# Structural System Selection for a Building Design based on Energy Impact

## ABSTRACT

*A building structure's ecological impact due to the embodied carbon in the building materials chosen has become an increasingly prominent factor in the selection of building structural systems. Understanding the relative embodied carbon of different structural systems allows students to make informed decisions in the design process that better achieve the increasingly demanding goal of producing sustainable architecture. The inclusion of this topic in academia has the benefit of giving students experience with energy assessment tools that could be utilized in the profession upon their graduation.*

*This paper presents an overview of and assesses the relative utility of three emerging life cycle assessment tools (ATHENA, EC3, and TALLY) for comparing the carbon impact of timber, steel, and concrete as a building's structural system. It includes an exploration of incorporating these tools into the classroom to allow students to arrive at a decision for the building structural system based on the total embodied carbon of the design. To round-out its assessment, the paper includes a literature review of similar research being incorporated into undergraduate education.*

*A case study that forms the backdrop of this research is the work of a student in our Graduate Certificate Program (first author of this paper). He utilized a section of an existing project designed in the capstone studio as a baseline design for each of the three assessment tools, altering only structural materials in each design iteration. The paper's conclusions and recommendations derive largely from the results of this student's project.*

## INTRODUCTION

The 2014 Intergovernmental Panel on Climate Change (IPCC) reported that carbon reduction must occur immediately to avoid climate catastrophe, as shown by De Wolf [1]. If we are to address this in the Architecture, Engineering, and Construction (AEC) industries, then a systematic method needs to be employed by which higher education can address the issue as it teaches future professionals. Though there are several factors against which carbon reduction in building design can be considered, this paper focuses on the seldom addressed selection of structural systems for use in building design and construction. When teaching undergraduate architecture and architectural engineering students about the selection of structural systems for a building, the focus has historically centered on such aspects as the economy of the structure, the structural system types available in the market based on geographic location of construction, or the building code allowances based on construction type. Recently in higher education, the additional parameter of embodied carbon in a building has become quantifiable. Currently, several computer programs are available to help determine the amount of embodied carbon in a building, and these programs are available for free, or at a nominal cost, and thus are accessible to most higher education programs. By introducing students to this process, they can be ready to design using this new environmental parameter in the profession upon graduation.

The selection of the material for use in a building structure will have a large effect on the carbon footprint for the design. For example, in a concrete structure the cement accounts for a large percentage of the carbon footprint. Cement is formed by heating limestone in a process that emits $CO_2$, accounting for 60% of the emissions from the process of producing cement. The other 40% of the emissions is the result of the fuel required for the heating process, per Pearson [2]. Educating students on the environmental impact of building materials and how to quantify carbon footprint of structural systems should prepare them to tackle future challenges for the profession.

The AEC industry has evolved to the point that the inclusion of carbon embodiment analysis into both the building design and construction processes is efficient, and in some cases, expected. Though historically not considered when deciding on which structural system to use for a building, with current availability of analysis programs, the selection of the structural system can now be analyzed based on carbon footprint. The expansion of the availability of programs that can be utilized for this process have grown substantially in the past decade, and it is currently a parameter that should be included in education. Lack of information and assessment tools hindered the quest to lower carbon emissions, which has long been treated as cost-free. Therefore, any resources devoted to lowering emissions were pure outlay with no corresponding returns. Economists largely agree that for carbon reduction to become a factor in investment decisions, nations will need to enact some sort of carbon tax by which the cost of carbon forcing into the atmosphere begins to entail a price to emitters. If and when a carbon tax program becomes enacted, developers and building owners will look to their architects and engineers to provide good information on the relative emissions of various alternatives. It is not too soon to prepare ourselves for that future demand, as shown by Labatt and White [3].

## PROGRAMS FOR USE IN EVALUATING A BUILDING'S CARBON FOOTPRINT

There are multiple analysis and evaluation programs that can be used in determining the carbon footprint of buildings. In addition to the three (*Athena, EC3, and Tally*) that are featured in this paper, and that will be further discussed, there are others that are available. Table 1 gives an overview of the analysis and evaluation programs and tools available to help with various aspects of embodied energy in buildings. The AIA released a document in 2010 that explored numerous life-cycle assessment (LCA) programs available at the time, several of which are included in the Table 1, per Bayer [4]. Although many of the emerging programs listed by the AIA could no longer be located, LCA programs at large continue to grow in number and power, and they will probably become a vital part of the design process for the analysis, evaluation, and design of buildings as data computation continues to improve. Below is a brief overview of the three programs tested in this paper.

**ATHENA:** The Athena Impact Estimator calculates carbon footprint estimates based on user-defined building assemblies. Depending on the type of assembly being added to the project, the Athena program automatically adds supplementary material to better represent a true-to-life construction. For example, when the program recognized that a brick veneer has been added to the wall assembly, it will automatically include an averaged amount of mortar for typical brick veneer walls. All these assumed values are visible in the Bill of Materials, but they are not modifiable to the same degree as Tally. However, every assembly group in Athena contains a section for extra materials that can account for atypical constructions or conditions.

**EC3:** EC3 uses the exhaustive (and often overwhelming) data of Tally and processes it into an elegant visualization of carbon impact flows based on materials present in the project. The resulting flow chart quickly shows what materials are demanding the most carbon as well as which category of the assembly is most impactful to global warming potential.

**TALLY:** Tally utilizes BIM data present in a Revit model to perform a life cycle assessment of the project based on quantities of materials used. Tally calculations cover a building "from cradle to grave," or from production of materials to the end of the building's life, giving a broad spectrum of true carbon impact. Tally is very thorough in disclosing data assumptions and allowing plenty of user-specified data, but this necessarily means that Tally also requires a highly refined BIM model with precise material choices. For this study, interior materials were minimally considered so that the data primarily reflected changes to the building envelope and structural variations.

Table 1: Analysis and Evaluation Tools/Programs for use in Calculating Energy Embodiment

| **Tool / Program Name** | **Developer** | **Country** | **Most Recent Version** | **Program Plugins** | **Visual Output** | **Free for Educational Use?** |
|---|---|---|---|---|---|---|
| **ATHENA** | Athena Sustainable Materials Institute | Canada | 2020 | Excel | Tables | Yes |
| **EC3** | C Change Labs | Canada | 2019 | None | Flow charts | Yes |
| **TALLY** | Kieran-Timberlake | USA | 2019 | Revit | Charts | Yes |
| **Cove Tool** [5] | Cove Tool | USA | 2020 | Revit, ArchiCAD, Rhino 3D, Sketchup | Tables, graphs, 3D model | Yes |
| **One-Click LCA** [6] | Bionova | Finland | 2020 | Revit, ArchiCAD, Rhino 3D, Sketchup, Tekla | Tables, graphs | Yes, limited features |
| **eToolLCD** [7] | eToolLCD | Australia | -- | Revit | Tables, charts | Yes, limited features |
| **IMPACT** [8] | BRE | UK | -- | Revit, AutoCAD | Tables, graphs | No |
| **Umberto** [9] | IFU | Germany | -- | Excel | Tables, flow charts | Must apply |
| **SimaPro** [10] | PRé Sustainability | Netherlands | 2020 | -- | Tables, graphs | Demo only |
| **BEES** [11] | NIST | USA | 2011 | | Tables, graphs | Yes |
| **EIO-LCA** [12] | Carnegie Mellon | USA | 2008 | | Tables | Yes |

## LITERATURE REVIEW

A brief search was undertaken to find published research on the topic of incorporating the evaluation of building structure design based on embodied carbon within higher education architecture and/or engineering programs. No significant amount of published research of this topic, however, one publication in particular stood out. A PhD dissertation titled "*Low Carbon Pathways to Structural Design: Embodied Life Cycle Impacts of Building Structures*" by Catherine De Wolf, was published in 2017 on the topic of an assessment approach that compares the embodied life cycle impacts for different building structures. This detailed document gives a comprehensive overview of the process of including carbon embodiment in the process of structural selection for buildings. It delves into the embodied carbon on the material, structural, and urban scales and how each of these can be analyzed for various structural materials, differing building uses, sizes, and heights, and how neighborhoods can consider carbon embodiment as they are developed, per De Wolf [1]. And though this document is not necessarily written from the standpoint of higher education and teaching students, much of the content could still be adapted for meeting educational objectives in the architecture, engineering, and construction programs. It is highly recommended that if anyone is interested in furthering their knowledge on the topics included in this paper, they should refer to this PhD dissertation for a more fully informative explanation, exploration, and expansion of including embodied carbon in the process of determining building structural systems.

## OVERVIEW OF THE COMPREHENSIVE DESIGN STUDIO, AND THE INCLUSION OF CARBON EMBODIMENT SOFTWARE IN THE DESIGN PROCESS

In the five-year curriculum for architecture and architectural engineering students at Oklahoma State University, though the topic is discussed throughout the curriculum, quantification of embodied carbon in a building is not possible until the Comprehensive Design Studio (CDS). The CDS is taken as a required set of courses by both fourth year architecture and fifth year architectural engineering majors. In the CDS, students enroll in a 12-credit hour block of three interconnected courses, including the 6-credit hour comprehensive studio, a 3-credit hour concurrent technology seminar, and a 3-credit hour project management course, all focusing on the semester long project in the CDS. The 15-week semester is divided into five weeks of Schematic Design (SD), in which students work in teams, and ten weeks of Design Development (DD) and Construction Documents (CD) phases when each student works on their own development of a significant space within the building, which is referred to as the DD focus space. The CDS emphasizes synthesis and application of all design skills including the technical and general knowledge that architectural or architectural engineering students have developed in previous undergraduate courses. This studio helps to develop the ability to design rational solutions to biological, emotional, physiological, spiritual, and social needs in the built environment. Emphasis in the studio is placed on developing the ability to synthesize the visual systems of color, form, rhythm, space, and texture; the technical systems of structure, acoustics, heating, ventilating, air conditioning, and lighting; and the legal systems of building, material, and systems codes, along with zoning ordinances and other regulations that, along with function, form organizing influences that affect virtually every architectural project. The educational objective of the CDS is to allow the student to develop a comprehensive and mature understanding of the interaction of aesthetic influences and the technical, legal, and human factors that shape the design of architectural projects. Additionally, the impact that a building design can have on climate change is included in the process to allow students to experience how evaluating a building design for this condition can achieve a more climate friendly design.

Within the CDS, quantification of embodied carbon has been part of the course for a couple of years. Athena is the program that has been adopted in the CDS to evaluate a student’s design from the standpoint of embodied carbon. Incorporating this program into the curriculum allows students to experience the use of carbon analysis as a part of the design process. The process involves identifying the basics of building location, use, size, structural system and façade type and materials. This degree of detail is what Athena needs to begin generating comparisons of carbon emissions from the combination of embodied sources, use sources, and end of life sources, as presented in Brandvold et al. [13].

## CASE STUDY RESEARCH

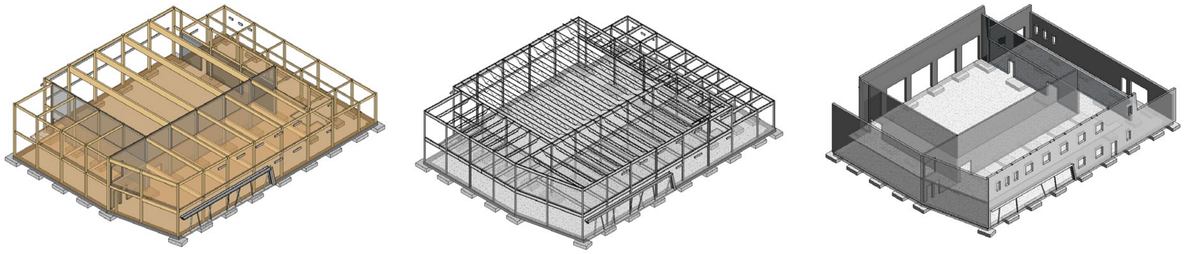
As part of a Graduate Certificate research project within our program, one student (first author on this paper) explored the embodied carbon with a building project design. This process involved utilizing a portion of a building design from the comprehensive design studio the student had completed the previous semester, exploring how different structural systems affected the carbon footprint of the design. For these studies, the only variation in the analysis was the structure used for the building, as shown by Crawford [14].

Before testing could begin, the Revit model from the comprehensive design studio had to be altered for each structural permutation. This required significantly more precision than was achieved with the model previously, specifically in the wall assemblies, to prepare each model for the analysis phase. The three structural variants, illustrated in Figure 1, were modified as follows:

**Variant 1:** The first variant was composed of primarily mass timber, which was chosen based on goals already set forth in the studio. A post-and-beam system carried the structural load, while Cross Laminated Timbers (CLT) spanned beams as decking and stabilized against lateral loads. Steel supports over glazing and concrete for foundation footings remained in the model. Nonstructural walls were modeled with 2x4 wood studs.

**Variant 2:** The second variant relied mostly on steel. Posts were modified into steel tubing; glulam beams were replaced with steel I-beams for the second-floor load and joists for the roof load. CLT decking was replaced by composite metal decking, and lateral resistance was achieved by metal cross bracing where necessary. All nonstructural walls were modeled with metal 3 1/2-inch studs instead of wood studs.

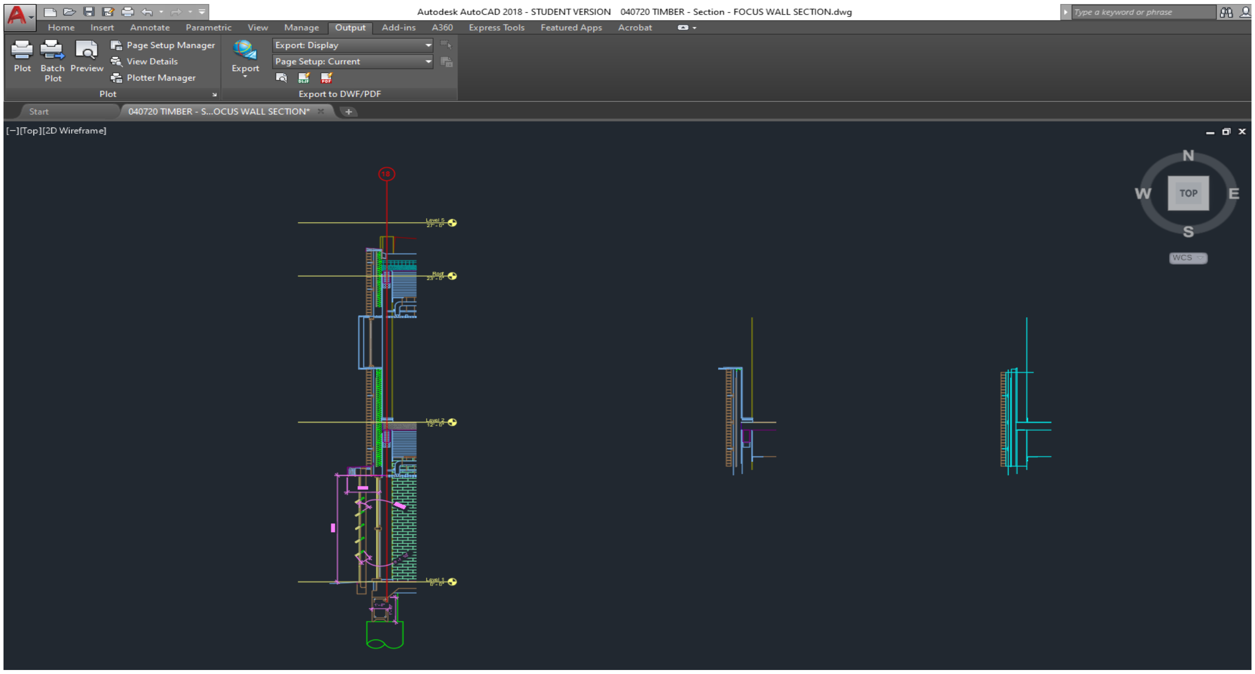
**Variant 3:** The third variant was entirely comprised of concrete. Steel columns were exchanged for concrete load-bearing walls, and the steel floor and roof members were replaced by a one-way concrete system. Little steel remains except for composite decking and reinforcement embedded in the concrete.



**Variant 1: Timber** **Variant 2: Steel** **Variant 3: Concrete**

Figure 1: Revit Models for Variants 1 (Timber), 2 (Steel), and 3 (Concrete) used in the Analysis

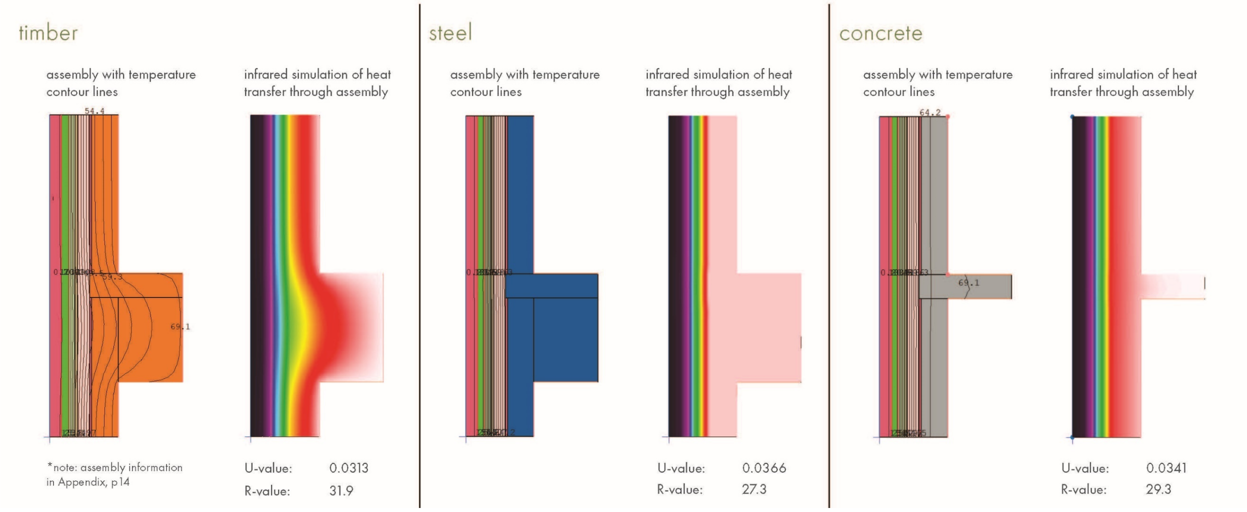
With the variations properly modeled, analysis could begin. THERM was used to evaluate Envelope performance of each variation to determine the impacts of structure on a smaller scale. Heat transfer was analyzed at the point in which the floor plate meets the wall, a location that can lead to some unintended



Autodesk AutoCAD 2018 - STUDENT VERSION 040720 TIMBER - Section - FOCUS WALL SECTION.dwg

Figure 2: Simplifying Revit wall detail in AutoCAD to prepare for export to THERM

thermal bridging, and corresponding wall details were captured within Revit. Because perhaps it was the oldest program of the three, THERM lacked an intuitive user interface. Initial attempts to draw the wall assemblies directly in the program were fruitless, and most every task involved navigating through a series of dialogue boxes to type in the appropriate information. Ultimately, each wall assembly was taken from Revit into AutoCAD to clean up and simplify the drawing before exporting it into the THERM program. This middle step facilitated the process. Fortunately, the resulting data from THERM was precise and easily comprehended for comparing each variant wall assembly, which was useful in making sure all three variations share the same thermal properties (U-factor of the wall assembly).

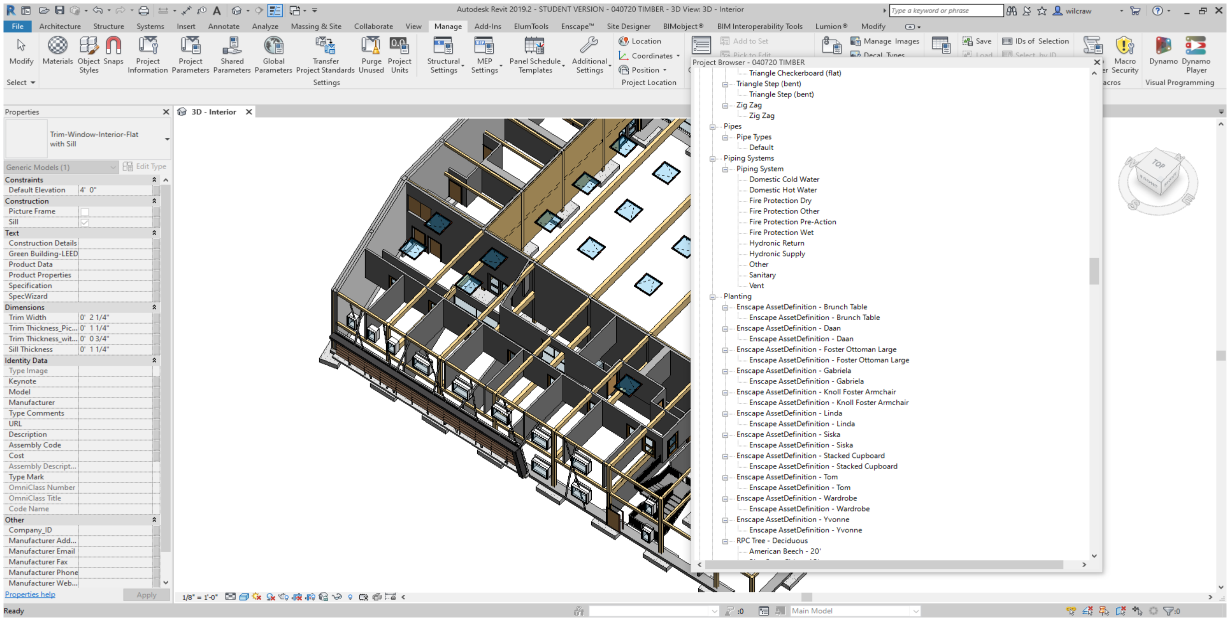


*note: assembly information in Appendix, p14

| | timber | steel | concrete |
|---|---|---|---|
| U-value: | 0.0313 | 0.0366 | 0.0341 |
| R-value: | 31.9 | 27.3 | 29.3 |

Figure 3: Isotherm (left) and infrared (right) data outputs of each THERM wall assembly for each variant with resulting U-values

Next, the three models were loaded into Tally, which could be readily transferred to EC3. As mentioned previously, Tally required highly precise information from the Revit model in order to process the most comprehensive results. For example, every layer modeled in a Revit wall was assumed by Tally to be a specific material of the exact thickness as designed in the wall family. Although the comprehensive


Autodesk Revit 2019.2 - STUDENT VERSION - 040720 TIMBER - 3D View: 3D - Interior

Properties

Trim-Window-Interior-Flat with Sill

Generic Models (1)

| | |
|---|---|
| **Constraints** | |
| Default Elevation | 4' 0" |
| **Construction** | |
| Picture Frame | ☐ |
| Sill | ☑ |
| **Text** | |
| Construction Details | |
| Green Building-LEED | |
| Product Data | |
| Product Properties | |
| Specification | |
| SpecWizard | |
| **Dimensions** | |
| Trim Width | 0' 2 1/4" |
| Trim Thickness_Pic... | 0' 1 1/4" |
| Trim Thickness_wit... | 0' 0 3/4" |
| Sill Thickness | 0' 1 1/4" |
| **Identity Data** | |
| Type Image | |
| Keynote | |
| Model | |
| Manufacturer | |
| Type Comments | |
| URL | |
| Description | |
| Assembly Code | |
| Cost | |
| Assembly Descript... | |
| Type Mark | |
| OmniClass Number | |
| OmniClass Title | |
| Code Name | |
| **Other** | |
| Company_ID | |
| Manufacturer Add... | |
| Manufacturer Email | |
| Manufacturer Fax | |
| Manufacturer Phone | |
| Manufacturer Web... | |

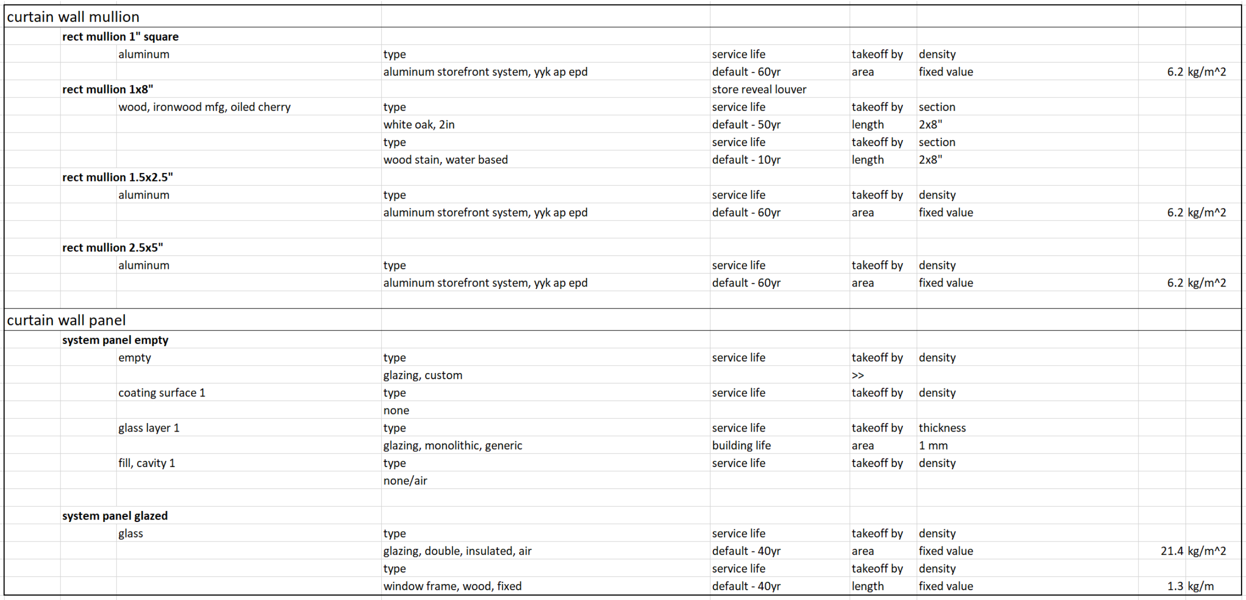
Project Browser - 040720 TIMBER

- Triangle Checkerboard (flat)
- Triangle Step (bent)
  - Triangle Step (bent)
- Zig Zag
  - Zig Zag
- Pipes
  - Pipe Types
    - Default
- Piping Systems
  - Piping System
    - Domestic Cold Water
    - Domestic Hot Water
    - Fire Protection Dry
    - Fire Protection Other
    - Fire Protection Pre-Action
    - Fire Protection Wet
    - Hydronic Return
    - Hydronic Supply
    - Other
    - Sanitary
    - Vent
- Planting
  - Enscape AssetDefinition - Brunch Table
    - Enscape AssetDefinition - Brunch Table
  - Enscape AssetDefinition - Daan
    - Enscape AssetDefinition - Daan
  - Enscape AssetDefinition - Foster Ottoman Large
    - Enscape AssetDefinition - Foster Ottoman Large
  - Enscape AssetDefinition - Gabriela
    - Enscape AssetDefinition - Gabriela
  - Enscape AssetDefinition - Knoll Foster Armchair
    - Enscape AssetDefinition - Knoll Foster Armchair
  - Enscape AssetDefinition - Linda
    - Enscape AssetDefinition - Linda
  - Enscape AssetDefinition - Siska
    - Enscape AssetDefinition - Siska
  - Enscape AssetDefinition - Stacked Cupboard
    - Enscape AssetDefinition - Stacked Cupboard
  - Enscape AssetDefinition - Tom
    - Enscape AssetDefinition - Tom
  - Enscape AssetDefinition - Wardrobe
    - Enscape AssetDefinition - Wardrobe
  - Enscape AssetDefinition - Yvonne
    - Enscape AssetDefinition - Yvonne
  - RPC Tree - Deciduous
    - American Beech - 20'

Figure 4: Reviewing material definitions in Tally and reworking Revit model as needed

design studio required a well-developed design in Revit, it did not demand the level of model accuracy demanded by the Tally program; therefore, all three models underwent another round of model refinement. All generic materials that still lingered from less thoroughly designed or less critical portions of the building had to be either eliminated or reworked as typical construction details, like the largely undeveloped interior partition assemblies. This led to input from both professors and reliable internet resources as to typical construction methods of components, from varying interior wall conditions to structural detailing around openings. Tally would only accept materials assigned in the model, so all conditions had to be fully modeled in Revit in order to count towards carbon impact.

After another round of model refinement the task of assigning specific attributes to each generic BIM material began. A plethora of unfamiliar materiality terms was introduced upon specifying exact material types present in the model. This may seem like an unnecessary step, but Tally needed precision to output any results whatsoever, so each unique material, structural shape, or wall assembly had to be painstakingly ascribed a specific material through a series of dropdown menus within the Tally program. Resulting data was fortunately highly customized to the specific conditions of the building, but it would not have been ideal in its present form for a project at the schematic level. Another phase of research went into exploring different types of paint, insulation, structural fireproofing, decking, sheathing, etc. to determine a reliable guess for how this structure would be constructed under typical real-world conditions. Tally treated each structural variant as a completely new model, so duplicating material properties across the variations was not achievable, at least not in the way the BIM model input process was approached. So, to remain as consistent as possible among the three separate structural variations, an excel spreadsheet was populated in conjunction with every material-based decision made in Tally. This spreadsheet essentially recorded all the selections in Tally's various dropdown menus for each component that Tally recognized in the model. To expand upon the need for this external record of the selections made, consider this: though the same generic Revit door was used in every application of an exterior door in each structural model variant, the Tally dropdown menu could specify the components within that door quite differently. If not handled the same in Tally throughout the model variations, this door introduces several more variables into total carbon impact outside the intended scope of structural impact alone; therefore, the spreadsheet ensured consistency across the models and prevented unwanted, error-inducing variables. The organized documentation of the



| curtain wall mullion | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **rect mullion 1" square** | | | | | | | |
| | | aluminum | type | service life | takeoff by | density | | |
| | | | aluminum storefront system, yyk ap epd | default - 60yr | area | fixed value | 6.2 | kg/m^2 |
| | **rect mullion 1x8"** | | | store reveal louver | | | | |
| | | wood, ironwood mfg, oiled cherry | type | service life | takeoff by | section | | |
| | | | white oak, 2in | default - 50yr | length | 2x8" | | |
| | | | type | service life | takeoff by | section | | |
| | | | wood stain, water based | default - 10yr | length | 2x8" | | |
| | **rect mullion 1.5x2.5"** | | | | | | | |
| | | aluminum | type | service life | takeoff by | density | | |
| | | | aluminum storefront system, yyk ap epd | default - 60yr | area | fixed value | 6.2 | kg/m^2 |
| | | | | | | | | |
| | **rect mullion 2.5x5"** | | | | | | | |
| | | aluminum | type | service life | takeoff by | density | | |
| | | | aluminum storefront system, yyk ap epd | default - 60yr | area | fixed value | 6.2 | kg/m^2 |
| | | | | | | | | |
| curtain wall panel | | | | | | | | |
| | **system panel empty** | | | | | | | |
| | | empty | type | service life | takeoff by | density | | |
| | | | glazing, custom | | >> | | | |
| | | coating surface 1 | type | service life | takeoff by | density | | |
| | | | none | | | | | |
| | | glass layer 1 | type | service life | takeoff by | thickness | | |
| | | | glazing, monolithic, generic | building life | area | 1 mm | | |
| | | fill, cavity 1 | type | service life | takeoff by | density | | |
| | | | none/air | | | | | |
| | | | | | | | | |
| | **system panel glazed** | | | | | | | |
| | | glass | type | service life | takeoff by | density | | |
| | | | glazing, double, insulated, air | default - 40yr | area | fixed value | 21.4 | kg/m^2 |
| | | | type | service life | takeoff by | density | | |
| | | | window frame, wood, fixed | default - 40yr | length | fixed value | 1.3 | kg/m |

Figure 5: Sample of Excel spreadsheet data for documenting material selections in Tally

material assumptions improved the efficiency of the later portion of the process. Eventually, only nuanced components had to be researched and thought through.

After specifying every material used in each BIM model with every unique material condition, Tally was ready for the second round of assumed variables. For the sake of time, these variables were largely left at their generic values, but they were no less critical to accurate results of a real-life scenario. Tally's ability to accurately assess "cradle to grave" carbon impact becomes quite evident in this set of global variables that apply to each project. If desired, the travel distance of each material can be clarified to reflect a true-to-life analysis of transportation on carbon required for construction, and inputs for building life demonstrate the environmental impacts upon demolition of the structure. All these variables were left to generic assumptions in an effort to isolate variables, but if more exact figures could be ascertained for another project, the accuracy would increase even more.

Once every material was specified and assumption was made, Tally at last released its exhaustive, and almost overwhelming, flow of data. The comprehensive analysis in the form of visuals, graphs, charts, and raw numbers provided a vast array of information to process. Fortunately, all the time put forth on the front-end lead to a wealth of insight later, and no assumption was left uncertain. Tally thoroughly recorded and documented carbon impact in a variety of dimensions, which was vital in analyzing how and why the three structural variations differed in their carbon impacts and in what ways.

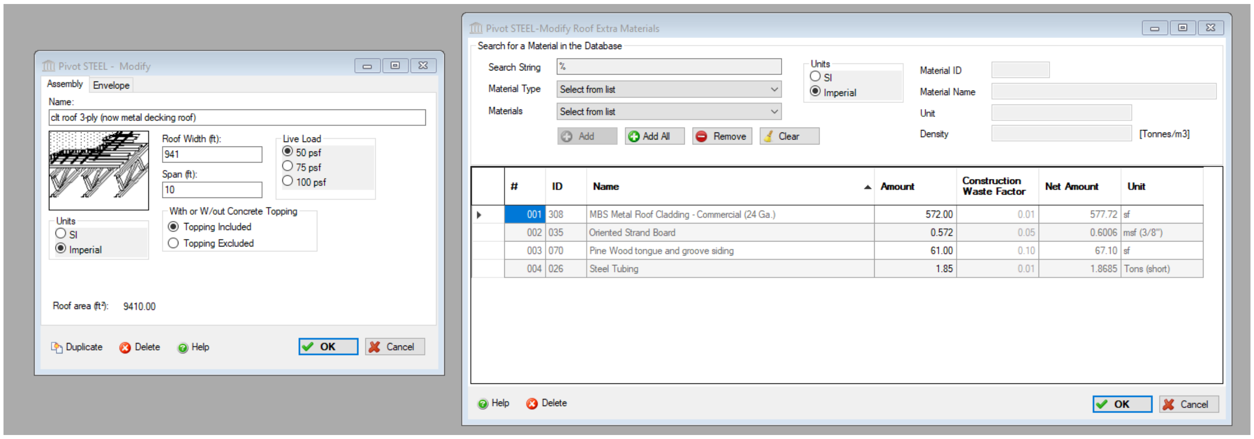
Figure 6: Global Warming Potential (GWP) by life cycle stage for each variant, as output by Tally

The EC3 program flowed rather effortlessly from Tally, for all the data needed for the program was already put into and processed by Tally. Initially, EC3 refused to accept the Tally models, but after a few attempts the snag was resolved. After that, EC3 had some slightly different material profiles that needed to be re-specified, but this was easily achieved in a dropdown menu sequence like that of Tally. Once

EC3 had all the data inputs required, it output both a mass-Sankey diagram and a global warming potential (GWP) flow chart based on the materials specified, as shown in Figure 7. This ultimately served as an alternative way to view the embodied carbon by material that was otherwise expressed by pie charts in Tally, shown in Figure 6. In addition, the GWP flow chart also visualizes potential carbon reduction by material, which demonstrates materials that have the highest potential to remove energy contribution from the building. Although these flow charts greatly simplify the information in a pleasing way, they do not express concrete numerical evidence by which to compare each structural variation. EC3 did have an option to directly load a model from BIM360 as a workaround from using Tally, but this was not explored further once the Tally model was accepted.

Figure 7: Mass-Sankey and GWP flow chart for Variant 1, as output by EC3

The user interface of Athena was comparable to THERM in that it involved very specific preset options and little visual evidence of making changes. Athena does not readily link with building models, so material quantities were extracted from the Revit model manually. This became time consuming and possibly erroneous if the user is not thorough in his/her calculation of quantities - for example, all interior partitions had to be added together in linear feet of wall to be properly represented in the program. Athena also grouped assemblies in unexpected ways, like combining the column and beam system into a single package of inputs. Few visuals were provided by the program to assist with data input; all the building information was input into text boxes and output as simple charts. However, being more generalized than Tally, Athena was much easier to alter entire structural assemblies with just a few clicks.



Name: clt roof 3-ply (now metal decking roof)

Roof Width (ft): 941

Span (ft): 10

Live Load: ● 50 psf ○ 75 psf ○ 100 psf

Units: ○ SI ● Imperial

With or W/out Concrete Topping: ● Topping Included ○ Topping Excluded

Roof area (ft²): 9410.00

Search for a Material in the Database

Search String: %

Material Type: Select from list

Materials: Select from list

Units: ○ SI ● Imperial

Material ID:

Material Name:

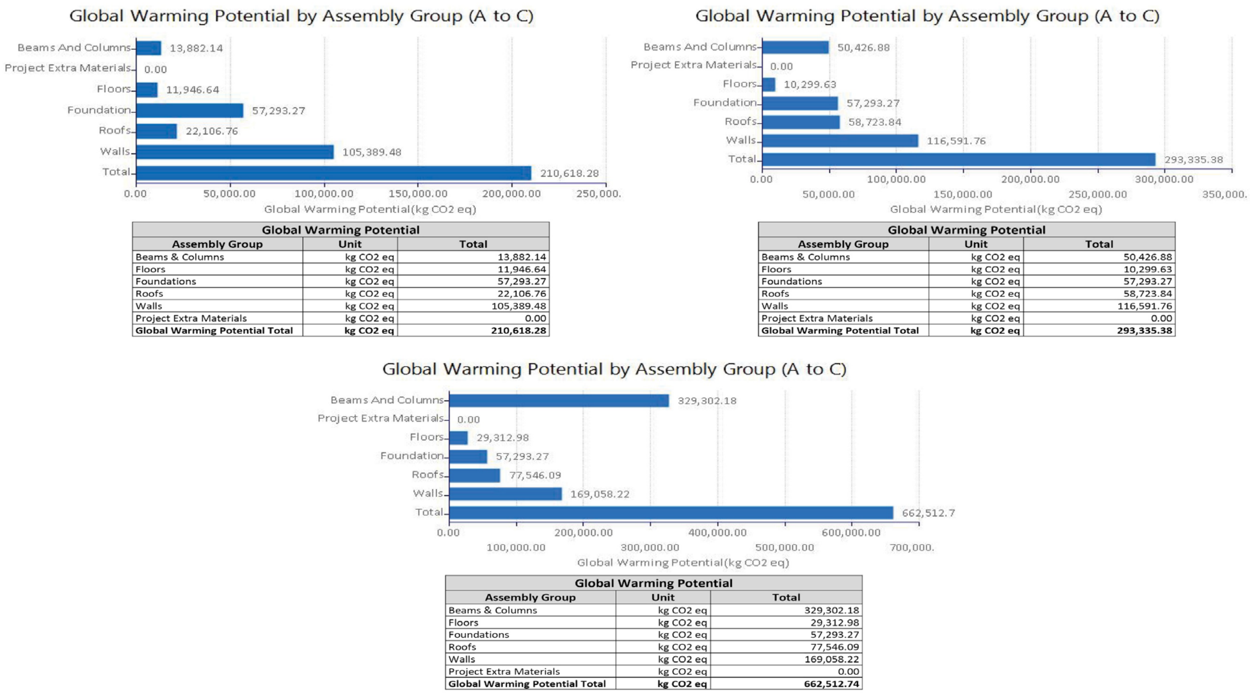
Unit:

Density: [Tonnes/m3]

| # | ID | Name | Amount | Construction Waste Factor | Net Amount | Unit |
|---|---|---|---|---|---|---|
| 001 | 308 | MBS Metal Roof Cladding - Commercial (24 Ga.) | 572.00 | 0.01 | 577.72 | sf |
| 002 | 035 | Oriented Strand Board | 0.572 | 0.05 | 0.6006 | msf (3/8") |
| 003 | 070 | Pine Wood tongue and groove siding | 61.00 | 0.10 | 67.10 | sf |
| 004 | 026 | Steel Tubing | 1.85 | 0.01 | 1.8685 | Tons (short) |

Figure 8: Modifying roof decking assembly in Athena interface to accommodate for unique condition

Data from Athena was much harder to distinguish between each structural variation, especially given the fact that all the charts scaled to the highest local value instead of maintaining a global scale. However, the more limited set of data from Athena was easier to digest than the mountains of charts from Tally. Once the metrics were analyzed, a direct comparison between the three variations could be ascertained.



Global Warming Potential

| Assembly Group | Unit | Total |
|---|---|---|
| Beams & Columns | kg CO2 eq | 13,882.14 |
| Floors | kg CO2 eq | 11,946.64 |
| Foundations | kg CO2 eq | 57,293.27 |
| Roofs | kg CO2 eq | 22,106.76 |
| Walls | kg CO2 eq | 105,389.48 |
| Project Extra Materials | kg CO2 eq | 0.00 |
| **Global Warming Potential Total** | **kg CO2 eq** | **210,618.28** |

Global Warming Potential

| Assembly Group | Unit | Total |
|---|---|---|
| Beams & Columns | kg CO2 eq | 50,426.88 |
| Floors | kg CO2 eq | 10,299.63 |
| Foundations | kg CO2 eq | 57,293.27 |
| Roofs | kg CO2 eq | 58,723.84 |
| Walls | kg CO2 eq | 116,591.76 |
| Project Extra Materials | kg CO2 eq | 0.00 |
| **Global Warming Potential Total** | **kg CO2 eq** | **293,335.38** |

Global Warming Potential

| Assembly Group | Unit | Total |
|---|---|---|
| Beams & Columns | kg CO2 eq | 329,302.18 |
| Floors | kg CO2 eq | 29,312.98 |
| Foundations | kg CO2 eq | 57,293.27 |
| Roofs | kg CO2 eq | 77,546.09 |
| Walls | kg CO2 eq | 169,058.22 |
| Project Extra Materials | kg CO2 eq | 0.00 |
| **Global Warming Potential Total** | **kg CO2 eq** | **662,512.74** |

Figure 9: GWP for Variants 1, 2, and 3, respectively, as output by Athena

## CONCLUSION

When environmental impact is a concern, carbon footprint within a building must be given consideration during the design process. Type of structural system and material used to support the design will affect this consideration. The use of readily available analysis programs allows for a building design to be evaluated based on the carbon footprint. Incorporating this software into the undergraduate curriculum for an architecture and architectural engineering program will give students exposure to the current and evolving environmental issues. This exposure will allow students to better understand the design choices they make in response to the carbon footprint of their design, and it will give them experience with software they will use as architects and engineers.

The three programs utilized all provided different approaches to analyzing energy impact. Some approaches were more straightforward; others took much more effort up front to extract meaningful data. Tally, for example, required the largest quantity of input information by the user, but it also provided the most comprehensive results of the three programs. Although data input was erroneous, Tally was a straightforward process of defining variables. EC3 was dependent on Tally's data, thus it made the program difficult to use without first going through the process of analyzing the building in Tally; however, integration from Tally to EC3 involved only a few clicks. Athena's interface seemed visual at first, but it quickly turned into a numbers-only exercise. As an example, Athena needed total linear feet of interior partitions, which it did not derive from the model, so the process was inefficient. Data like this took time to estimate, and only a few of them were intuitive values like floor square footage or number of stories. Tally took the most time initially, but it also had the most developed user interface.

The programs all interacted with the BIM model's data to varying degrees. On the one extreme, Tally could only calculate what was fully defined in the Revit model – any extra materials or unique conditions had to be represented by a detailed BIM manifestation in the model itself. This was admittedly frustrating for a model that was only intended to reach a certain level of development. An example of Tally's strict adherence to the BIM model came in the window openings of the façade. Tally would not simply assume that the openings contained steel reinforcement at the headers of each opening, so it had to be retroactively modeled in Revit so that it could be calculated by Tally. On the other extreme, Athena had little to no integration with the BIM model. What was modeled in Revit became only a reference point for numerical data inputs in Athena. This meant that a less developed model could be input into Athena, but this also could easily reduce the accuracy of its results. Athena could have been utilized with a non-BIM 3D model such as one made in SketchUp or Rhino. EC3's reliance on material quantities from BIM fell somewhere in the middle. It needed precise material quantities from the model, but its categories to produce the output data were more broadly defined than Tally.

For the precision and time that Tally required to provide resulting data, it by far yielded the most extensive energy impact analysis. Its output included thorough graphical documentation packaged into an easily to understand PDF, though the amount of data was almost overwhelming. EC3 and Athena, on the other hand, only produced two meaningful visualizations each. The EC3 flow chart visualizations are elegant, but they lack numerical information. Athena's graphs and accompanying charts were informative, but the output was not nearly as exhaustive as Tally.

With this variability of data and precision, each program naturally works better for different settings than others. Overall, it seems that Tally is best used on a project that has been well-developed, with materials chosen, details modeled, and dimensions established. These parameters seem to best place it in a professional application rather than an education setting; its interoperability with BIM does, however, make it simple to modify as the project develops. EC3 can be used without Tally, but it seems optimized to work alongside Tally to produce results quickly. Athena's more basic interface makes it more cumbersome to use, and the input data requires additional calculation because Athena does not extract

BIM data like Tally and EC3. But it is because of this lack of BIM reliance that Athena can be used better with a less developed project, making it better suited for educational use or use earlier in the design phase.

Tally's ability to extract so much data from the BIM model paves the way for future programs to extract even more data from BIM. With current real-time update technology already compatible between Revit and several rendering programs, perhaps real-time updates can come to energy analysis programs such as the ones studied. This would enable evidence based decisions to be made during the design process rather than analyzing major design decisions retrospectively, such as which structural system was chosen. If the building industry wishes to continue its push towards de-carbonization, it will need to utilize such advanced tools to assess design decisions being made along the way.

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