert material waste. This stage also encompasses the transport from the construction site to end-of-life treatment based on national averages, and accounts for waste processing and disposal.

Module D - Reuse and Efficiency

This accounts for the reuse potentials that fall beyond the system boundary, such as energy recovery and recycling of materials. Along with processing requirements, the recycling of materials is modeled using an avoided burden approach, where the burden of primary materials production is allocated to the subsequent life cycle based on the quantity of recovered secondary material. Incineration of materials includes credit for average US energy recovery rates. (figures 7, 8 & 9)

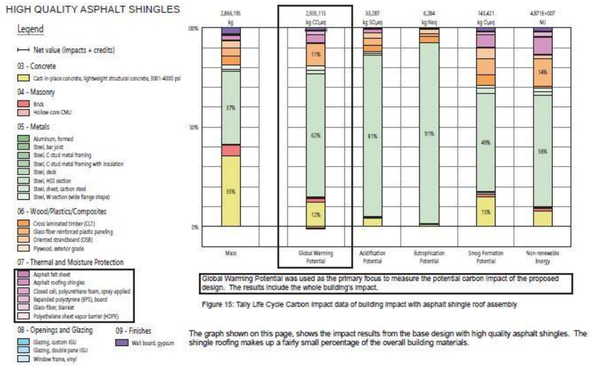


Global Warming Potential was used as the primary focus to measure the potential carbon impact of the proposed design. The results include the whole building's impact, the roof assembly makes up about 11% of the impact.

Figure 14: Tally Life Cycle Carbon Impact data of building impact with standing seam steel roof assembly

The above graphs show the results of each impact category from Tally separated by material division, which is again separated by itemized entry. This provides an in-depth understanding of how each material division affects the impact categories. The graph shown on this page, shows the impact results from the base building design with a 24 gauge standing seem steel roof. Metals make up the largest percentage of the building materials, with the sheet steel primarily making up the roofing materials.

Figure 7: impact estimator for standing seam roof



Global Warming Potential was used as the primary focus to measure the potential carbon impact of the proposed design. The results include the whole building's impact.

Figure 15: Tally Life Cycle Carbon Impact data of building impact with asphalt shingle roof assembly

The graph shown on this page, shows the impact results from the base design with high quality asphalt shingles. The shingle roofing makes up a fairly small percentage of the overall building materials.

Figure 8: impact estimator for asphalt shingle roof

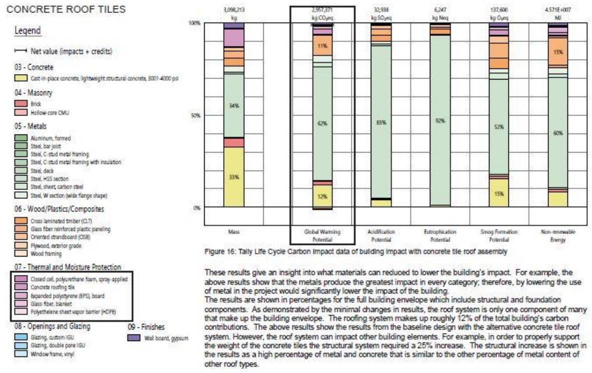


Figure 16: Tally Life Cycle Carbon Impact data of building impact with concrete tile roof assembly

These results give an insight into what materials can reduced to lower the building's impact. For example, the above results show that the metals produce the greatest impact in every category; therefore, by lowering the use of metal in the project would significantly lower the impact of the building.
The results are shown in percentages for the full building envelope which include structural and foundation components. As demonstrated by the minimal changes in results, the roof system is only one component of many that make up the building envelope. The roofing system makes up roughly 12% of the total building's carbon contributions. The above results show the results from the baseline design with the alternative concrete tile roof system. However, the roof system can impact other building elements. For example, in order to properly support the weight of the concrete tiles the structural system required a 25% increase. The structural increase is shown in the results as a high percentage of metal and concrete that is similar to the other percentage of metal content of other roof types.

Figure 9: impact estimator for concrete tile roof

The Tally results show that in many categories, the results differ only slightly for the standing seam steel roof and concrete roof tiles, while the asphalt roof produced the greatest impact potential in all categories. Due to the concrete tile roof's added weight to the structure, it was a surprising result to have the concrete roof tiles have as one of least impactful roof systems. However, the affects from the added weight from the concrete tiles created a lot of needless weight that only added to the overall building's impact. Tally shows that the asphalt roof system is the most harmful, creating the most impact. This is due to the 20 year lifespan of the shingle roof. The repair and maintenance needed to restore the asphalt roof several times throughout the lifespan of the building, greatly adds to the roof's impact. Each impact category affects its immediate environment differently, and may have a higher degree of urgency depending on location and climate. This information is valuable when discerning the environmental and life cycle impacts of the material choice.

Athena Impact Estimator

The Athena Sustainable Materials Institute is a non-profit research collaborative that understands that the design, construction, and product supply sectors are quickly approaching an industry concerned with life cycle assessment, and have provided the tools needed to make that possible with its Impact Estimator Buildings and Pavement LCA. This is a design tool that allows for designers to visualize the environmental footprint of the different material choices as well as basic system options. The estimator provides a cradle to grave life cycle database profile for the whole building. Much like Tally, the Athena Impact Estimator bases its analysis on impact measures of the US EPA TRACI method in addition to an added analysis on fossil fuel consumption. The software has the ability to be as accurate as possible when calculating energy consumption data through its database gathered from regional electrical grids, transportation modes and distances, and product manufacturing technologies. The operating energy determined by EQuest was also included as a factor in the Impact Estimator analysis along with material manufacturing, on-site construction, maintenance and replacement effects, and demolition and disposal. This approach also helps designers to consider a number of trade-offs which ensures informed decision making.

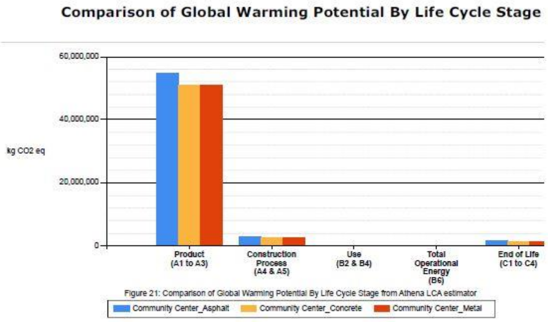


Figure 10: Athena and Tally estimators agree

The global warming impact chart shows that, the asphalt shingle roof has the highest global warming potential. The results for the standing seam steel roof and the concrete roof tiles are also as expected. The results were very close with the standing seam steel roof having only the slightest advantage. Much like the results from Tally, the results gathered for the asphalt shingle roof from Athena produced large carbon estimates are largely due to the material's short lifespan. (figures 10 and 11)

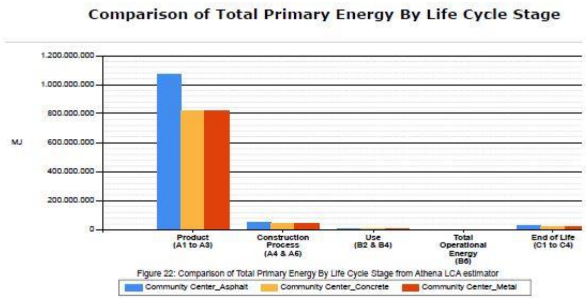


Figure 11: Primary energy of asphalt shingles far exceeds steel or concrete tile roof when replacement is considered

FINAL ATHENA IMPACT ESTIMATOR RESULTS

The results from the Athena Impact Estimator show that in all impact categories, the asphalt shingle roofing has the greatest footprint, which is due to its short lifespan and in the production and manufacturing of the material properties. The maintenance, replacement, and disposal of this roof system greatly increases the carbon impacts by roughly 26% from the other roof assemblies. According to the Athena program, the standing seam steel roof system had a slight advantage over the concrete tile roofing in every category, while the Tally program produced different results in a few categories with the concrete tile roof performing slightly better than its steel variation. Each roof variation has its pros and cons when understanding the various impact categories. The importance of these factors can be based on anything from climate to personal design goals for the building. While the results of the standing seam steel and concrete tile roofs have proven to only have slight differences, which result from their similar embodied energy in their production and similar lifespans.

Conclusions

The roof system is the most exposed building component to the harsh elements of its climate; therefore, demands the most attention of the building envelope in terms of performance. The roof system also has the most variations in maintenance and lifespan discrepancies. For these reasons, the design decision regarding roof materiality can make a big impact to the overall design and its performance.

Importance of Detailing Life Cycle Analysis Assumptions

Life cycle assessment programs have the capability of making performance-based design decisions with a fair amount of accuracy as long as the correct inputs are used in the systems analysis. This study demonstrates why ensuring that the correct inputs for each material's performance and lifespan are significant. Many analysis programs have the capability of making base assumptions; however, these are basic assumptions that are general and based on the building's life expectancy, and not that of each individual material's

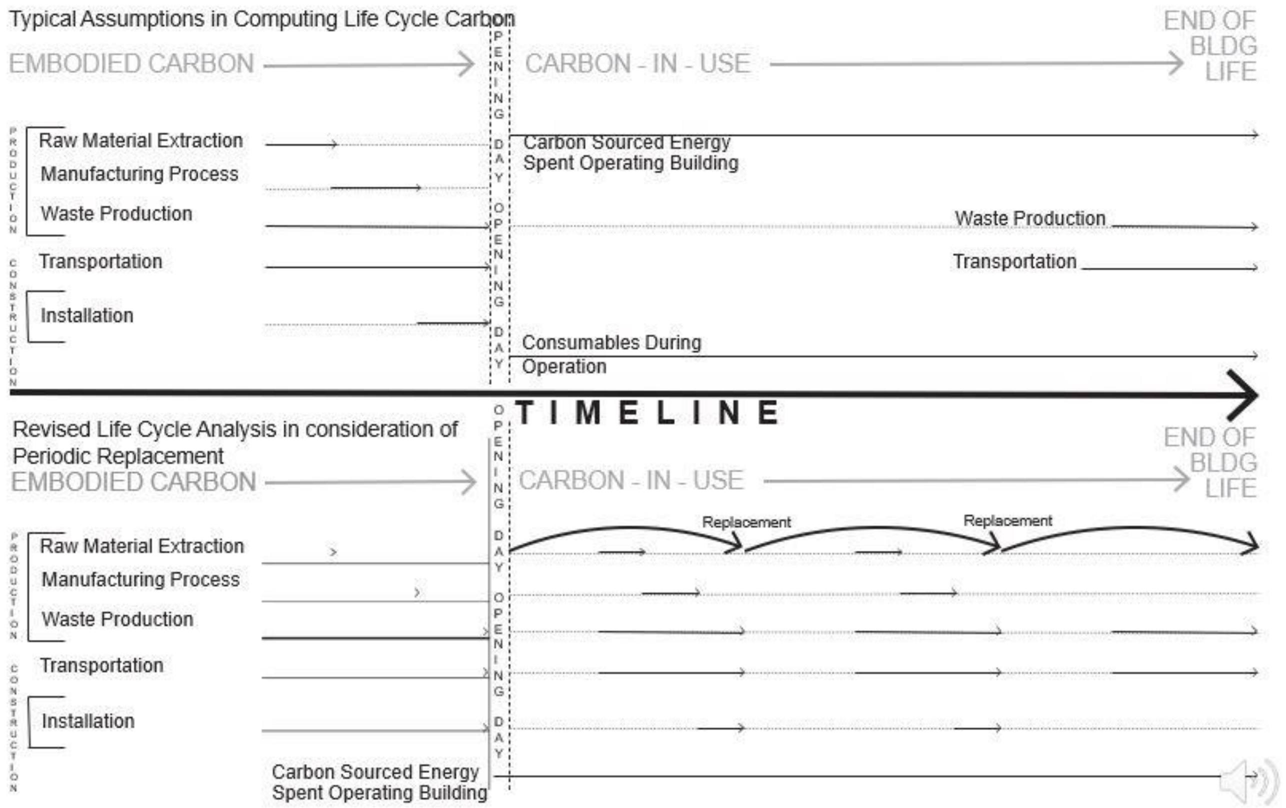


Figure 12: rethinking embodied carbon

capabilities. Tally allows you see the individual differences between materials' lifespans As long as your Revit model is clean and accurate, fewer assumptions are made and you can receive accurate results from Tally. While Athena also accounts for lifespan differences, in an effort to be more user friendly it can be difficult to determine what assumptions were made by the program, particularly with the program's end-of-life impact assumptions. Over the course of a building's lifespan, maintenance and the replacement of components are necessary for the building's performance, which will also add to the building's overall carbon's impact. Therefore, if these assumptions are taken into account, the carbon impact estimates made by these programs would miscount for such a large portion of the carbon estimate. The following results are based on the carbon assumptions of each material's estimated lifespan as per the manufacturer, and the conclusions are as follows.

Material Performance and Durability

Asphalt shingles have proven to have a lower quality and durability to the other roof variations. While an asphalt shingle roof has to be replaced every 20 years or so, concrete tile and metal roofs can easily last anywhere from 40-60 years. Along with having a tendency to come loose and need repairs after heavy winds or bad weather, the asphalt shingle roofing system does not outperform the other roofs. Concrete tile roofs have been found superior over clay tile roof for their durability; however, the tiles can still retain damage in rough weather. Concrete roof tiles are also a much heavier alternative to most other roofing options, which adds a considerable weight to the structure of the building that will add additional embodied carbon in the supporting structure. A steel roofing system is a durable and lightweight option that is common for residential and commercial, which has streamlined the installation of the system. (Figure 12.)

Energy and Thermal Performance

To maintain consistency in the analysis of the various roof systems, a consistent thermal value of the roof systems was achieved by adjusting the thickness of rigid insulation of each type until the systems were within 0.1 of the same U-value. Due to this adjustment, the energy performance data taken by EQuest resulted in indistinguishable energy loads. The same results hold true for the heat transfer thermal data taken from Therm. The heat transfer results between the three roof variations are mostly unchanging with the standing seam steel roof having a slightly better thermal performance than the other roof systems; however, this was negligible.

Carbon Analysis and Impact Performance

The Tally and Athena programs were developed to help designers make informed decisions of building materials regarding their environmental impact. Both programs cover eight impact categories which include; fossil fuel depletion, other non-renewable resource use, water use, global warming potential, stratospheric ozone depletion ground level ozone (smog) creation, neutrification/eutrophication of water bodies, acidification and acid deposition, and toxic release to the air, water and land. Tally and Athena were used to calculate the impacts of each roof variation, in order to determine the roof system with the least overall impact. In the majority of the categories the results differ only slightly for the standing seam steel roof and concrete roof tiles, while the asphalt roof produced the greatest impact potential in all categories. Due to the concrete tile roof's added weight to the structure, it was a surprising result to have the concrete roof tiles have as one of least impactful roof systems. We were not able to determine if the Athena and Tally programs corrected for this added construction weight, but it may be the case that the added weight of the concrete roof system further adds to the carbon advantages of the steel roof. This would be a ripe area for further investigation. The asphalt shingle roofing has the greatest

footprint, which may be due to its short lifespan. The maintenance and replacement period of this roof system greatly increases the carbon impacts. Each roof variation has its pros cons when understanding the various impact categories, which may hold more importance based on any variety of factors from climate to personal design goals for the building. The Tally program calculated the concrete tile roof system to have a slight advantage, while the Athena program calculated the steel roof having the least impactful system. There

was approximately an 8% margin of error between the two programs, which could have easily occurred due to 3D modeling errors from Tally and/or slight variations in program assumptions. We were not able to investigate the source of the discrepancies between the Tally and Athena results, but hypothesize that the discrepancies could be the result of inaccurate BIM model representation or rounding errors during calculation.

Overall Summary

This study looked at the in-depth analysis of the roof system best suited for US climate zone 3 by comparing three common roof systems based on a variety of factors in order to determined the most optimized system over the lifetime of the building, which was estimated at 60 years. Out of the many factors taken into account, each of the roof systems maintenance and lifespans contribution to the building's carbon impact became the controlling factor when finding an optimized roof system. The roof system with the greatest lifespan and least carbon impact; therefore, was determined that the most optimized system was a 24 ga. standing seam steel roof system.

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