Arch 598 – Life Cycle Analysis Seminar	Brian D. Rich #1363194
Assignment 7 – Life Cycle Analysis of Future-Proof Buildings	10 June 2014

Introduction

It is widely acknowledged that Carl Elefante coined the phrase "the greenest building is the one that is already built." (Elefante 2014) As a result of this, several recent studies on the environmental impacts of buildings and building construction have explored the short term impacts of renovating existing buildings. Examples include the 2012 study by the Preservation Green Lab titled "The Greenest Building: Quantifying the Environmental Value of Building Reuse," (Frey et al. 2011) and studies by Larry Strain of Siegel and Strain. (Strain 2014) These studies often focused on the immediate goal of carbon reduction and the resulting global warming impacts. However, because these studies have been limited to time scales of approximately 20 years, the true long term impacts of reuse if our built environment are not well developed. This research intends to begin to quantify the impacts of initial construction, periodic renovation, and regular maintenance impacts for reuse of a building.

GOAL AND SCOPE

The goal of this research is to compare the long term impacts of resilient construction with low cost, short service life construction observed in contemporary educational facilities. This study is based on the Lakota Middle School Gymnasium in Federal Way, WA which was renovated in 2009. See figure 1 through 3 for images of the renovated gym at Lakota. At the time of the project design, there was considerable discussion over the retention of the existing gym structure versus building a new gymnasium structure. The discussion was resolved based on the estimated cost of renovation versus new construction. However, there was the belief that retention of the existing building was a sustainable practice.

Figure 1: Exterior view of the gym at Lakota Middle School in Federal Way, WA. The existing concrete wall and wood framed roof structure of the 1950's gym was retained and renovated. The addition on the left is for locker rooms and ancillary spaces. Credit: Brian Rich, 2013.

Figure 2: The interior of the Main Gym at Lakota Middle School in Federal Way, WA. Credit: Brian Rich, 2013.

Figure 3: The interior of the Auxiliary Gym at Lakota Middle School in Federal Way, WA. Credit: Brian Rich, 2013.

This research could have been used by the Owner and Design Team to assist in the decision of which option to choose. This Life Cycle Analysis is intended for the internal use of the project team and is not intended to be used in comparative assertions. There are several sub-goals for this research:

1. This author proposes the concept of "first impacts." Similar to the concept of first cost in construction, "first impacts" are the environmental impacts of construction from extraction of raw materials to initial occupancy of the building. This research investigates "first impacts" versus long term environmental impacts of different building materials and techniques.
2. While wood materials have significantly less environmental impacts in the short term (20 to 40 years), how does this compare to more durable materials over the long term (200 to 1000 years)? And how does this compare to wood structures when biogenic carbon is not taken into account due to the long time period to be studied?
3. Wood and light gauge metal building materials are anticipated to have shorter service lives compared to brick, steel, and concrete due to the rapid deterioration of the material. What are the environmental impacts of shorter life span materials (and thus anticipated higher frequency of replacement) compared to longer life span materials?
4. Do buildings that are typically considered to be more future-proof (or resilient), such as steel and concrete construction, have more or less environmental impact on the Earth than ones considered to be less resilient?
5. What might these conclusions suggest with regards to the existing built environment in general and historic buildings in particular?

FUNCTIONAL OR DECLARED UNIT

The declared unit in this LCA is one 12,150 square foot Middle School gymnasium including a main gym and an auxiliary gym. The gym building consists only of the athletic spaces (a main gym and an auxiliary gym) and excludes the locker rooms, offices, storage, lobby, and other related spaces. The study will also exclude mechanical, electrical, plumbing, fire sprinkler, alarm systems, and exterior site features. The above features are not included in the models to maximize similarity and simplicity of the models.

SCOPE OF THE STUDY

This study proposes to begin with new construction for each of the four gymnasiums and track the impacts of a 200 year period of time. The study utilizes the Athena Impact Estimator for Buildings, version 4.5.0102 to model the buildings. The proposed wood gym is also analyzed using Athena Impact Estimator version 4.2 which did not include biogenic carbon in the calculations to understand the impacts of biogenic carbon sequestration in wood construction better. This gym is referred to as Gym A1. Athena Impact Estimator is "a whole building, life cycle based environmental assessment tool that lets building designers, product specifiers and policy analysts compare the relative environmental effects or trade-offs across alternative building design solutions at the conceptual design stage…. …[Athena] evaluates whole buildings and assemblies based on internationally recognized life cycle assessment (LCA) methodology" (Athena: Introduction)

It will include maintenance and replacement cycles for each building appropriate to their planned service lives and material selections. Both minor and major renovations are anticipated by the Athena calculator and are planned to double the actual service life. Further, only the total impacts for the service lives calculated are considered in this analysis. Impacts of individual phases of the life cycle are not included in this analysis.

The literature describing the Athena Software indicates that the following life cycle phases are accounted for in this model:

- Material manufacturing, including resource extraction and recycled content
- Related transportation
- On-site construction
- Regional variation in energy use, transportation and other factors
- Building type and assumed lifespan
- Maintenance, repair and replacement effects
- Demolition and end-of-life disposition
- Operating energy emissions and pre-combustion effects (requires input from another model)

In order to accurately model “first impacts” (as opposed to “first cost”), the data is extracted from each model with a 1 (one) year service life, intended to represent initial construction. Since Athena includes maintenance, repair, and replacement impacts for the systems involved, the buildings are modeled again with their anticipated service life (20, 50, and 100 years, and a third time with double service life (40, 100, and 200 years).

It is not clear whether Athena incorporates major renovations at intervals within the service life of the buildings or whether buildings are simply demolished at the end of their service lives. For the purposes of this study, limited service lives are anticipated based on the authors experience as an architect. New buildings are anticipated to be built at the end of the 200% service life anticipated. Building impact data can be modeled at 50%, 100%, and 200% of anticipated service life and the data extrapolated to determine if the “maintenance, repair, and replacement effects” are linear. This data is then evaluated for the impacts of major renovations assumed to occur at the end of the anticipated service life.

LIFE CYCLE ANALYSIS DIAGRAM

See LCA diagram below for an illustration of the LCA process analyzed for this project.

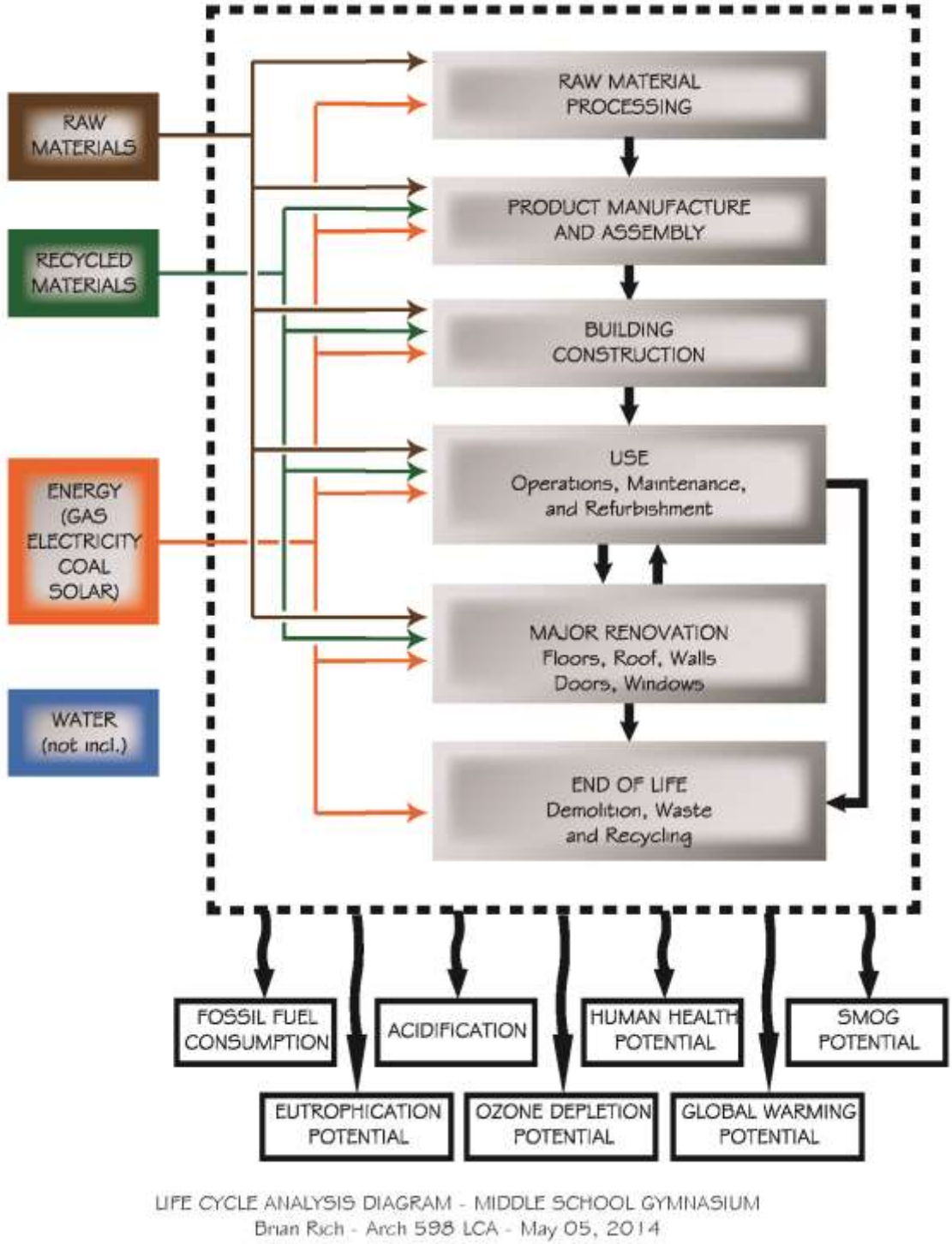

Figure 4: The basic life cycle phases included in this analysis are illustrated here. Credit: Brian Rich, 2014.

As Figure 4 illustrates, the intent of the use of Athena for the Analysis is to include all phases of the life cycle from cradle to grave for raw material extraction, manufacturing, building construction, occupancy, and end of life. Figure 10 details which phases of the life cycle are included in the scenarios analyzed. One notable exclusion from the analysis is the use of water in all of the life cycle stages of the building's service life. To be clear, however, Athena, by default, includes impacts on water in the impact analysis.

This LCA study uses the 7 summary environmental impacts as output from Athena as the basis of comparison. Raw impacts are not used in this analysis. The summary environmental impacts include:

- Fossil fuel consumption (MJ)
- Global Warming Potential (kg CO2 eq)
- Acidification Potential (kg SO2 eq)
- Human Health Particulate (kg PM2.5 eq)
- Eutrophication Potential (kg N eq)
- Ozone Depletion Potential (kg CFC-11 eq)
- Smog Potential (kg O3 eq)

Default allocations for environmental impacts from Athena are accepted as baseline criteria for this LCA study and are not altered. Two default allocation techniques are worthy of note in this analysis. First, Athena does account for end of life recycling of steel building components (structural and reinforcing steel). Similar end of life allocations to recycling for other buildng materials are not applied despite potential recycling rates over 95% for some projects.

The second allocation technique worthy of note in this analysis is for biogenic carbon. Biogenic carbon is the carbon that is sequestered in a wood product as the natural material grows in the forest and a tree converts CO2 through the photosynthesis process. As noted elsewhere, a comparison of Gym A and Gym A1 endeavored to determine the effects of biogenic carbon sequestration in wood materials for the life of the wood. While this does not affect the data in most environmental impacts, Global Warming Potential (GWP) is higher when biogenic carbon is not taken into account. This result is noteworthy to this analysis because of the time span analyzed for the buildings. See Figure 5. A 200 year service life is a sufficiently long time that the vast majority of wood products have completed their life cycle and released the carbon that was sequestered in the material. Thus the beneficial effects of the carbon sequestration are negated.

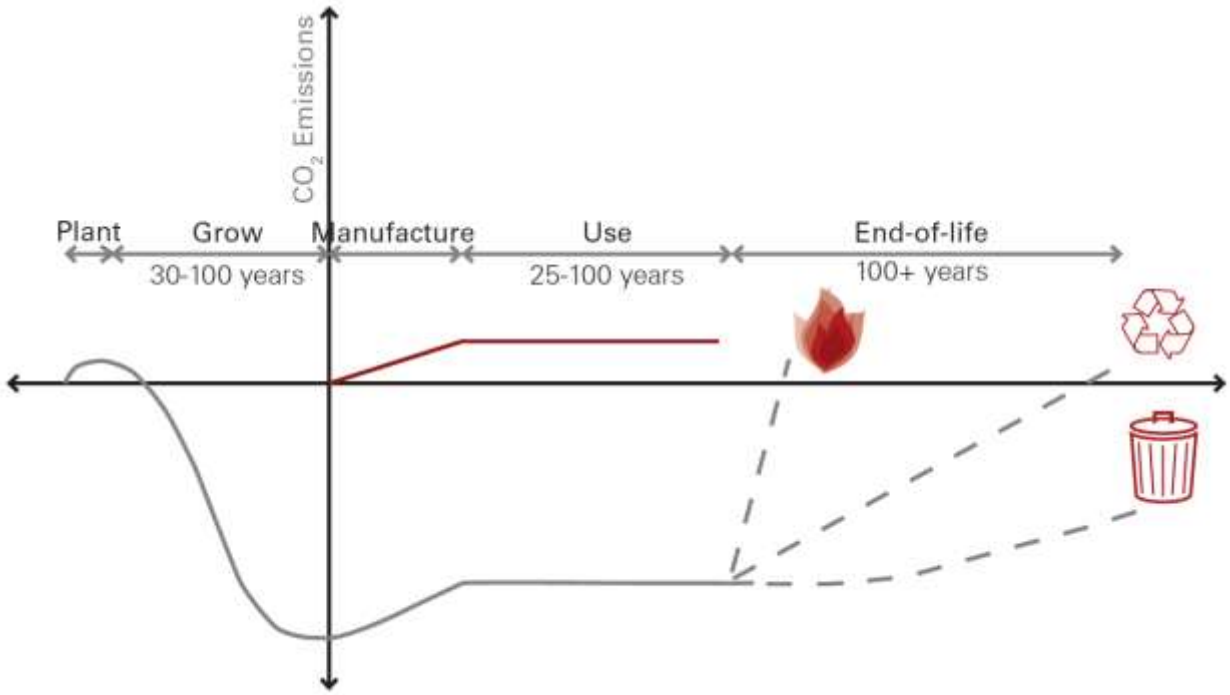

Figure 5: A time chart of the biogenic carbon sequestration and release in wood products. Carbon is sequestered prior to harvesting timber. Once harvested, additional emissions increase through fabrication and transportation, but are eventually released. Credit: Kathrina Simonen, 2014.

This LCA has not been reviewed by a critical review panel. This LCA is intended to comply with the requirements of ISO 14040, and would be ISO compliant pending the completion of critical review.

This LCA study could be improved in multiple different ways. Inclusion of water use in the analysis would be beneficial. Adjustment of power sources for specific locations for the project, travel distance of raw and recycled materials to manufacturing plants, travel distance from manufacturing plants to the building site, and a clearer outline of the use/maintenance/renovation cycle could also be specified, rather than accepting baseline information from Athena. The capability of understanding the service life of a particular material in the model versus a building system versus the entire building would be very beneficial to understanding the impacts of short service life materials in the replacement of an entire building system. The essence is that the chain is only as storng as the weakest link, and if one component of a building system has a significantly shorter service life, this can impact entire building systems and perhaps the building as a whole. In addition, there are several ways in which the modeling capabilities of Athena may be improved. See Appendix A for examples of challenges modeling the gymnasia in Athena.

LIFE CYCLE ANALYSIS - INVENTORY

The building inventory was developed by modeling the four gymnasiums in Athena Impact Estimator. The scope of the research is a comparison of the long term impacts of four gymnasiums of differing construction types and anticipated service lives. All three gymnasiums are the same configurations: 135'x90'x30' high. The gym is divided into two parts by a bearing wall such that there is a 90'x90' Main gym and a 90'x45' Auxiliary gym. Foundations were kept identical between the three models due to limitations in the software. A summary table of the building systems follows at the end of this section. However, briefly, the design of the four gymnasiums may be described as follows:

Gym A is intended to represent a low first cost gym with a 20 year service life. It is planned to have a painted 4" concrete slab floor, dimensional wood lumber walls with batt insulation and wood siding, wood columns, beams, and roof structure with asphalt shingles. Gym A1 is modeled the same as Gym A, except that the data was run through Athena version 4.2, rather than 4.5. The distinction is that Athena version 4.2 does not account for biogenic carbon. Due to the long term duration of the buildings in this study, biogenic carbon is considered to be neutral and not a major contributor to decreases in environmental impacts.

The gym at Lakota Middle School is an excellent example of the roof framing for Gym A and A1. See Figures 2 and 3 above.

Gym B is also anticipated to have a low first cost with a 20 year life span. However, this gym is designed with a 4" slab on grade floor, metal panel walls and sub-girts with batt insulation and painted drywall, steel columns and truss structure, and metal truss roof structure with asphalt shingles.

Figure 6: The gym at Skyline High School in Issaquah, WA, is an example of the metal framed roof structure in Gym B and C.

Gym C is typical of contemporary gym construction representing a mid-level first cost with a 50 year service life. It is designed with an 8" concrete floor slab representing a recessed slab plus topping and a wood floor, CMU walls with metal stud furring, batt insulation and drywall finishes, steel column and

beam structure with an EPDM membrane roofing system. The gymnasiums at Shorewood High School in Shoreline, WA, and Skyline High School in Issaquah, WA are examples of this type of design.

Figure 7: This gym is typical of the exterior CMU wall construction for Gym C. Note that the brick facing on the right edge of the photo is not included in Gym C.

Figure 8: The Gym at Shorewood High school in Shoreline, WA is an example of Gym C construction. The main volume of the gym has CMU exterior walls and metal roof structure. The brick section at the left houses ancillary spaces not included in this LCA analysis.

Gym D is intended to be a resilient/future-proof structure representing upper level first cost and a 100 year service life. It is designed with an 8" concrete floor slab representing a recessed slab plus topping and a wood floor, brick clad concrete walls with metal stud furring, batt insulation and stucco plaster finishes, steel column and beam structure with a composite concrete and metal roof deck and 4 ply modified bitumen membrane roofing system. See Figure 9 for an example of this type of construction.

Figure 9: The Gym at Elon University is a typical example of Gym D construction with concrete structural walls, brick, and stone facing.

The following table summarizes the key features of each gymnasium design:

200 Year Comparison				
Gymnasium Building Systems Summary				
	Gym A & A1	Gym B	Gym C	Gym D
General Description	"Wood" Gym	"Metal Siding" Gym	"Steel + CMU" Gym	"Concrete" Gym
Foundations & Footings	36"Wx16"D strip footing	36"Wx16"D strip footing	36"Wx16"D strip footing	36"Wx16"D strip footing
Floors	4" slab on grade + 2" Extruded Polystyrene Insulation + Polyethylene vapor barrier	4" slab on grade + 2" Extruded Polystyrene Insulation + Polyethylene vapor barrier	8" slab on grade + 2" Extruded Polystyrene Insulation + Polyethylene vapor barrier	8" slab on grade + 2" Extruded Polystyrene Insulation + Polyethylene vapor barrier

Columns & Beams	Glu-lam columns & beams	Hollow structural steel columns + wide flange steel beams	Steel wide flange beams and columns	Concrete columns + steel beams
Wall Systems	Beveled cedar siding + air barrier + 1/2" OSB sheathing + 2x8 wood stud framing + R-21 Batt Insulation + painted drywall	Metal siding + air barrier + OSB Sheathing + gypsum sheathing + 8” metal studs +R-30 batt insulation + painted drywall	12" reinforced CMU + 2x6 wood stud furring + R21 batt insulation + painted drywall	Single wythe brick facing + 8" reinforced cast in place concrete + 6" metal studs + R-20 batt insulation + stucco over metal mesh
Windows & Doors	1500 SF of Vinyl double glazed argon filled windows + 18 Half glass steel doors	1500 SF of PVC double glazed argon filled windows + 18 Half glass steel doors	1500 SF of aluminum clad wood framed triple glazed argon filled windows + 18 Half glass steel doors	1500 SF of aluminum clad wood framed triple glazed argon filled windows + 18 Half glass steel doors
Roof System	20 year asphalt shingles + 15lb roofing felt + OSB sheathing + R-50 batt insulation + Vapor barrier + painted drywall	EPDM roofing membrane + 8" polyisocyanurate insulation + gypsum fiber board + metal decking + Open web joist + alkyd paint	EPDM roofing membrane + 8" polyisocyanurate insulation + gypsum fiber board + metal decking + Open web joist + alkyd paint	Mod-bit roofing membrane + 8" polyisocyanurate insulation + gypsum board liner + composite concrete and metal deck + alkyd paint

See Appendix A for challenges with the use of Athena to model the impacts of gymnasium construction. Many of the systems noted above are awkward in their construction due to limitations in Athena to model realistic building systems.

MAINTENANCE AND REPLACEMENT CYCLES

Athena was also used to model the individual impacts of building components that would need to be replaced on a regular cycle so as to simulate the ongoing maintenance and renovations over the lifespan of the building. The results of this study subtracted first impacts from total 200 year impacts to discover the maintenance and replacement impacts over the 200 year service life that was assumed for the buildings.

Building components often included in regular maintenance cycles include:

1. Roofing systems (asphalt shingles, EPDM, and modified bitumen)
2. Insulation systems (roofing insulation is replaced with roof replacements)
3. Interior and exterior paint finish systems
4. Flooring materials
5. Exterior wall cladding systems
6. Windows
7. Interior wall materials (drywall and plaster)

Not surprisingly, the top replacement contributors are roofing, siding, and windows, as exemplified in Figure 10. This is a relatively consistent result regardless of the gym construction type or material quantity versus mass value, with the exception of Gym D. In Gym D, the brick facing is not considered required to be replaced over a 200 year life span. One might also conclude that the higher mass materials are also more durable and thus have a lower replacement frequency.

However, the maintenance regime in Athena is not transparent and thus it is unclear what materials are considered to require maintenance versus replacement at the end of the component's life cycle. Nor is it clear what impacts maintenance has on the overall life cycle of the structure. Further, it is not clear what impacts removal of a material that has reached the end of it's service life has on the remainder of the building. For instance, does removal of wood siding have an impact upon the weather barrier that may wrap the building?

In addition, Athena assumes that building systems include certain components which are not clearly delineated in the system descriptions. For example, built-up roofing systems include ballast rock, as discovered in this analysis. The ballast rock was discovered when it rose to the top of the material replacement list during the maintenance analysis. The roofing system was revised to provide a more common modified bitumen roofing system.

This analysis also found that maintenance cycles included in Athena are for a specific use of a material. For example, since wood flooring was not available as a material for the interior gym floors, gyms C and D were modeled with tongue and groove wood siding as a flooring component. While this material was not an exact match to the sprung maple flooring systems typically used, this was believed to be an approximate match. However, no warnings were displayed that this was an inappropriate material or use of material in ths application. Data extracted from the model was thus severely distorted and required recalculation.

The maintenance and replacement calculations revealed that interior finish materials rarely appeared in the maintenance cycle calculations. The most common materials found to be replaced were siding, roofing and windows. These were closely followed by wood siding materials. The 200 year comparison of replacement materials in Gym A1 is typical of the results. In Figure 9, is is clear that the wood siding

of the gym was the dominant material replaced by material quantity. While the figure is not adjusted to accommodate different units for material quantities, it is indicative of the types of materials that commonly appeared on the material replacement lists.

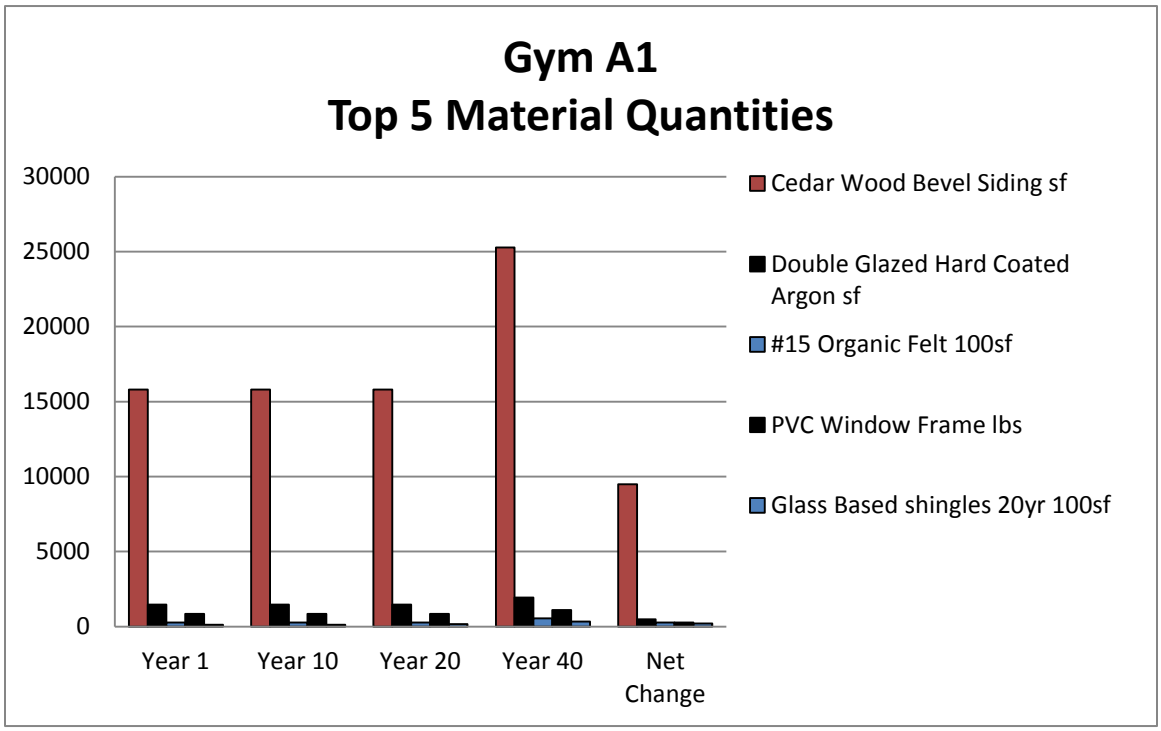

Figure 10: 200 Year Comparison – Gym A1 - Top 5 Material Quantities with the largest net change (maintenance or replacement).

ENVIRONMENTAL IMPACTS

Environmental impacts may be studied under several different scenarios to develop appropriate responses to specific situation within the built environment. Four scenarios are envisioned in this analysis. Figure 11 diagrams the four different scenarios.

Scenario 1: First Impacts of New Construction

The first scenario analyzes the environmental impacts of the construction of a new gym from raw materials to completion of construction. This analysis focuses on the first impacts of new construction and does not include any operation or maintenance impacts.

Scenario 2: Operations and Maintenance Impacts

The second scenario analyzes maintaining and operating an existing gym for 200 years. In this scenario, all five gym designs are to be maintained and operated. The first impacts are considered sunk impacts that cannot be recovered or avoided. The intent of this scenario is to compare the operating impacts of the different gyms and their respective environmental impacts. The graph below characterizes the impacts of the gym designs

Scenario 3: Combined Total Impacts (First Impacts and Maintenance Impacts)

The third scenario analyzes the total environmental impacts of constructing a new middle school gymnasium on an undeveloped site, including all new materials and site work, and operating and maintaining it for 200 years. This analysis includes first impacts as well as maintenance and replacement impacts. Further, this scenario assumes that Gym A, A1 and B have a 40 year life, including regular maintenance and material replacement, and then is demolished and a new gymnasium is built. Similarly, this scenario assumes that Gym C has a 100 year life including regular maintenance and material replacement, and then is demolished and a new gymnasium is built. Last, this scenario assumes that Gym D has a 200 year life and is not replaced. The intent in scenario one is to compare the environmental impacts of shorter service life structures to those of more durable longer service life materials.

One hazard with this scenario is that the building is only as good as the weakest portion of the design. Often this weak link in modern construction is sealant or roofing systems. These elements can deteriorate and cause more rapid deterioration of even more durable building material products and systems.

Scenario 4: Total Impacts – New Wood vs. Maintenance of Metal, Masonry, or Concrete

The fourth scenario includes replacement of an existing gym versus ongoing operation of the existing facility. Further it supposes that Gym A or A1 are proposed for the replacement due the low first cost of construction and that they will be maintained and operated for 200 years rather than being replaced every 40 years. Gym B, C, and D are assumed to be maintained and operated for another 200 years. The first impacts are considered sunk impacts that cannot be recovered or avoided. Environmental impacts are then evaluated for a period of 200 years.

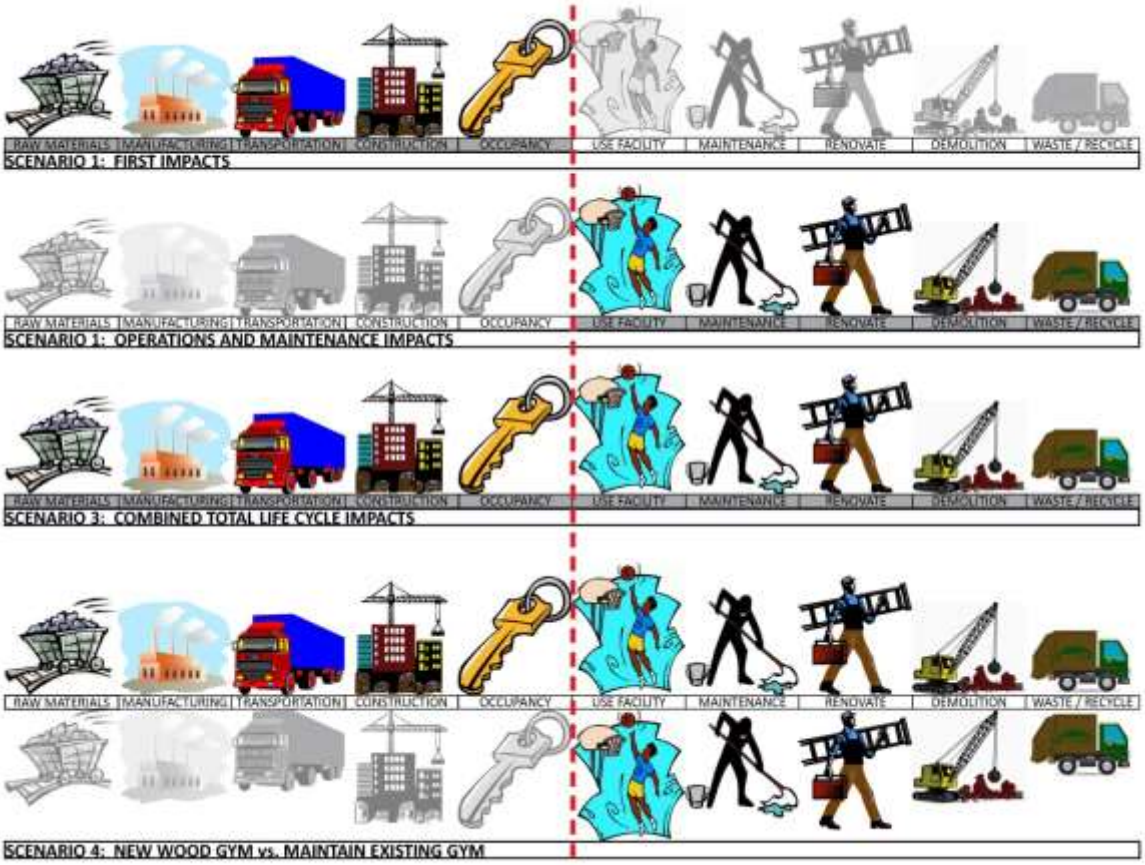

Figure 11: Life Cycle Analysis phases are diagrammed here for each of the four different scenarios analyzed in this LCA study. Credit: Brian Rich, 2014.

INTERPRETATION

In this section, the results of the data provided by the Athena models are interpreted. However, there are a few appropriate notes about the data that was extracted that are important.

First, each of the three gyms was consistently modeled in terms of size and functions within the building, therefore the data should also be consistent. The one intentional exception to this is Gym A1 which was modeled in Athena 4.2 rather than Athena 4.5 in order to assess the impacts of biogenic carbon.

Second, the models varied in terms of the materials used. This is a deliberate variation in order to study the environmental impacts of different building systems.

Third, this study makes certain assumptions about the predicted service life for the entire building. Due to assumptions within Athena, this may lead to errors since the assumptions made in the spreadsheet calculations were based on author defined service lives for each building rather than the service lives included by Athena. The data produced by Athena should also be timely as the most recent update to the software was less than 1 year prior to the analysis.

Last, Athena is a good tool for use for projects in the Seattle area because of the location specific data available in its calculations. What could be better explained are the effects of data location on the model. For example, does location affect the energy mix used in the analysis?

The major contributors to the environmental impacts of the buildings modeled are readily split into two categories: first impacts versus maintenance and replacement impacts. As predicted prior to the study, building materials with higher levels of durability also have significantly higher first impacts. For example, the environmental impacts of making and installing concrete, steel, and CMU materials are higher than that of wood materials. See Figure 12. In Figure 12, the normalized data for First Impacts clearly indicates that Gym D has the highest environmental impacts in most categories. Gym A and A1, the wood structures, have the lowest first impacts.

Conversely, the maintenance and operations impacts of lower durability materials, such as metal siding and wood, are higher than the impacts of high durability materials, such as concrete, brick, and structural steel. See Figure 13. It is interesting to note that while Gym D, built of concrete and brick, has the least impact; the highest impact is actually that of Gym B with metal siding and an EPDM roof. Wood structures, with or without biogenic carbon, have varying impacts.

When the environmental impacts of maintenance and replacement are considered with first impacts for each gymnasium, a complete picture of the 200 year environmental impacts are formed. See Figure 14. This figure demonstrates the significant variability in the overall environmental impacts of each gym type. While gym A and A1 (wood) continue to demonstrate the lowest overall impacts, the other gym designs show mixed results.

The results of the LCA analysis are more favorable for buildings of higher durability materials, such as Gym D, when one is considering replacement of an existing gym with a new wood framed structure. Here, the impacts of the higher durability materials are shown to pay off. See Figure 15.

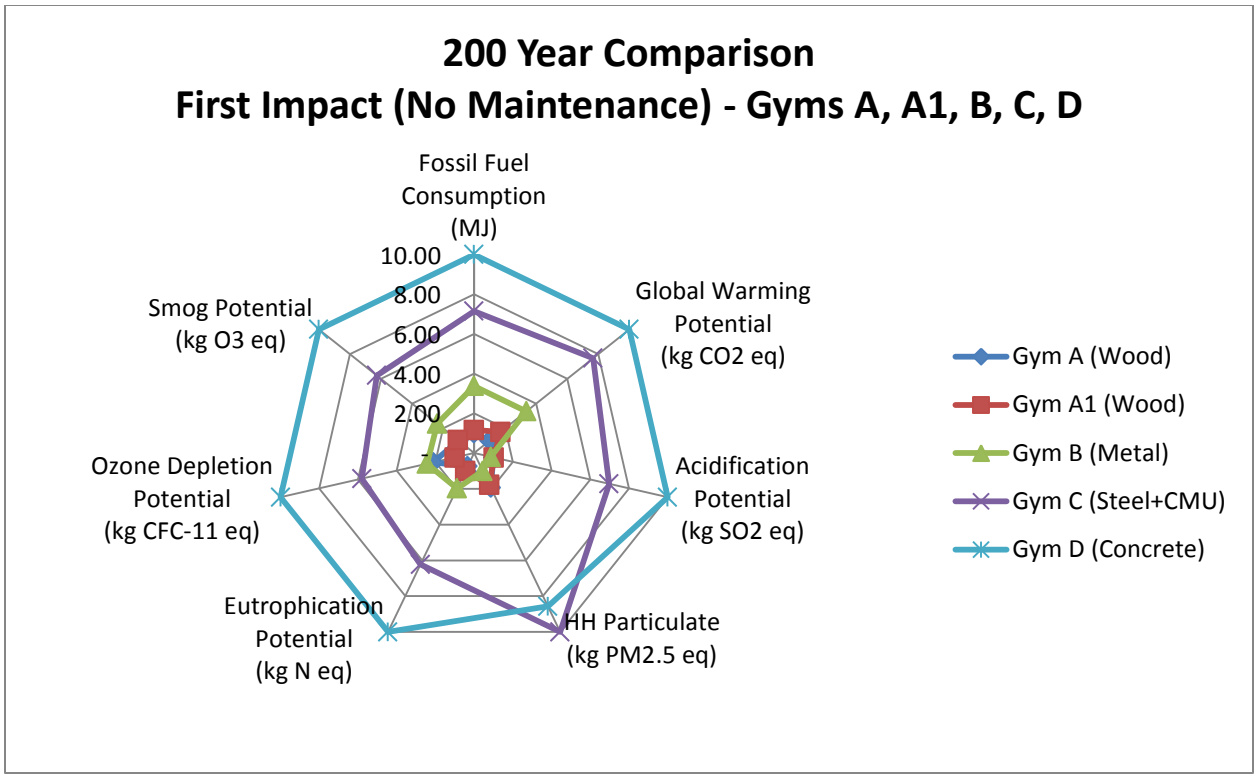

Figure 12: First Impact Comparison, normalized on a scale of 10. Note that the buildings involving masonry and concrete (Gym C and D) have the most significant first impacts and wood (A and A1) the least.

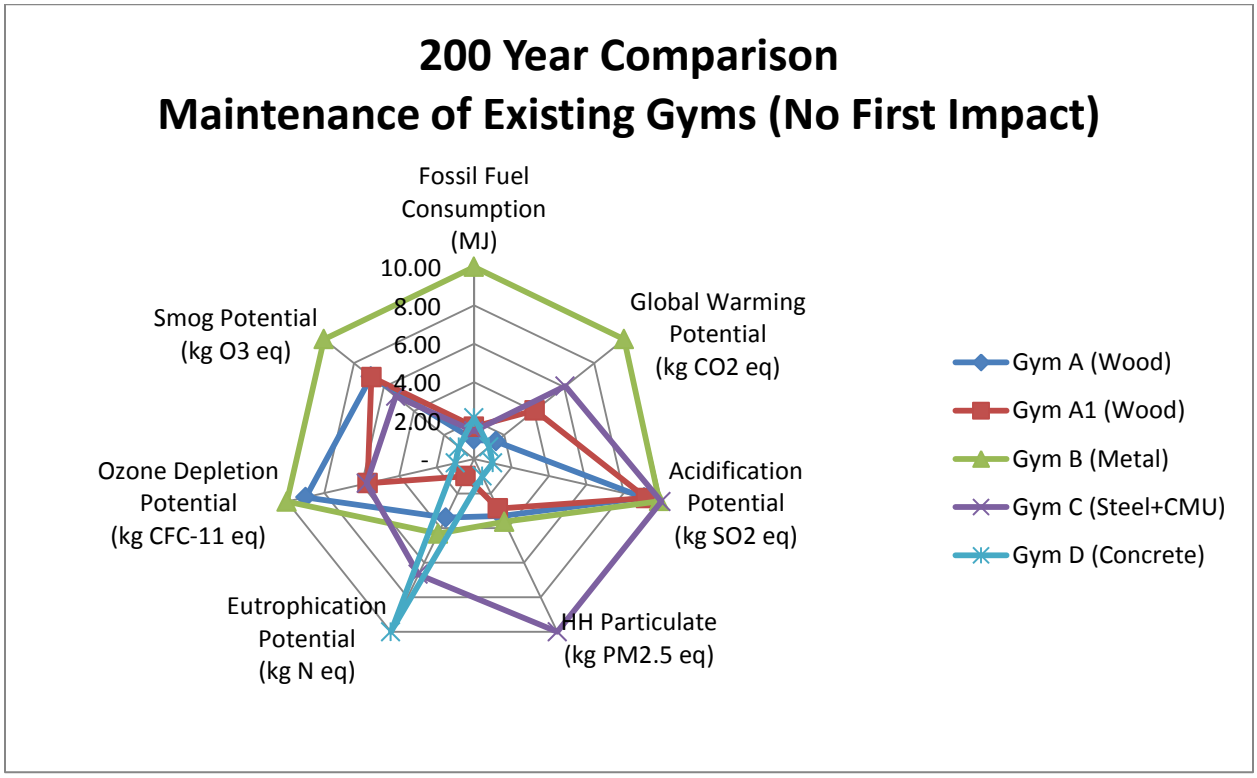

Figure 13: 200 year comparison of maintenance requirements, not including first impacts, normalized on a scale of 10. Note that the Gym D has the least maintenance impact in most categories and Gym B has the largest impacts in most categories.

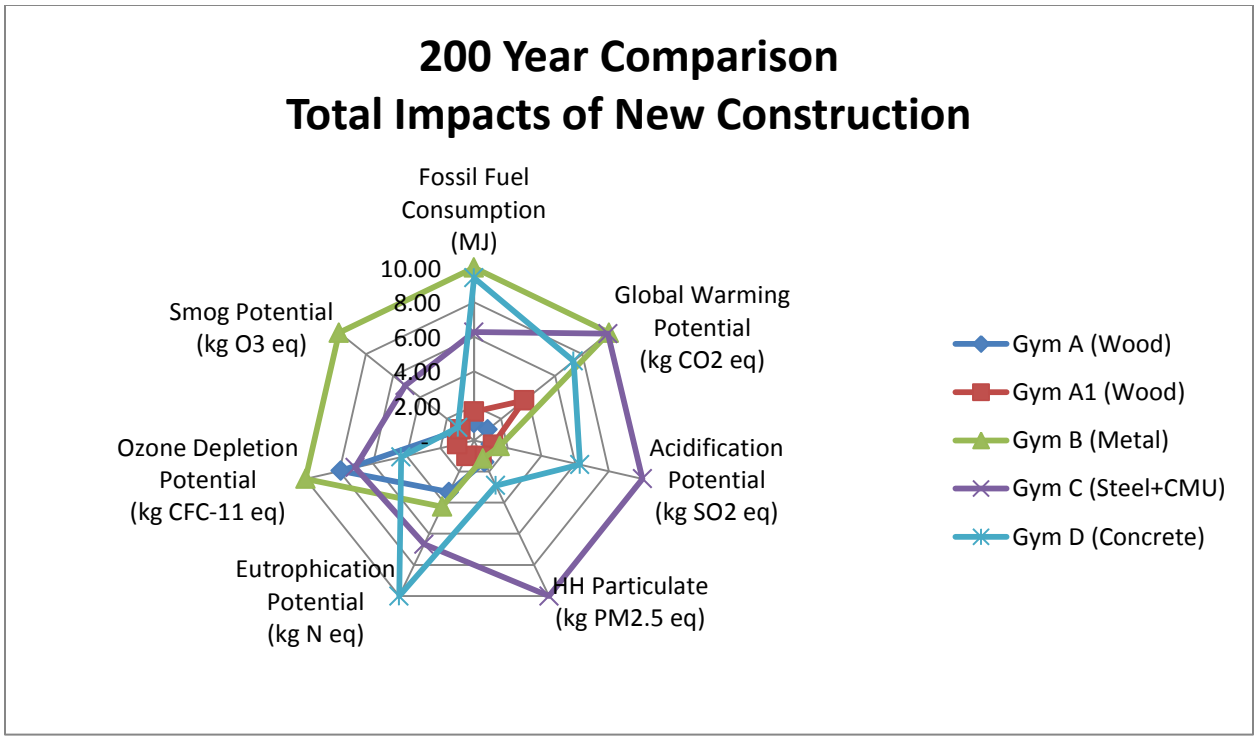

Figure 14: 200 year comparison of total environmental impacts including first impacts and maintenance, normalized on a scale of 10. Gym B and C typically have the largest impacts while Gym D has mixed total impacts and Gym A and A1 the least total impacts.

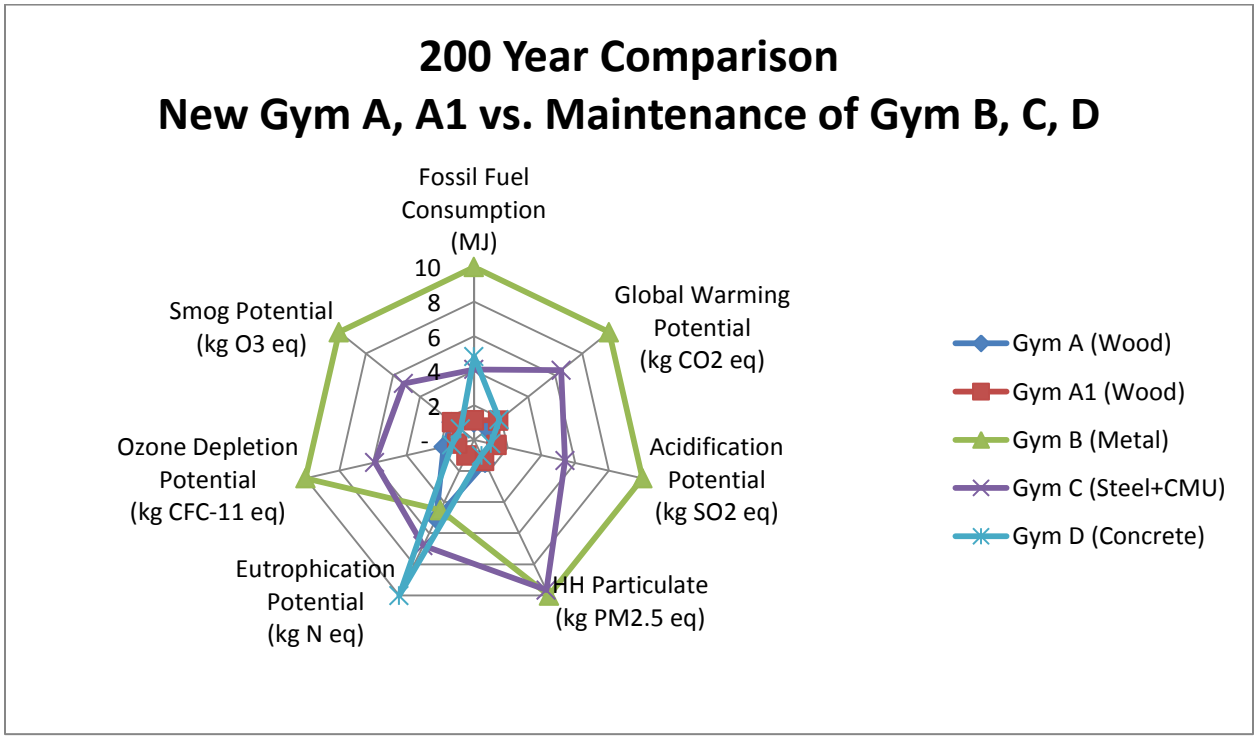

Figure 15: 200 year comparison of total environmental impacts, normalized on a scale of 10. This answers the question: If I am considering a new Gym, should I build a new wood gym or continue to maintain my existing concrete or masonry one? Note that there are many respects in which Gym A and A1 have lower impacts, Gym D has moderate impacts, and Gym B and C have the largest impacts.

ERROR ASSESSMENT

MATRIX OF POTENTIAL ERROR SOURCES IN LIFE CYCLE ANALYSES			
LCA Stage	Random	Choice	Ignorance
Activity Data	Errors out of the control of the modeler that create different activities	Modeler selects a particular scenario which includes specific activities	Modeler is unaware of what activities the model includes
LCI Data	Errors out of control of the modeler that create erroneous data	Modeler selects data for the model that is erroneous	Modeler is not aware that the data is erroneous
Model	Errors in building the model that create erroneous data	Modeler selects options in the model that create erroneous data	Modeler is unaware of correct options in the model building process

As the matrix above suggests, there are multiple potential ways in which uncertainty and error can be introduced into an LCA model. Random errors can occur at any time and are difficult to diagnose. Choice errors are often made when the modeler is not aware of or able to make the correct choices in the analysis. Ignorance usually occurs with a new user of a modeling tool who does not understand the way the models are intended to be built.

In the course of this Life Cycle Analysis, there is definite potential for errors in the Activity Data or the LCI data used to model the gymnasia. Because the Athena Impact Estimator was used to model the different gym designs without critical analysis of the data behind the analysis, errors in these two areas are unknown at this time and would be a welcome part of a critical review. Some of the potential sources of these types of errors are discussed in the interpretation section above and Appendix A. Errors in Athena and/or the data used in Athena's calculations are consistently accepted and no adjustments have been made for them in this analysis.

Modeling errors have been identified and deleted as much as possible in this analysis. Examples of errors include inappropriate use of materials and ignorance of the materials included in default building systems. In the course of modeling this project, incorrect materials were included in order to simulate certain anticipated features of a real building design. For instance, ballast rock was included as a building component under the floor slabs because no other aggregate base was indicated in the standard building systems. Similarly, tongue and groove wood siding was modeled as a floor material because maple flooring for the gyms was not available. Both of these errors were discovered through the examination of the Bill Of Materials analysis for the materials that had high impacts due to high replacement rates.

Additional errors areintroduced due to limitations in the building software. For example, the actual amount of wood for the roof beams in Gym A is known to be modeled incorrectly because the model limits the span of wood beams to 45 feet. The actual span across the gym is 90 feet. To mitigate this effect, the roof was modeled in two 45 foot wide sections. However, this does not truly reflect the impacts of the roof because to complete the 90 foot roof spans in one beam requires a significantly larger beam section than for a 45 foot span. These errors fall under the category of Choices in the Modeling of the building.

Modeling errors have also been introduced due to ignorance of the modeler regarding the actual components included in a building system that was selected for the model. For example, in Gym B, OSB sheathing and gypsum sheathing are included because it was not clear that the wall system selected included sheathing. This error has not been corrected in the model.

Random errors in the model are always a possibility in the course of the data entry and transfer to additional spreadsheets for calculations. In this Life Cycle Analysis, the output spreadsheets from Athena were heavily manipulated to extract meaningful data and to develop information. In the courseof this manipulation, 68 separate spreadsheets, 32 graphs and numerous tables are used to calculate and convey the information. Minor errors in the data transfer, formulas, or graphing techniques may have also introduced errors into the results.

CONCLUSIONS

Several conclusions may be made based on this Life Cycle Analysis:

1. The concept of "First Impacts" is introduced in this research and reflects the environmental impacts of new construction from raw material extraction to occupancy of the building. As anticipated, "first impacts" are greater for steel and concrete structures than for wood structures.
2. Prima facie evidence suggests that wood structures are a more sustainable building alternative when considering new construction. This is true not only in the shorter 20 year term, but also in the 200 to 1000 year term as well when starting with new construction, regardless of how biogenic carbon is counted. Ripple effects of a shift to a wood-based construction economy are unknown, though, and may outweigh the benefits of this building system. Significant ripple effect impacts may include wildlife habitat loss and reduction in the capability of the planet to convert CO2, thus increasing global warming potential.
3. When considering existing buildings, first impacts are "sunk costs" and may be disregarded. The evidence suggests that ongoing maintenance and operation of existing structures with higher durability and quality have comparable environmental impact to new wood construction. With the potential for durable construction to last beyond 200 years, the impacts may be lower than wood construction.
4. Biogenic Carbon affects only one environmental impact criteria: Global Warming Potential (GWP). When the benefits of the sequestration of carbon in wood materials are not included due to the relatively short life span of wood materials, wood materials still have less environmental impacts than steel and concrete materials (Gym A1).
5. Durability of all components of a building system should have equivalent service lives or allow for disassembly in order to maintain the shorter service life materials. This allows retention of materials that have longer service lives rather than disposing of them when removed to perform maintenance.
6. Though not clearly indicated in this study, proper maintenance of a building is critical to long term service life. Maintenance prevents deterioration of less durable materials and can significantly affect the service life of a building. (Grant, Ries, and Kibert 2014) In this research, light wood framing and metal siding systems are assumed to have shorter design service lives due to the potential for rapid deterioration in the absence of a rigorous maintenance program.
7. Historic buildings have value that go beyond the environmental impacts of their materials and construction. The data in this analysis should be noted as a strictly numerical analysis. There are significant aspects of existing and historical buildings that have value beyond the environmental impacts, including the social, cultural, economic, and aesthetic value. Enduring buildings form the core identity of many places and provide stability and increased personal and community resilience because of the way people identify with their "homes."

FOR FUTURE RESEARCH

There are several ways in which future studies can be improved to understand the benefits of reuse of the existing built environment better. Future studies should include the impacts of operational energy in order to establish the total impacts of buildings over their extended service lives. In this instance, the goals of reducing energy consumption would necessarily need to be estimated and the designs adjusted accordingly.

As discussed above and in Appendix A, the limitations of the Athena modeling software are numerous and can significantly impact the data extracted from the model. This is demonstrated through erroneous calculations using materials in inappropriate ways and distorting the impacts, such as ballast rock used under a floor slab and wood siding used to approximate floors. In both cases, impacts were seen in the maintenance and replacement of these materials which distorted their impacts significantly when considering long term service lives.

In addition, the limitations of the Athena modeling do not allow truly accurate modeling of the building. More data is needed to represent the actual building designs better. More options would allow for more flexibility with how materials are used and may allow better representation of the

The changing nature of building materials should be allowed for in the building model. Asphalt roof shingles may have up to 50 year lives now, compared to the 20 year materials allowed in Athena. Whereas softwoods have significantly shorter lives since we are using second and third growth timber which is of significantly lower quality. Modern wood shake roofs deteriorate within 10 to 15 years whereas old growth shingles could last for 50 years or more. It is not clear what service lives are allowed for in Athena for wood, so it is not clear how to account for old growth timber used in historic structures.

The buildings modeled in this analysis do not include significant efforts to incorporate sustainable design strategies. This is an area of significant potential additional research as it would include major portions of the operational aspects of the building. One may be able to argue that one could add insulation or a photovoltaic array to any building to make it perform better. However, there are significant differences in the way in which each mode of construction responds to regional environmental issues and which may result in recommending a particular type of building in a particular region of the world.

Last, total project cost over the life of the buildings would be an interesting area of further research. One could argue that repetitive demolition and reconstruction of a facility would repeatedly provide jobs inboth on site construction as well as the process of making the building materials, and thus stimulate the economy. However, from the point of view of the building owner, a lower total project cost over a 200 year service life is likely a more imporant consideration and may result in recommendation of a particular construction type.

APPENDIX A – LIFE CYCLE INVENTORY AND LIMITATIONS OF THE MODEL

Below are listed the typical building elements for which environmental impacts have not been able to be determined. Limitations on the Life Cycle Inventory data are based on the limitations of the Athena Impact Estimator. Theoretical buildings were modeled witin the limitations of the software.

1. Project Limitations
    a. The exact location of the building was not available. Seattle was used as the closest location to Federal Way, WA. Federal Way is about 24 miles south of Seattle.
    b. Educational Building Types were not available. Institutional building type was used due to the similarity of the structures.
    c. Operating Energy Consumption was not used in order to reduce the complexity of the model.
    d. This model includes regular maintenance cycles for selected components of the building model and does not includes the impacts of deferred maintenance nor the impacts of all building components.
    e. This model does not account for the impacts of natural disasters which negate the benefits of longer service life buildings. However, given a longer service life in the design of the building, it is reasonable that the Design Team would also assume that higher risks/more severe natural disasters would be accounted for in their designs.
2. Building Components
    a. Foundations
        i. Foundations were limited to strip footings around the perimeter of the building due to the software limitations. Modeling for spot loads under columns was not possible, so the footing rebar was adjusted to compensate.
        ii. The concrete floor slab was limited to either 4” or 8”. 4” was used to represent the 20 year gym and 8” to represent a thicker floor slab plus 2” of concrete leveling that is commonly observed under wood sprung floor construction.
        iii. Due to limitations of the software, the rubber floor system for the 20 year gym is not included.
        iv. The wood floors typically seen in a longer service life gym are represented by wood siding and do not accurately reflect the wood sprung floor system nor the Maple wood typically used.
    b. Walls
        i. Walls are selected to represent typical construction techniques, but may not reflect actual construction techniques. For instance, 30 foot tall wood framed walls of the 20 year gym are not realistic, but most closely represent 20 year construction methods.
        ii. The design of each of the wall systems is intended to reflect contemporary design requirements for energy code (R-21 insulation value).
        iii. Window types are severly limited. While vinyl windows are acceptable for a 20 year gym building, the 50 and 100 year buildings are modeled with aluminum clad wood windows, the closest building component to the extruded aluminum commercial storefront systems, Kal-wall and other systems often used for contemporary window openings.
        iv. Window types are also limited to one type of window opening, total area and quantity of openings. This does not allow for the realistic portrayal of the numerous

different types of openings and the ratio of frame to glass that occurs with different sized windows.

v. Door types in the model are also severely limited and do not allow for the variety of design commonly seen in gym construction. Half-lite steel exterior doors were used for all openings because heavy useage of doors in school buildings typically require such construction.

vi.

c. Columns & Beams

i. This category of building components focuses on primary building structure, but is severly limited in several ways.

ii. Beam limitations (49 feet or 69 feet, depending on the beam selected) do not accurately represent the 90 foot long span over the main gymnasium. This space was divided into two 45'x90' sections due to the limitations of the software. While this does not represent the actual sizes of the beams, the three gyms are consistently represented in this manner so as to be comparable.

iii. Beams are not required in all construction types and are thus modeled to reflect the reality of common design practice. For example, in the 50 year gym, beams are not shown because the trusses are anticipated to span the full 90' or 45' width of the gym. Also, beams are not included as a separate item in the 200 year gym because they are included in the design of the composite metal roof deck.

iv. Secondary steel structure is not included in the model.

v. Distinctions between structural requirements for different seismic zones and different types of buildings (i.e., critical facilities) was not possible, although seismic impacts for Seattle are included in general.

d. Roofs

i. The roof of the 20 year gym is assumed to be a sloped roof sufficient for a asphalt shingle roof. This may be achieved by either steping the beams up toward the middle or using a "boomerang" shaped glu-lam beam. In either case the intent is to have the highest part of the roof follow the longitudinal direction of the main basketball court. The walls would thus vary in height along two sides and are considered to average out to the nominal 30 foot height.

ii. The components of each roof system are selected to meet typical non-combustible construction observed in gymnasiums. The wood framed roof of the 20 year gym is thus sheathed at the ceiling with drywall. By contrast, the other two gymnasiums have non-combustible metal structure exposed on the interior.

iii. The roofing system for both the Auxiliary and Main gyms are kept consistent within each model in order to facilitate comparison of the three models.

iv. The design of each of the roof systems is intended to reflect contemporary design requirements for energy code (R-49 insulation value).

v. No skylights are alowed in the modeling software, yet skylights are becoming more common as passive lighting devices for large spaces such as gyms in order to balance light levels across the space and decrease the effects of glare.

vi. Within the roofing systems themselves, it is unclear as to exactly what components are included or not included. Items such as fasteners, different types of adhesives, cap sheets, parapet and coping flashing, termination bars and other components are not clearly indicated in the system decriptions.

3. Not Included in the Model

a. Several building components are not included in this model and thus the model does not represent a complete functional building. In addition to the building systems described above, the following items often observed in gymnasia are not included in this model:
    i. Wall pads
    ii. Acoustical panels on the walls and ceiling
    iii. Bleacher seating
    iv. Skylights
    v. Audio/Visual and Scorekeeping systems
    vi. Gym dividers (net walls)
    vii. Wrestling mats, basketball hoops, volleyball nets and poles or other athletic equipment
    viii. Mezzanine framing or catwalks
    ix. Theatre equipment, including curtains, lighting, and sound systems
b. Because all 4 building designs are the same size and configuration, designed to meet the same building and energy codes at the same time, and operational energy consumption is not considered in this model, the absence of the above items from the analysis is considered to have a negligible effect on the results.

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Gymnasium Comparison - Summary Measure Table By Total Effect

Note: Highlighted fields are provided by Athena. Remainder of values are calculated in Excel.

Summary Measures		Year 1	Year 10	Year 20	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90	Year 100	Year 110	Year 120	Year 130	Year 140	Year 150	Year 160	Year 170	Year 180	Year 190	Year 200
Fossil Fuel Consumption (MJ)	Gym A	1,698,521	1,711,018	1,770,699	2,131,916	3,830,437	3,842,934	3,902,615	4,263,833	5,962,354	5,974,851	6,034,532	6,395,749	8,094,270	8,106,767	8,166,448	8,527,666	10,226,187	10,238,684	10,298,365	10,659,582
	Gym A1	1,827,203	1,839,689	1,899,180	2,261,341	4,088,543	4,101,030	4,160,521	4,522,681	6,349,884	6,362,370	6,421,861	6,784,022	8,611,225	8,623,711	8,683,202	9,045,362	10,872,565	10,885,051	10,944,542	11,306,703
	Gym B	3,562,531	3,580,332	3,598,482	3,894,457	7,456,987	7,474,788	7,492,938	7,788,913	11,351,444	11,369,245	11,387,395	11,683,370	15,245,901	15,263,702	15,281,852	15,577,827	19,140,357	19,158,158	19,176,309	19,472,283
	Gym C	6,510,123		6,611,229		7,029,844					7,909,829	14,419,952		14,521,057		14,939,673					15,819,658
	Gym D	8,744,113				10,307,462					13,168,382										18,890,220
		Year 1	Year 10	Year 20	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90	Year 100	Year 110	Year 120	Year 130	Year 140	Year 150	Year 160	Year 170	Year 180	Year 190	Year 200
Global Warming Potential (kg CO2 eq)	Gym A	66,382	66,777	67,993	77,150	143,533	143,927	145,144	154,301	220,683	221,078	222,294	231,451	297,833	298,228	299,444	308,601	374,983	375,378	376,594	385,751
	Gym A1	125,235	125,617	126,611	137,639	262,874	263,256	264,250	275,278	400,513	400,895	401,889	412,917	538,152	538,534	539,528	550,556	675,791	676,172	677,167	688,194
	Gym B	264,998	265,778	266,146	277,953	542,951	543,731	544,099	555,906	820,904	821,683	822,051	833,858	1,098,856	1,099,636	1,100,004	1,111,811	1,376,809	1,377,589	1,377,957	1,389,764
	Gym C	624,956		628,021		647,297					689,751	1,314,708		1,317,772		1,337,049					1,379,503
	Gym D	820,680				857,939					937,392										1,096,298
		Year 1	Year 10	Year 20	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90	Year 100	Year 110	Year 120	Year 130	Year 140	Year 150	Year 160	Year 170	Year 180	Year 190	Year 200
Acidification Potential (kg SO2 eq)	Gym A	791	793	800	886	1,676	1,679	1,685	1,771	2,562	2,564	2,571	2,657	3,448	3,450	3,457	3,543	4,333	4,336	4,342	4,429
	Gym A1	799	801	807	893	1,691	1,693	1,700	1,785	2,584	2,586	2,592	2,678	3,476	3,478	3,485	3,570	4,369	4,371	4,377	4,463
	Gym B	1,412	1,419	1,421	1,493	2,905	2,911	2,914	2,986	4,398	4,404	4,407	4,478	5,890	5,897	5,899	5,971	7,383	7,390	7,392	7,464
	Gym C	2,994		3,015		3,141					3,423	6,417		6,438		6,564					6,847
	Gym D	4,107				4,346					4,847										5,850
		Year 1	Year 10	Year 20	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90	Year 100	Year 110	Year 120	Year 130	Year 140	Year 150	Year 160	Year 170	Year 180	Year 190	Year 200
HH Particulate (kg PM2.5 eq)	Gym A	280	284	292	325	606	609	618	651	931	935	943	976	1,257	1,260	1,269	1,302	1,582	1,585	1,594	1,627
	Gym A1	243	246	254	287	530	533	541	574	817	820	829	861	1,104	1,107	1,116	1,148	1,391	1,394	1,403	1,435
	Gym B	740	744	750	914	1,654	1,658	1,664	1,828	2,568	2,571	2,578	2,742	3,482	3,485	3,492	3,655	4,396	4,399	4,406	4,569
	Gym C	2,173		2,204		2,445					2,938	5,111		5,141		5,383					5,875
	Gym D	1,838				1,920					2,070										2,372
		Year 1	Year 10	Year 20	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90	Year 100	Year 110	Year 120	Year 130	Year 140	Year 150	Year 160	Year 170	Year 180	Year 190	Year 200
Eutrophication Potential (kg N eq)	Gym A	46	48	77	233	279	281	309	465	512	513	542	698	744	746	775	931	977	979	1,007	1,163
	Gym A1	49	49	49	53	102	102	102	106	155	155	155	159	208	208	208	211	260	261	261	264
	Gym B	59	61	64	305	364	366	369	609	668	670	673	914	973	975	978	1,218	1,277	1,279	1,282	1,523
	Gym C	102		138		498					1,228	1,330		1,366		1,725					2,456
	Gym D	141				573					1,629										3,742
		Year 1	Year 10	Year 20	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90	Year 100	Year 110	Year 120	Year 130	Year 140	Year 150	Year 160	Year 170	Year 180	Year 190	Year 200
Ozone Depletion Potential (kg CFC-11 eq)	Gym A	0.00188	0.00188	0.00188	0.00196	0.00384	0.00384	0.00384	0.00392	0.00580	0.00580	0.00580	0.00589	0.00776	0.00776	0.00777	0.00785	0.00973	0.00973	0.00973	0.00981
	Gym A1	0.00127	0.00128	0.00128	0.00136	0.00263	0.00264	0.00264	0.00272	0.00399	0.00399	0.00400	0.00408	0.00535	0.00535	0.00536	0.00544	0.00671	0.00671	0.00671	0.00680
	Gym B	0.00205	0.00205	0.00205	0.00214	0.00420	0.00420	0.00420	0.00429	0.00634	0.00634	0.00634	0.00643	0.00848	0.00848	0.00849	0.00858	0.01063	0.01063	0.01063	0.01072
	Gym C	0.00387		0.00388		0.00412					0.00472	0.00859		0.00860		0.00884					0.00944
	Gym D	0.00615				0.00639					0.00701										0.00825
		Year 1	Year 10	Year 20	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90	Year 100	Year 110	Year 120	Year 130	Year 140	Year 150	Year 160	Year 170	Year 180	Year 190	Year 200
Smog Potential (kg O3 eq)	Gym A	14,425	14,482	14,587	16,264	30,689	30,745	30,850	32,527	46,952	47,009	47,114	48,791	63,216	63,273	63,378	65,055	79,480	79,536	79,641	81,318
	Gym A1	14,684	14,741	14,840	16,264	30,948	31,004	31,104	32,527	47,212	47,268	47,367	48,791	63,476	63,532	63,631	65,055	79,739	79,795	79,895	81,318
	Gym B	22,094	22,308	22,338	23,095	45,189	45,403	45,433	46,190	68,284	68,498	68,528	69,286	91,379	91,594	91,623	92,381	114,474	114,689	114,718	115,476
	Gym C	43,838		44,198		45,507					48,423	92,261		92,621		93,930					96,846
	Gym D	64,694				66,901					71,962										82,083

Appendix B - Life Cycle Analysis – 200 Year Gymnasium Comparison - Total Impacts of New Construction

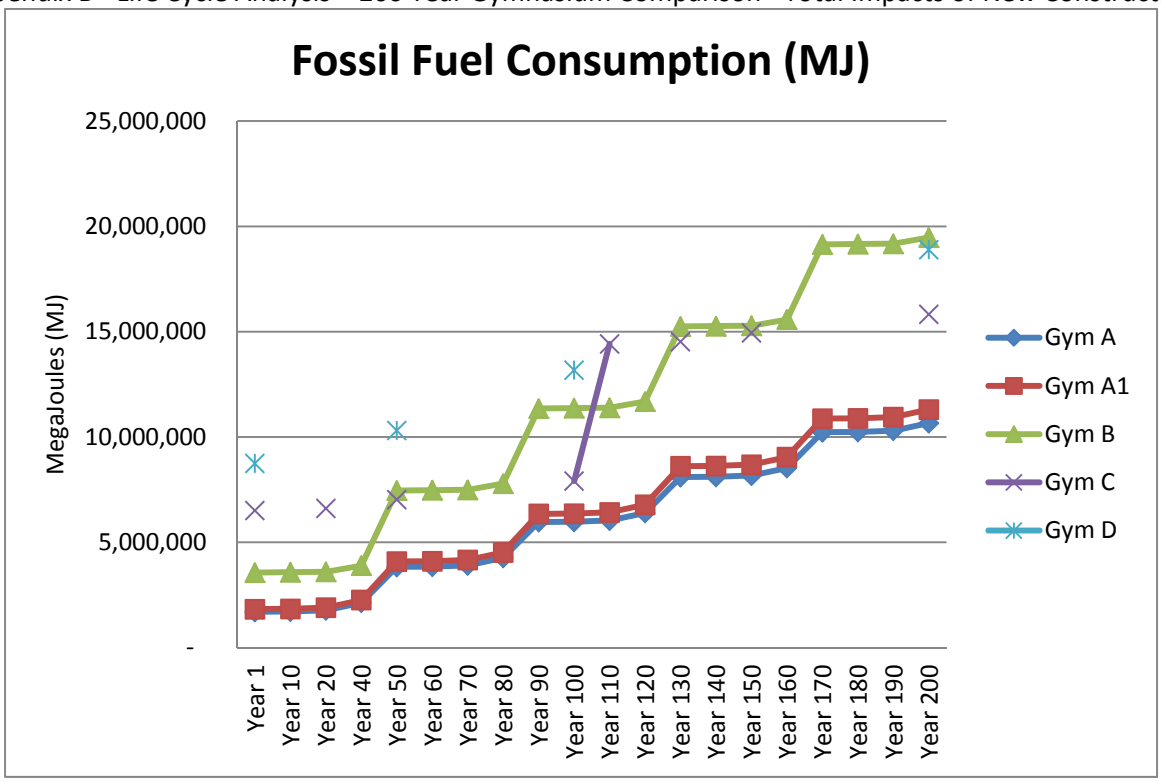

Figure 1: 200 year comparison - new gymnasium construction. Fossil fuel impacts are shown for 5 different gymnasia designs for a 200 year service life.

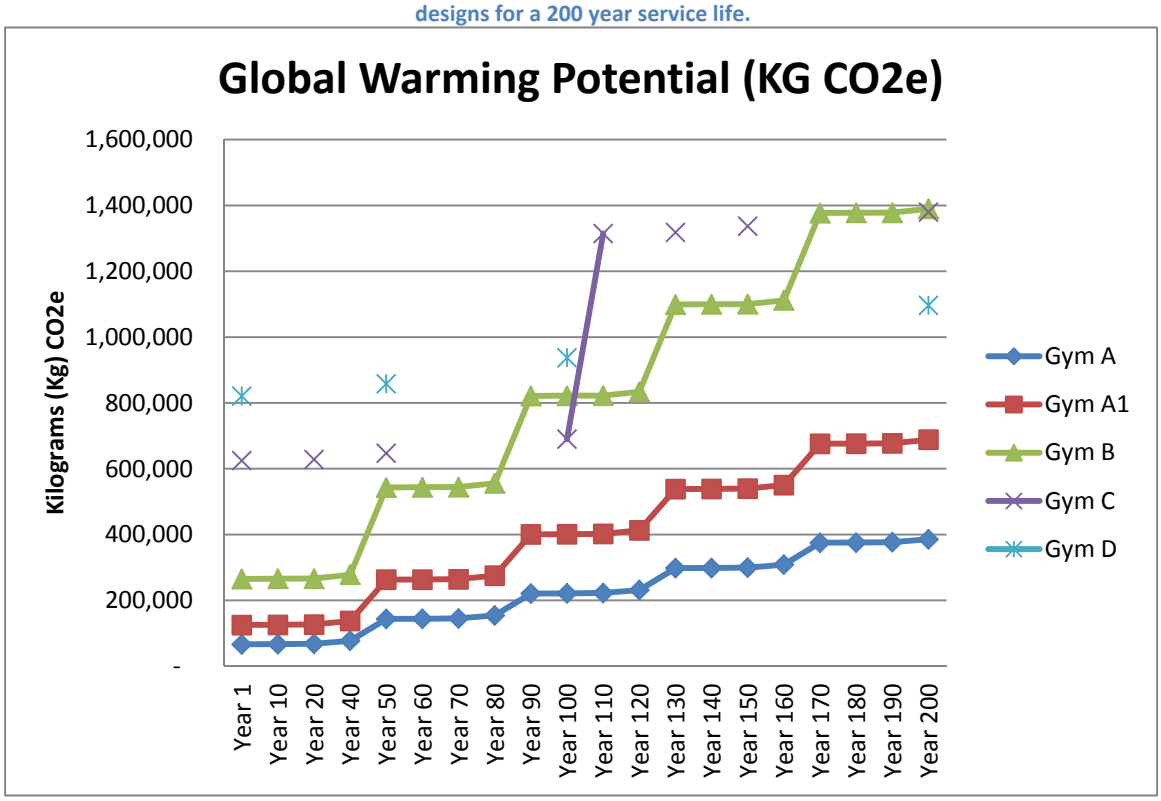

Figure 2: 200 year comparison - new gymnasium construction. Global Warming Potential impacts are shown for 5 different gymnasia designs for a 200 year service life.

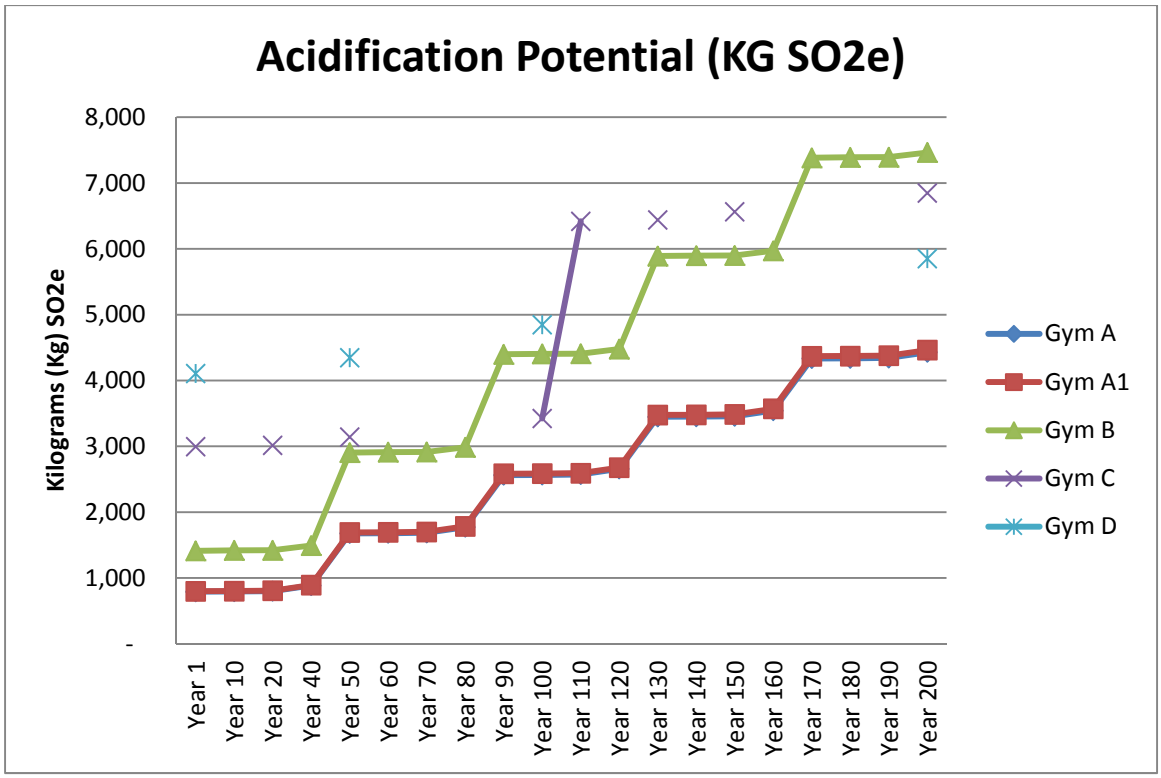

Figure 3: 200 year comparison - new gymnasium construction. Acidification Potential impacts are shown for 5 different gymnasia designs for a 200 year service life.

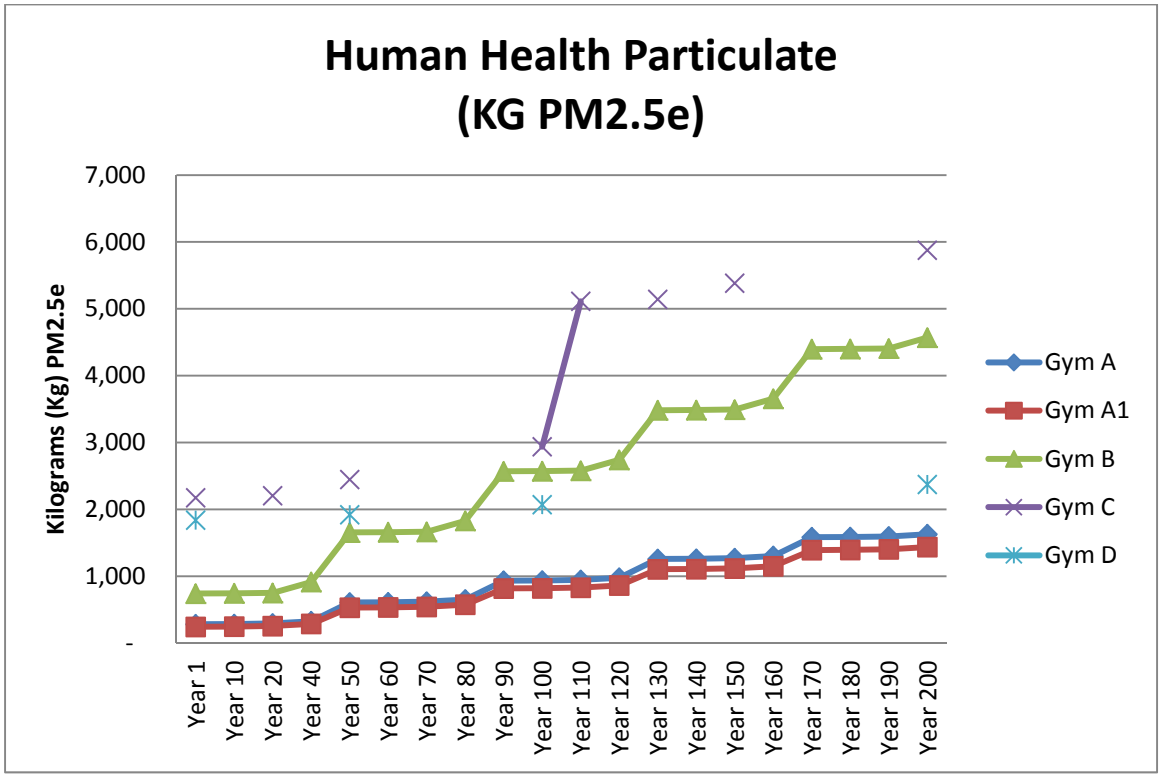

Figure 4: 200 year comparison - new gymnasium construction. Human Health Particulate impacts are shown for 5 different gymnasia designs for a 200 year service life.

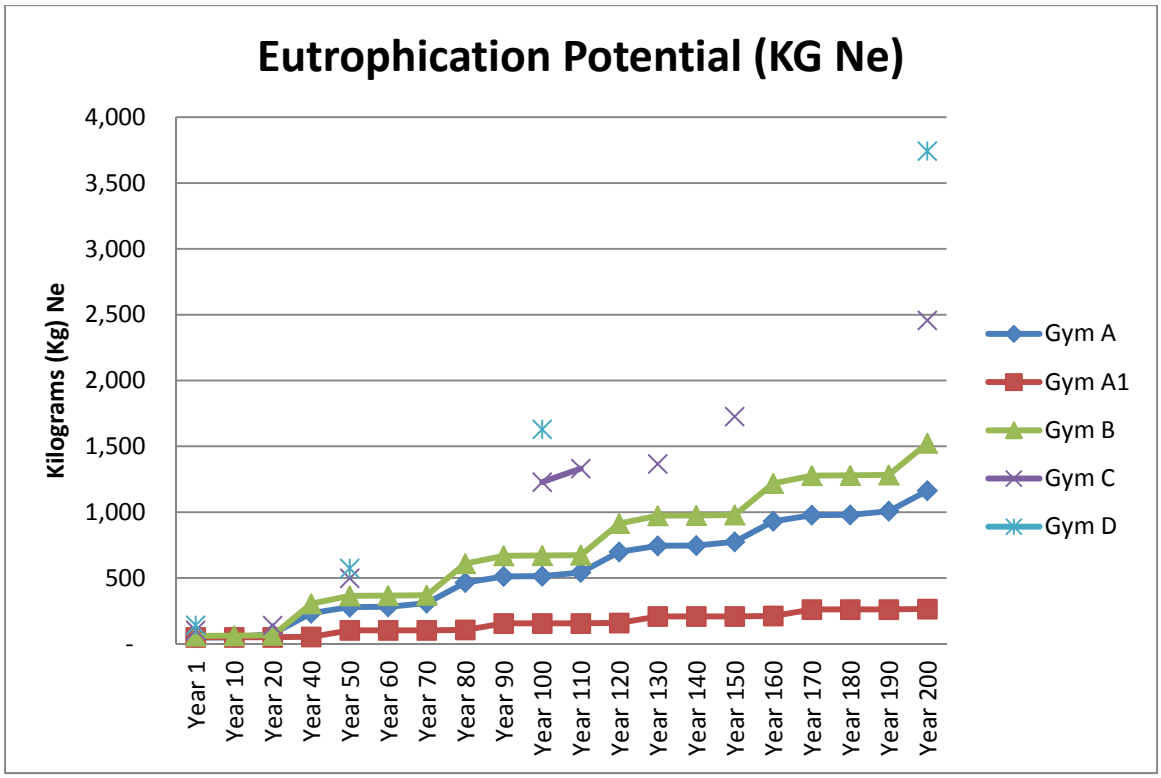

Figure 5: 200 year comparison - new gymnasium construction. Eutrophication Potential impacts are shown for 5 different gymnasia designs for a 200 year service life.

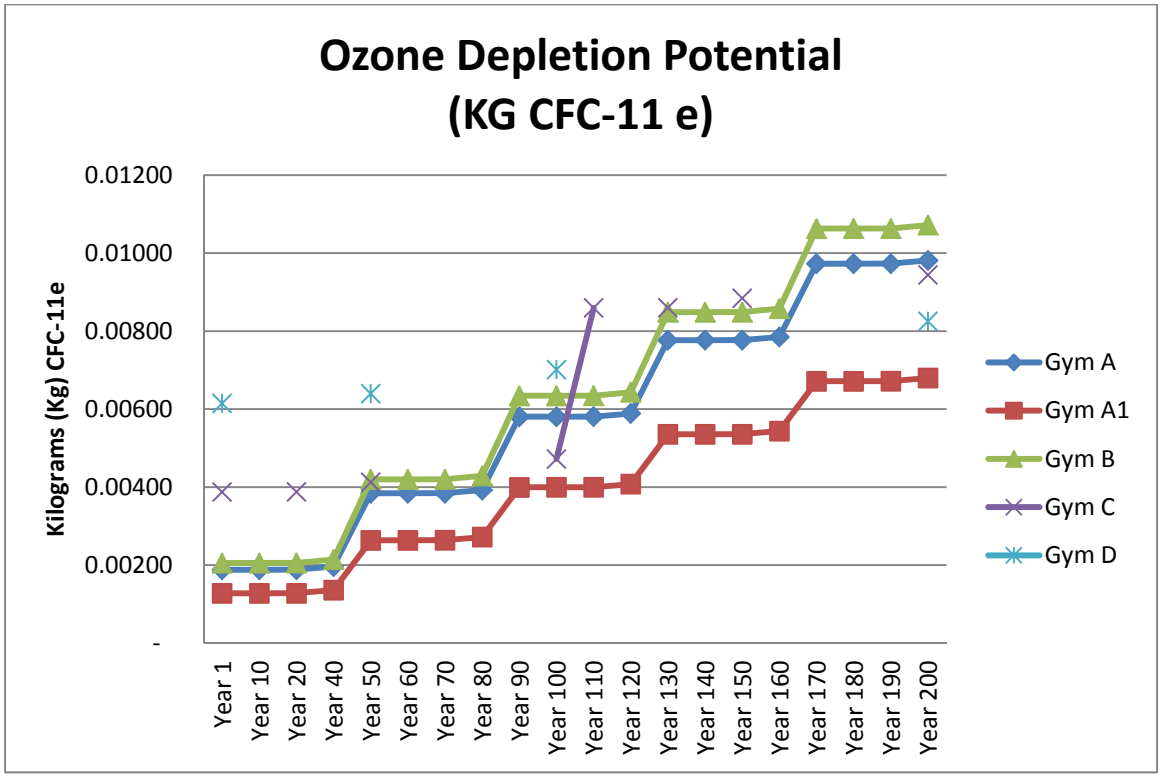

Figure 6: 200 year comparison - new gymnasium construction. Ozone Depletion Potential impacts are shown for 5 different gymnasia designs for a 200 year service life.

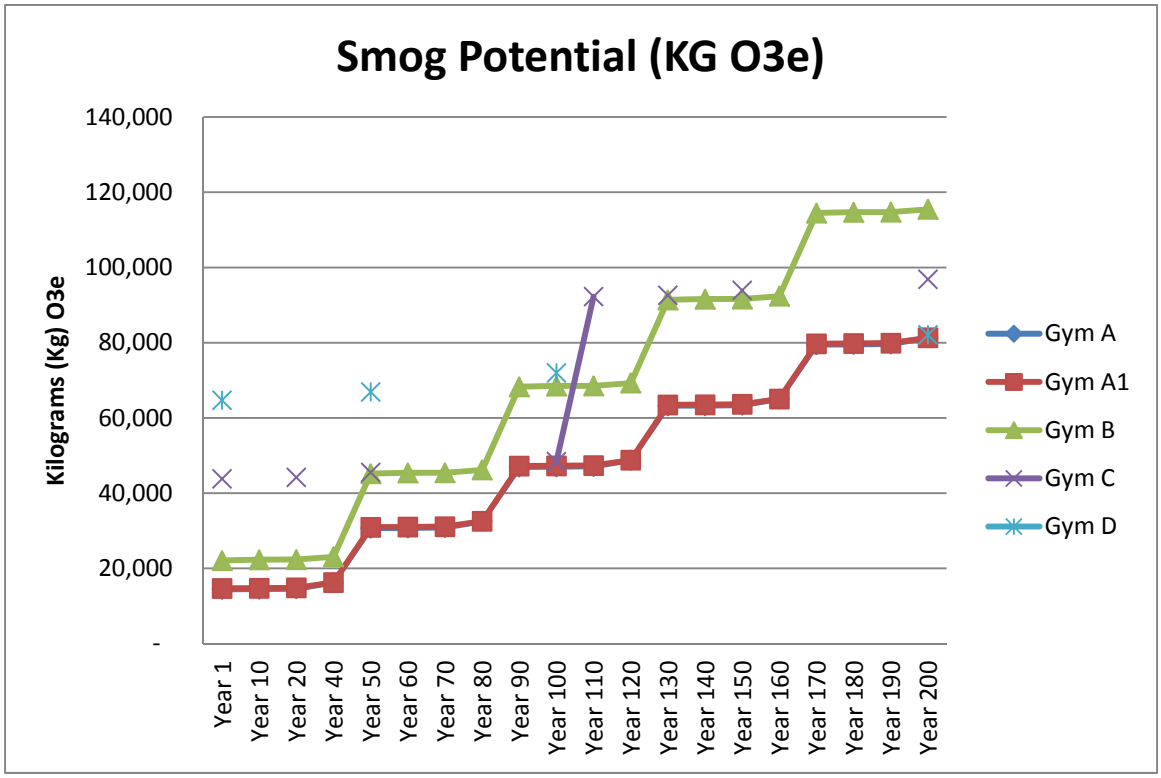

Figure 7: 200 year comparison - new gymnasium construction. Smog Potential impacts are shown for 5 different gymnasia designs for a 200 year service life.

200 Year Comparison - First Impact (No Maintenance) of New Gym A, A1, B, C, and D					
	Gym A	Gym A1	Gym B	Gym C	Gym D
Fossil Fuel Consumption (MJ)	1,698,521	1,827,203	3,562,531	6,510,123	8,744,113
Global Warming Potential (kg CO2 eq)	66,382	125,235	264,998	624,956	820,680
Acidification Potential (kg SO2 eq)	791	799	740	2,994	4,107
HH Particulate (kg PM2.5 eq)	280	243	59	2,173	1,838
Eutrophication Potential (kg N eq)	46	49	59	102	141
Ozone Depletion Potential (kg CFC-11 eq)	0.00188	0.00127	0.00205	0.00387	0.00615
Smog Potential (kg O3 eq)	14,425	14,684	22,094	43,838	64,694

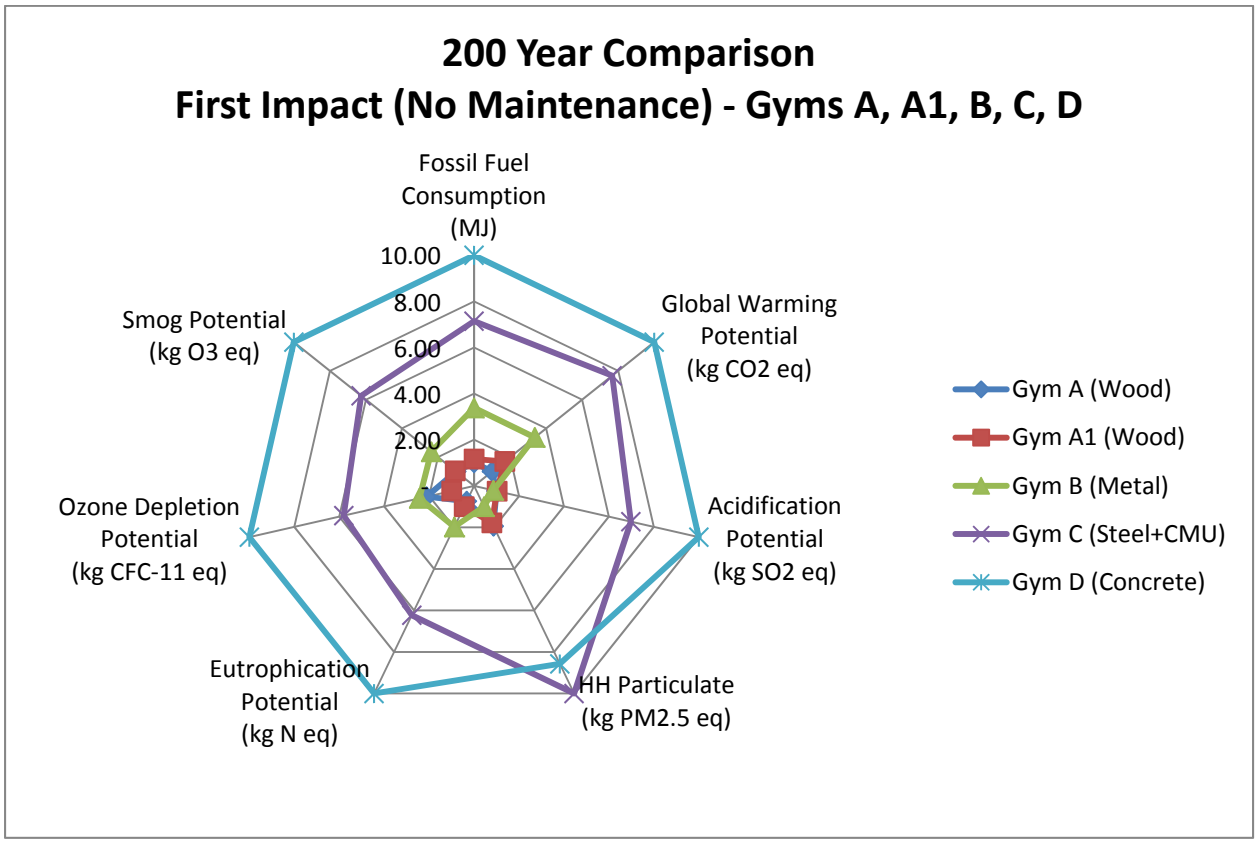

Figure 8: First Impact Comparison, normalized on a scale of 10. Note that the buildings involving masonry and concrete (Gym C and D) have the most significant first impacts and wood (A and A1) the least.

200 Year Comparison – First Impact (No Maintenance) of New Gym A, A1, B, C, and D					
Summary Measures		Year 1	Year 50	Year 100	Year 200
Fossil Fuel Consumption (MJ)	Gym A (Wood)	-	2,131,916	4,276,330	8,961,062
	Gym A1 (Wood)	-	2,261,341	4,535,167	9,479,500
	Gym B (Metal)	-	3,894,457	7,806,715	15,909,753
	Gym C (Steel+CMU)	-	519,721	1,399,706	9,309,535
	Gym D (Concrete)	-	1,563,349	4,424,269	10,146,107
		Year 1	Year 50	Year 100	Year 200
Global Warming Potential (kg CO2 eq)	Gym A (Wood)	-	77,150	154,695	319,369
	Gym A1 (Wood)	-	137,639	275,660	562,959
	Gym B (Metal)	-	277,953	556,685	1,124,766
	Gym C (Steel+CMU)	-	22,341	64,795	754,547
	Gym D (Concrete)	-	37,258	116,711	275,618
		Year 1	Year 50	Year 100	Year 200
Acidification Potential (kg SO2 eq)	Gym A (Wood)	-	886	1,774	3,638
	Gym A1 (Wood)	-	893	1,787	3,664
	Gym B (Metal)	-	1,493	2,992	6,052
	Gym C (Steel+CMU)	-	147	429	3,853
	Gym D (Concrete)	-	239	741	1,744
		Year 1	Year 50	Year 100	Year 200
HH Particulate (kg PM2.5 eq)	Gym A (Wood)	-	325	654	1,347
	Gym A1 (Wood)	-	287	577	1,193
	Gym B (Metal)	-	914	1,831	3,829
	Gym C (Steel+CMU)	-	272	765	3,702
	Gym D (Concrete)	-	82	232	534
		Year 1	Year 50	Year 100	Year 200
Eutrophication Potential (kg N eq)	Gym A (Wood)	-	233	467	1,117
	Gym A1 (Wood)	-	53	106	215
	Gym B (Metal)	-	305	611	1,464
	Gym C (Steel+CMU)	-	395	1,125	2,353
	Gym D (Concrete)	-	432	1,488	3,601
		Year 1	Year 50	Year 100	Year 200
Ozone Depletion Potential (kg CFC-11 eq)	Gym A (Wood)	-	0.00196	0.00393	0.00793
	Gym A1 (Wood)	-	0.00136	0.00272	0.00552
	Gym B (Metal)	-	0.00214	0.00429	0.00867
	Gym C (Steel+CMU)	-	0.00025	0.00085	0.00557
	Gym D (Concrete)	-	0.00025	0.00087	0.00210
		Year 1	Year 50	Year 100	Year 200
Smog Potential (kg O3 eq)	Gym A (Wood)	-	16,264	32,584	66,893
	Gym A1 (Wood)	-	16,264	32,584	66,634
	Gym B (Metal)	-	23,095	46,405	93,382
	Gym C (Steel+CMU)	-	1,669	4,585	53,007
	Gym D (Concrete)	-	2,207	7,268	17,389

200 Year Comparison - Maintenance of Existing Gyms (No First Impact)

	Gym A	Gym A1	Gym B	Gym C	Gym D
Fossil Fuel Consumption (MJ)	8,961,062	9,479,500	15,909,753	9,309,535	10,146,107
Global Warming Potential (kg CO2 eq)	319,369	562,959	1,124,766	754,547	275,618
Acidification Potential (kg SO2 eq)	3,638	3,664	3,829	3,853	1,744
HH Particulate (kg PM2.5 eq)	1,347	1,193	1,464	3,702	534
Eutrophication Potential (kg N eq)	1,117	215	1,464	2,353	3,601
Ozone Depletion Potential (kg CFC-11 eq)	0.00793	0.00552	0.00867	0.00557	0.00210
Smog Potential (kg O3 eq)	66,893	66,634	93,382	53,007	17,389

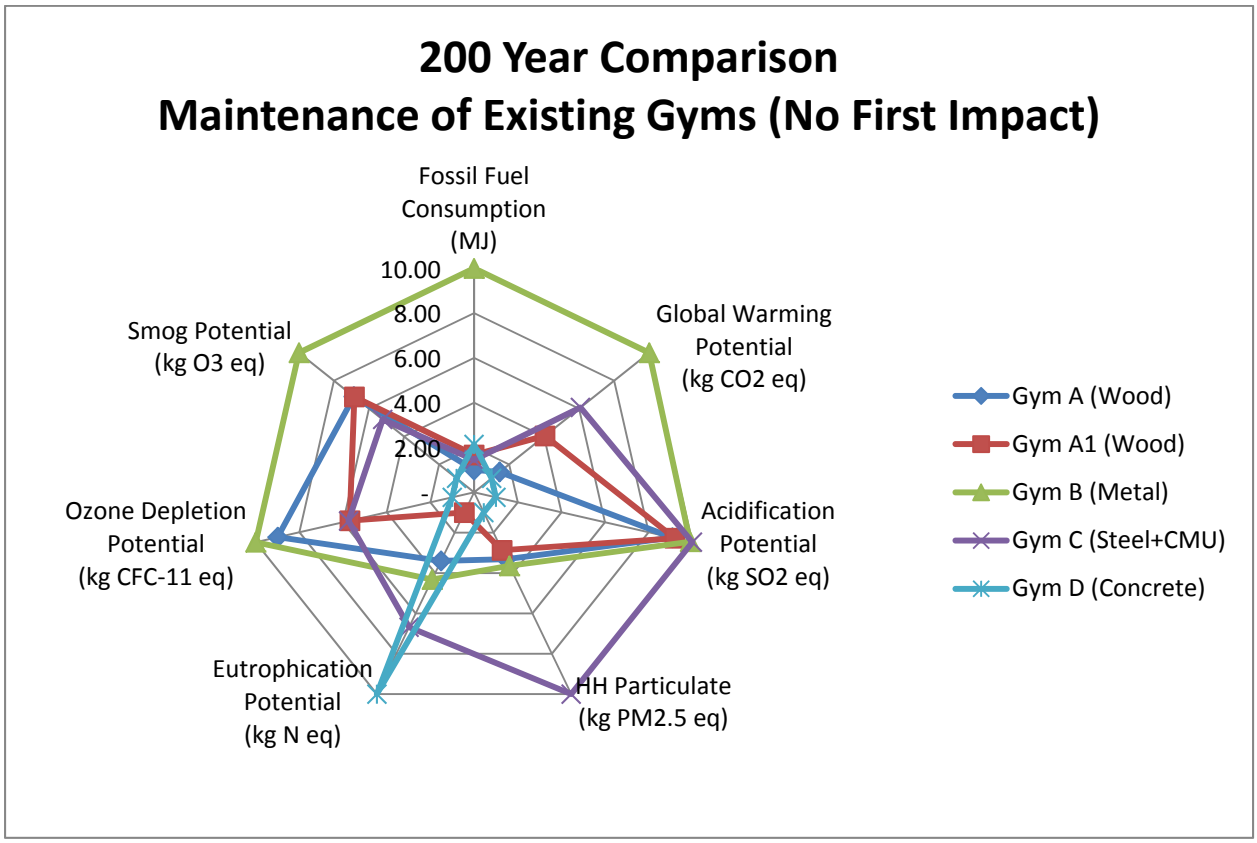

Figure 9: 200 year comparison of maintenance requirements, not including first impacts, normalized on a scale of 10. Note that the Gym D has the least maintenance impact in most categories and Gym B has the largest impacts in most categories.

200 Year Comparison - Maintenance of Existing Gyms (No First Impact)					
Summary Measures		Year 1	Year 50	Year 100	Year 200
Fossil Fuel Consumption (MJ)	Gym A (Wood)	-	2,131,916	4,276,330	8,961,062
	Gym A1 (Wood)	-	2,261,341	4,535,167	9,479,500
	Gym B (Metal)	-	3,894,457	7,806,715	15,909,753
	Gym C (Steel+CMU)	-	519,721	1,399,706	9,309,535
	Gym D (Concrete)	-	1,563,349	4,424,269	10,146,107
		Year 1	Year 50	Year 100	Year 200
Global Warming Potential (kg CO2 eq)	Gym A (Wood)	-	77,150	154,695	319,369
	Gym A1 (Wood)	-	137,639	275,660	562,959
	Gym B (Metal)	-	277,953	556,685	1,124,766
	Gym C (Steel+CMU)	-	22,341	64,795	754,547
	Gym D (Concrete)	-	37,258	116,711	275,618
		Year 1	Year 50	Year 100	Year 200
Acidification Potential (kg SO2 eq)	Gym A (Wood)	-	886	1,774	3,638
	Gym A1 (Wood)	-	893	1,787	3,664
	Gym B (Metal)	-	1,493	2,992	6,052
	Gym C (Steel+CMU)	-	147	429	3,853
	Gym D (Concrete)	-	239	741	1,744
		Year 1	Year 50	Year 100	Year 200
HH Particulate (kg PM2.5 eq)	Gym A (Wood)	-	325	654	1,347
	Gym A1 (Wood)	-	287	577	1,193
	Gym B (Metal)	-	914	1,831	3,829
	Gym C (Steel+CMU)	-	272	765	3,702
	Gym D (Concrete)	-	82	232	534
		Year 1	Year 50	Year 100	Year 200
Eutrophication Potential (kg N eq)	Gym A (Wood)	-	233	467	1,117
	Gym A1 (Wood)	-	53	106	215
	Gym B (Metal)	-	305	611	1,464
	Gym C (Steel+CMU)	-	395	1,125	2,353
	Gym D (Concrete)	-	432	1,488	3,601
		Year 1	Year 50	Year 100	Year 200
Ozone Depletion Potential (kg CFC-11 eq)	Gym A (Wood)	-	0.00196	0.00393	0.00793
	Gym A1 (Wood)	-	0.00136	0.00272	0.00552
	Gym B (Metal)	-	0.00214	0.00429	0.00867
	Gym C (Steel+CMU)	-	0.00025	0.00085	0.00557
	Gym D (Concrete)	-	0.00025	0.00087	0.00210
		Year 1	Year 50	Year 100	Year 200
Smog Potential (kg O3 eq)	Gym A (Wood)	-	16,264	32,584	66,893
	Gym A1 (Wood)	-	16,264	32,584	66,634
	Gym B (Metal)	-	23,095	46,405	93,382
	Gym C (Steel+CMU)	-	1,669	4,585	53,007
	Gym D (Concrete)	-	2,207	7,268	17,389

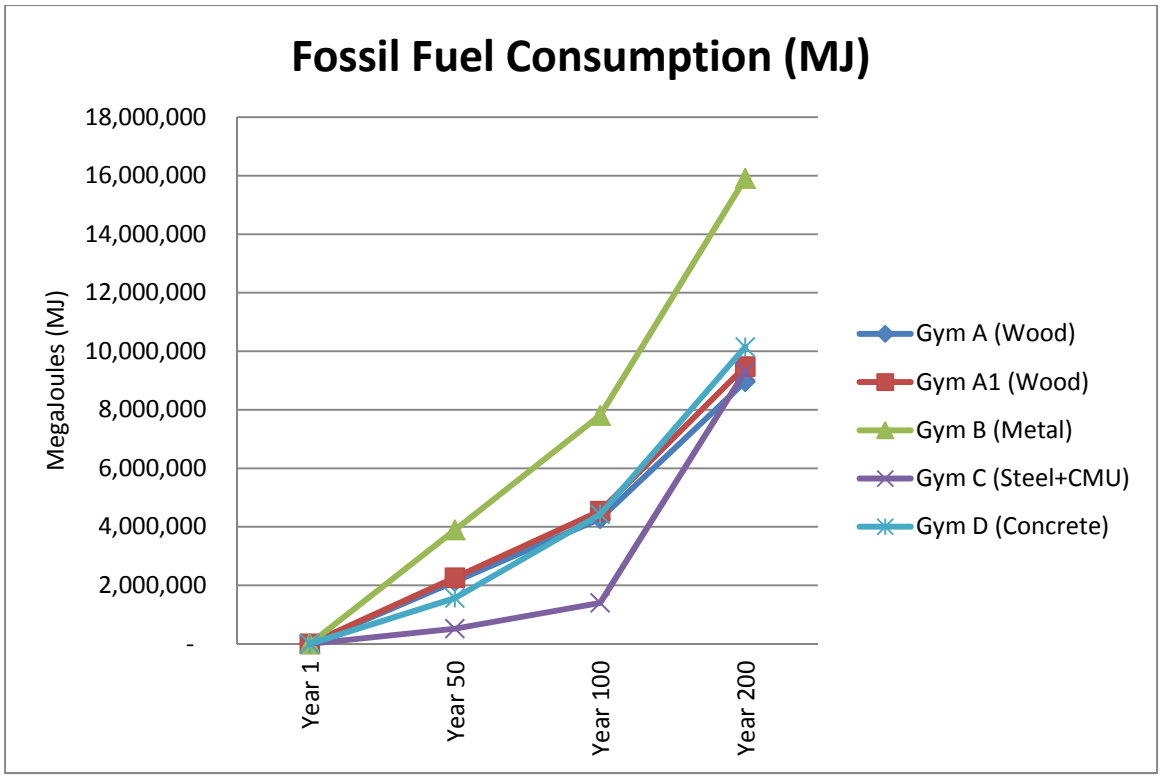

Figure 10: 200 year comparison of maintenance requirements, not including first impacts, for Fossil Fuel Consumption.

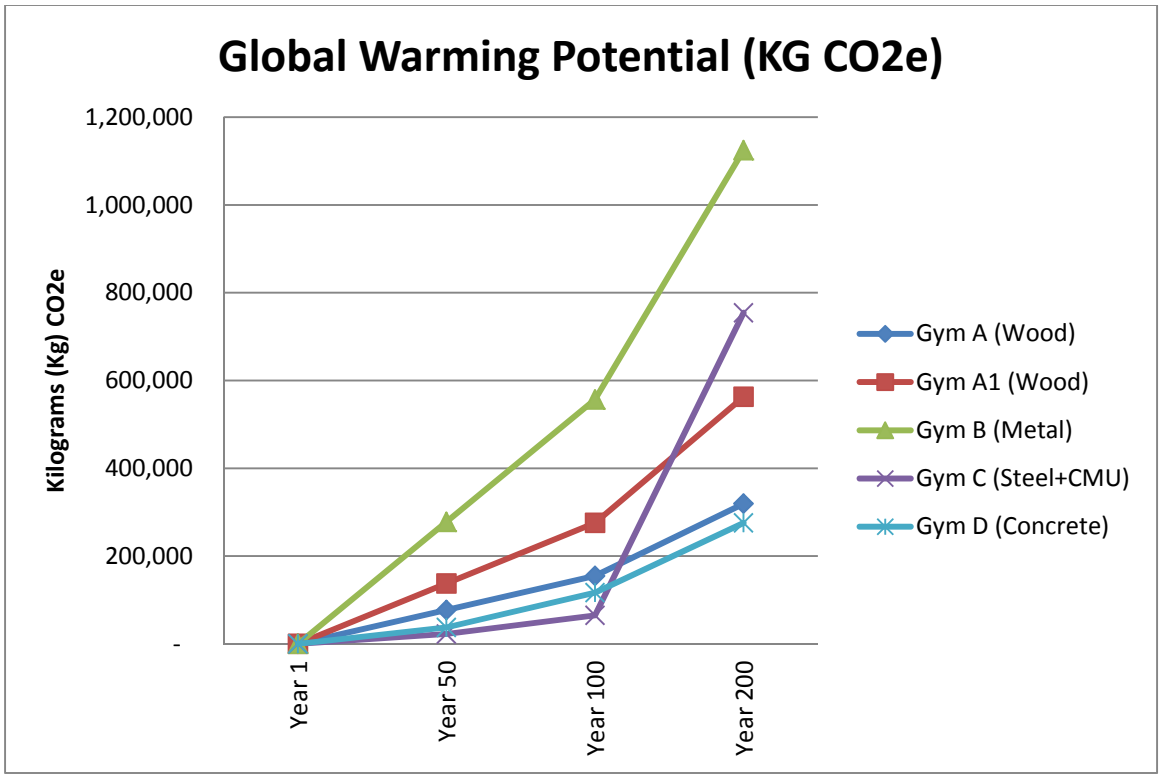

Figure 11: 200 year comparison of maintenance requirements, not including first impacts, for Global Warming Potential

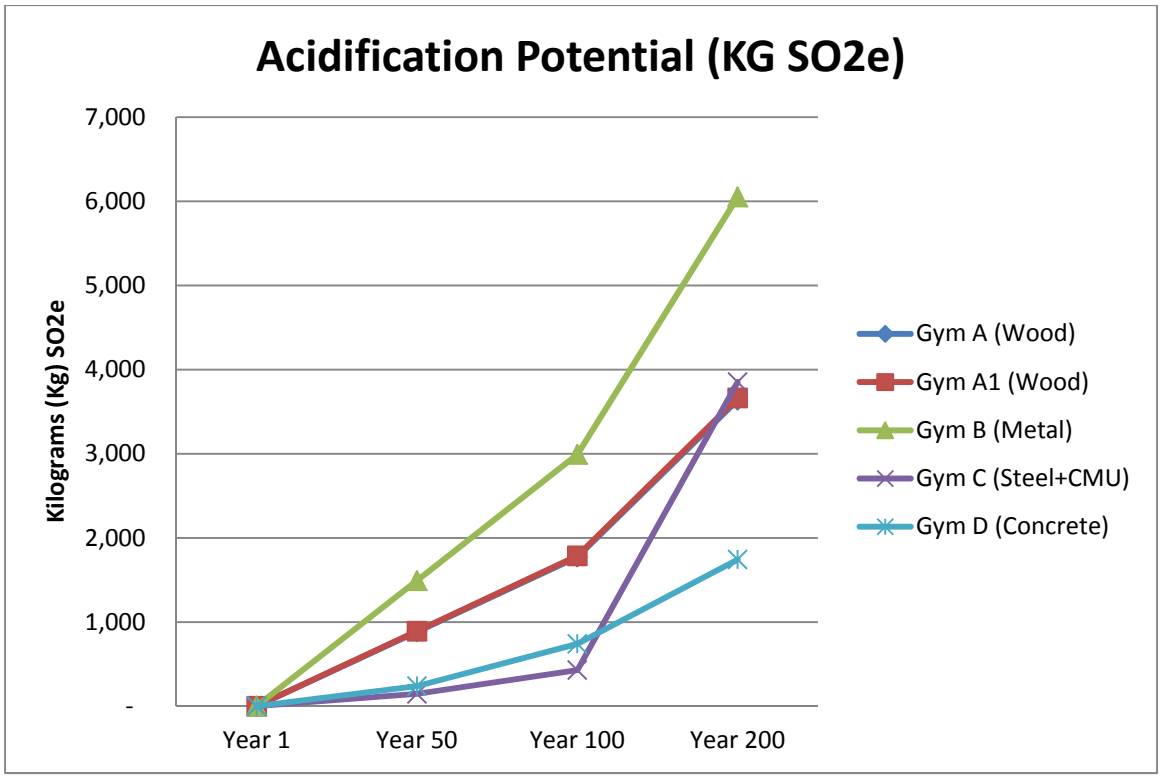

Figure 12: 200 year comparison of maintenance requirements, not including first impacts, for Acidification Potential

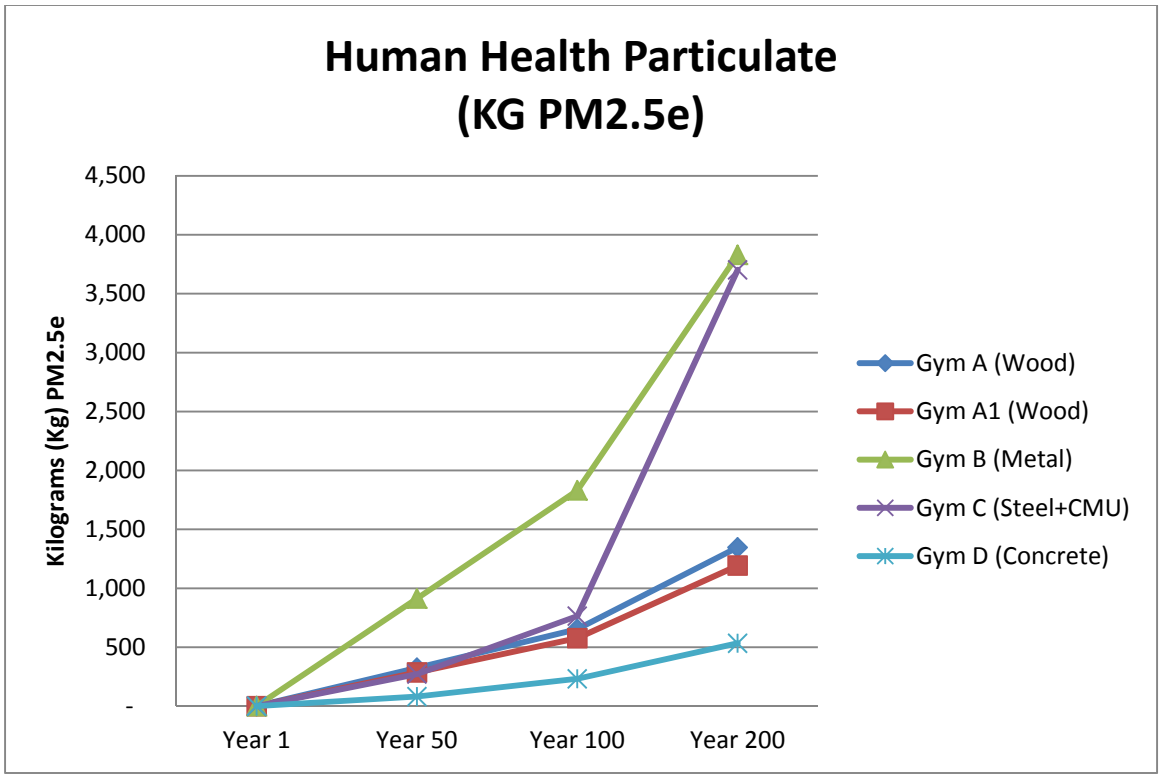

Figure 13: 200 year comparison of maintenance requirements, not including first impacts, for Human Health Particulate.

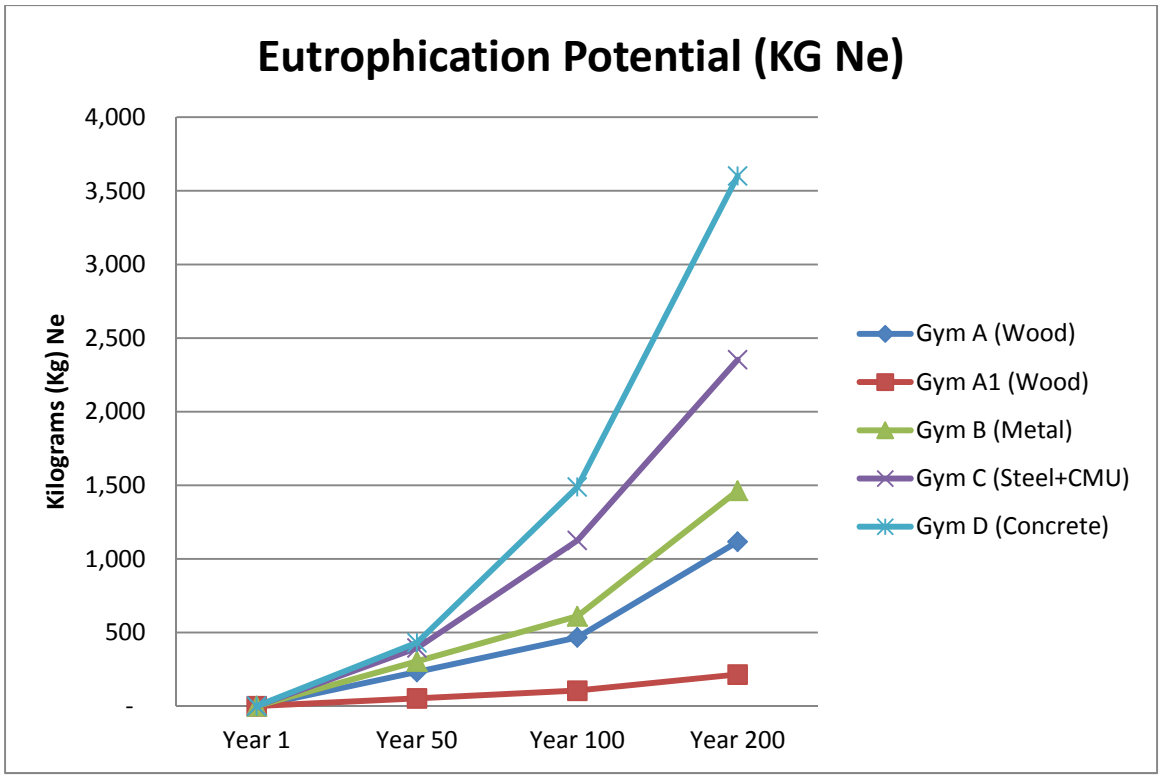

Figure 14: 200 year comparison of maintenance requirements, not including first impacts, for Eutrophication Potential.

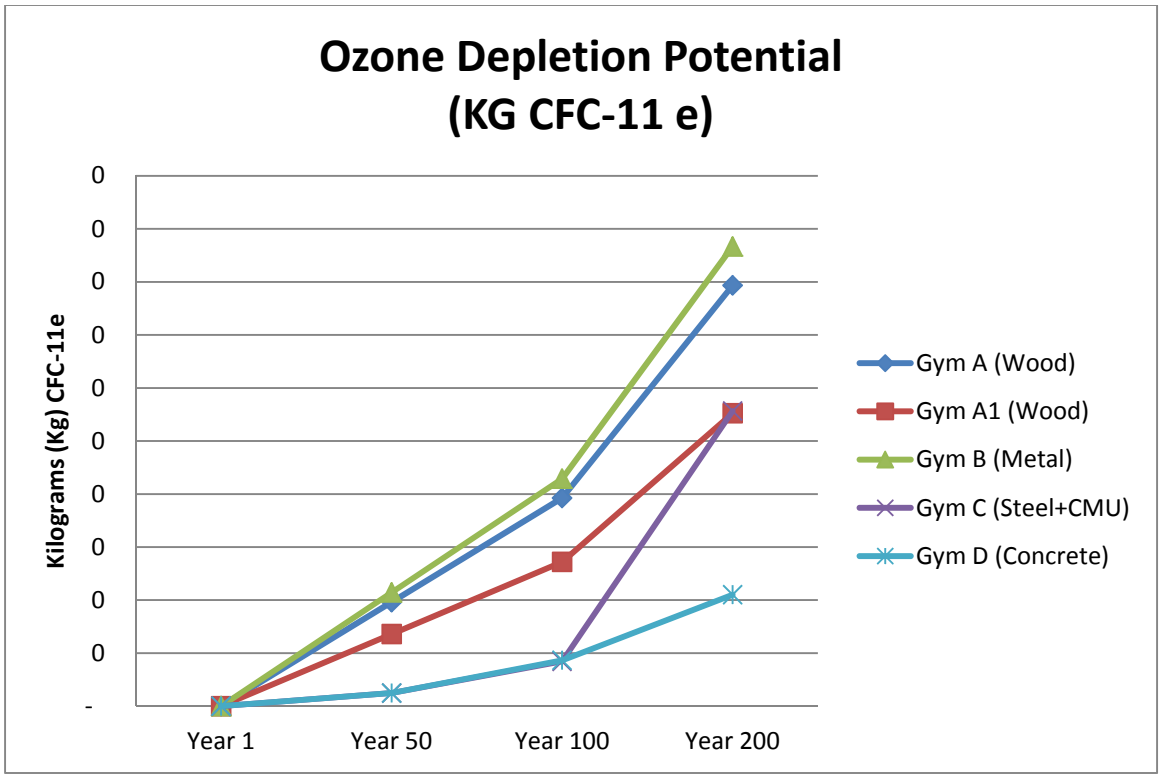

Figure 15: 200 year comparison of maintenance requirements, not including first impacts, for Ozone Depletion Potential.

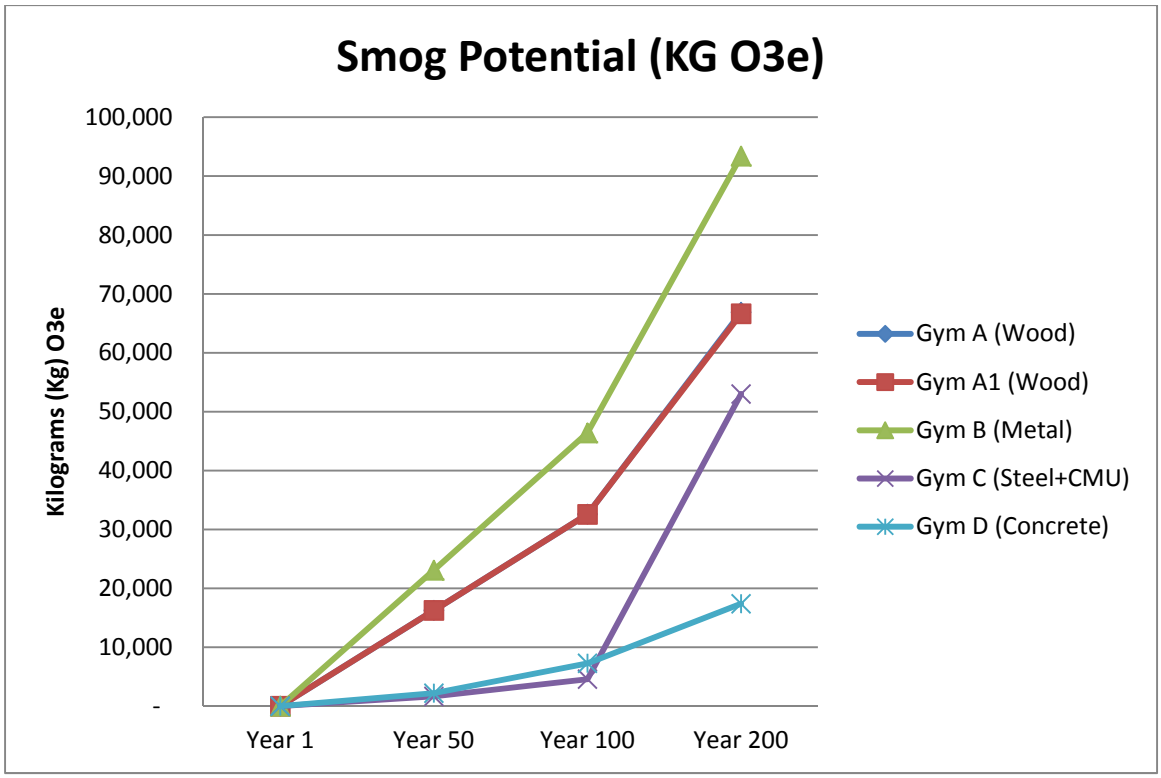

Figure 16: 200 year comparison of maintenance requirements, not including first impacts, for Smog Potential.

200 Year Comparison - Total Impacts of New Gym Construction

	Gym A	Gym A1	Gym B	Gym C	Gym D
Fossil Fuel Consumption (MJ)	10,659,582	11,306,703	19,472,283	15,819,658	18,890,220
Global Warming Potential (kg CO2 eq)	385,751	688,194	1,389,764	1,379,503	1,096,298
Acidification Potential (kg SO2 eq)	4,429	4,463	4,569	6,847	5,850
HH Particulate (kg PM2.5 eq)	1,627	1,435	1,523	5,875	2,372
Eutrophication Potential (kg N eq)	1,163	264	1,523	2,456	3,742
Ozone Depletion Potential (kg CFC-11 eq)	0.00981	0.00680	0.01072	0.00944	0.00825
Smog Potential (kg O3 eq)	81,318	81,318	115,476	96,846	82,083

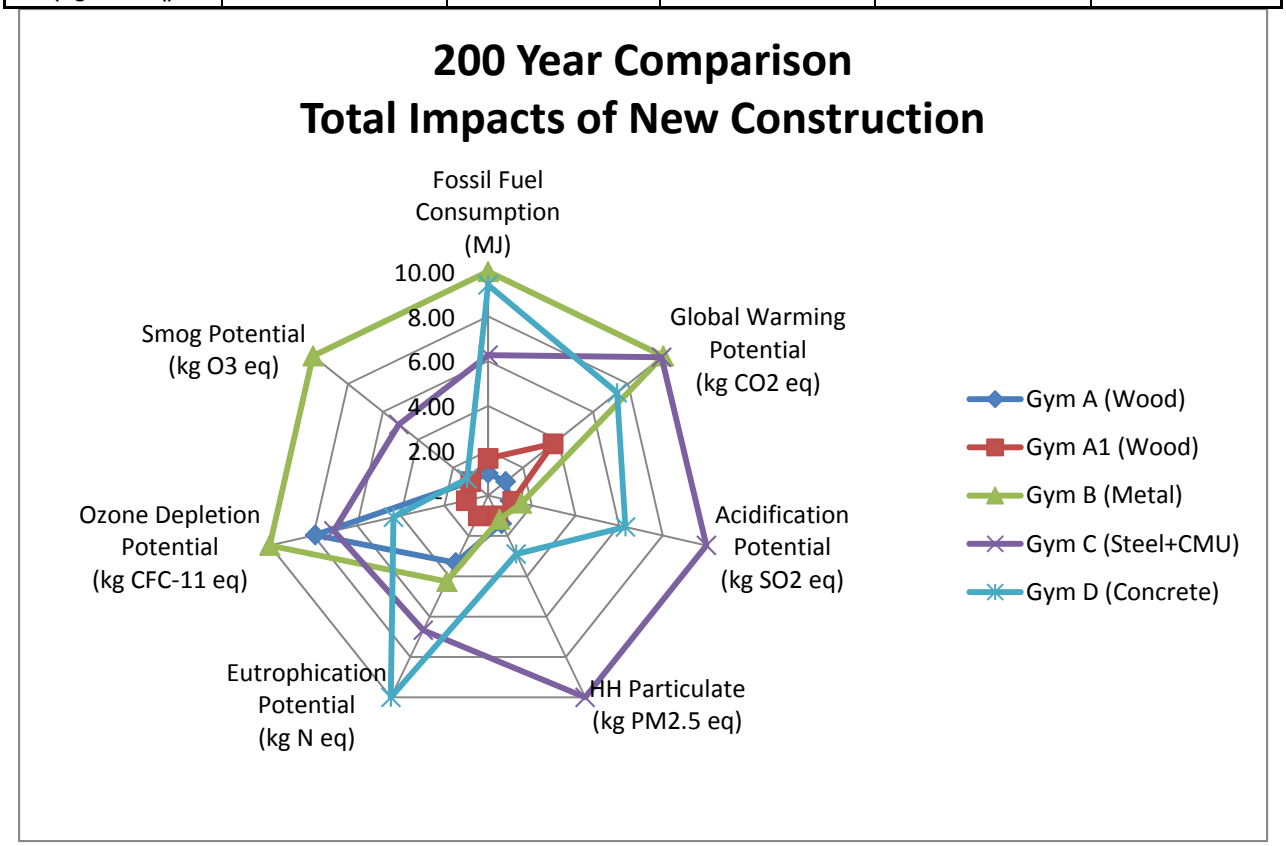

Figure 17: 200 year comparison of total environmental impacts including first impacts and maintenance, normalized on a scale of 10. Note that the Gym B and C typically have the largest impacts while Gym D has mixed total impacts and Gym A and A1 the least total impacts.

200 Year Comparison - Total Impacts of New Construction					
Summary Measures		Year 1	Year 50	Year 100	Year 200
Fossil Fuel Consumption (MJ)	Gym A (Wood)	1,698,521	3,830,437	5,974,851	10,659,582
	Gym A1 (Wood)	1,827,203	4,088,543	6,362,370	11,306,703
	Gym B (Metal)	3,562,531	7,456,987	11,369,245	19,472,283
	Gym C	6,510,123	7,029,844	7,909,829	15,819,658
	Gym D (Concrete)	8,744,113	10,307,462	13,168,382	18,890,220
		Year 1	Year 50	Year 100	Year 200
Global Warming Potential (kg CO2 eq)	Gym A (Wood)	66,382	143,533	221,078	385,751
	Gym A1 (Wood)	125,235	262,874	400,895	688,194
	Gym B (Metal)	264,998	542,951	821,683	1,389,764
	Gym C	624,956	647,297	689,751	1,379,503
	Gym D (Concrete)	820,680	857,939	937,392	1,096,298
		Year 1	Year 50	Year 100	Year 200
Acidification Potential (kg SO2 eq)	Gym A (Wood)	791	1,676	2,564	4,429
	Gym A1 (Wood)	799	1,691	2,586	4,463
	Gym B (Metal)	1,412	2,905	4,404	7,464
	Gym C	2,994	3,141	3,423	6,847
	Gym D (Concrete)	4,107	4,346	4,847	5,850
		Year 1	Year 50	Year 100	Year 200
HH Particulate (kg PM2.5 eq)	Gym A (Wood)	280	606	935	1,627
	Gym A1 (Wood)	243	530	820	1,435
	Gym B (Metal)	740	1,654	2,571	4,569
	Gym C	2,173	2,445	2,938	5,875
	Gym D (Concrete)	1,838	1,920	2,070	2,372
		Year 1	Year 50	Year 100	Year 200
Eutrophication Potential (kg N eq)	Gym A (Wood)	46	279	513	1,163
	Gym A1 (Wood)	49	102	155	264
	Gym B (Metal)	59	364	670	1,523
	Gym C	102	498	1,228	2,456
	Gym D (Concrete)	141	573	1,629	3,742
		Year 1	Year 50	Year 100	Year 200
Ozone Depletion Potential (kg CFC-11 eq)	Gym A (Wood)	0.00188	0.00384	0.00580	0.00981
	Gym A1 (Wood)	0.00127	0.00263	0.00399	0.00680
	Gym B (Metal)	0.00205	0.00420	0.00634	0.01072
	Gym C	0.00387	0.00412	0.00472	0.00944
	Gym D (Concrete)	0.00615	0.00639	0.00701	0.00825
		Year 1	Year 50	Year 100	Year 200
Smog Potential (kg O3 eq)	Gym A (Wood)	14,425	30,689	47,009	81,318
	Gym A1 (Wood)	14,684	30,948	47,268	81,318
	Gym B (Metal)	22,094	45,189	68,498	115,476
	Gym C	43,838	45,507	48,423	96,846
	Gym D (Concrete)	64,694	66,901	71,962	82,083

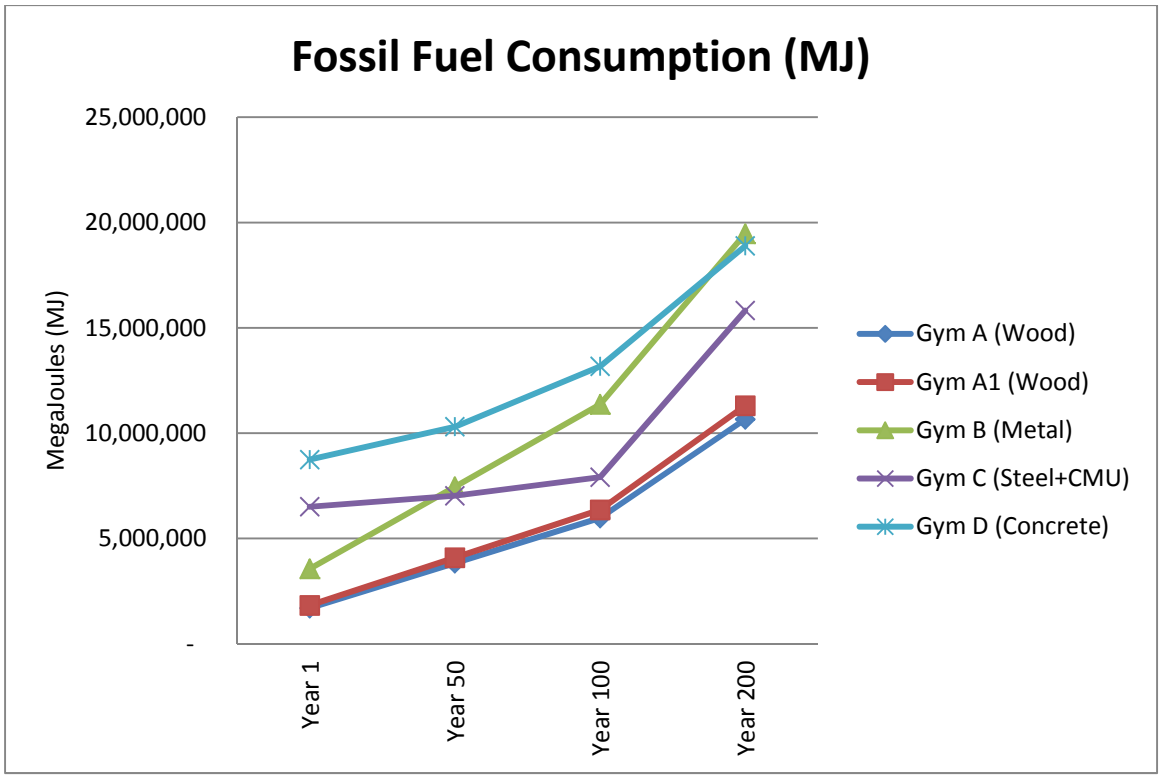

Figure 18: 200 year comparison of total impacts, including first impacts and maintenance impacts, for Fossil Fuel Consumption.

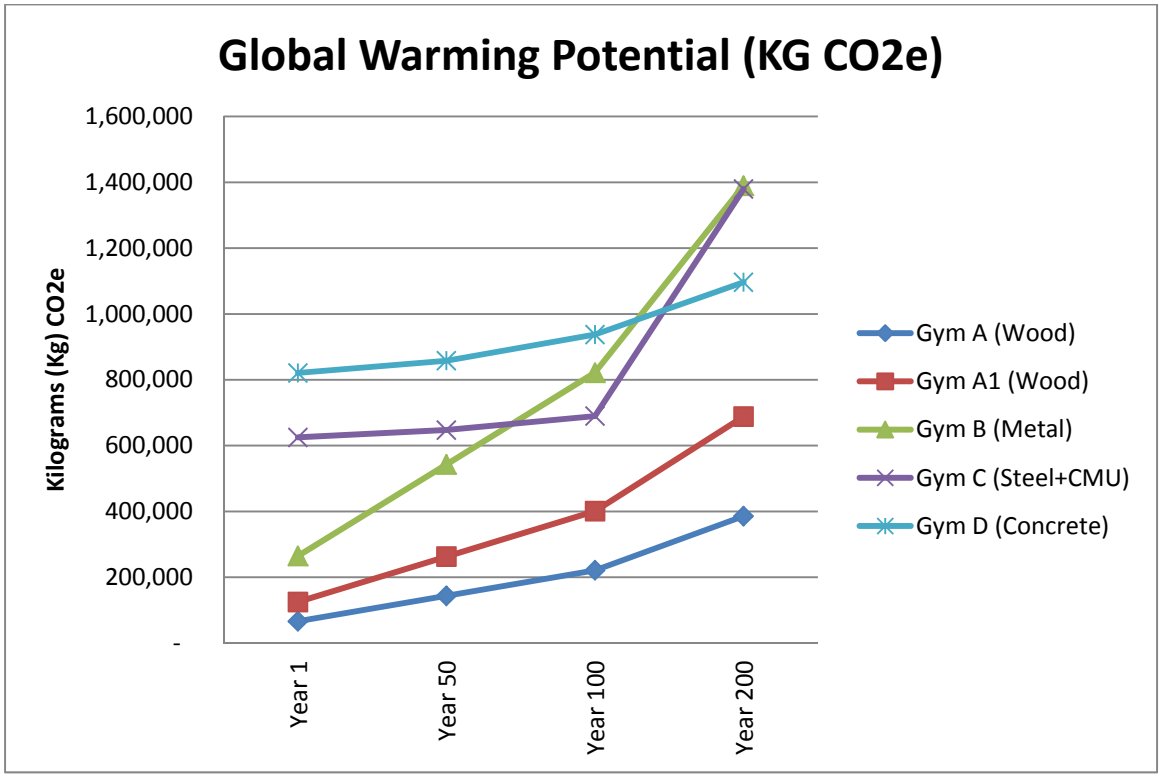

Figure 19: 200 year comparison of total impacts, including first impacts and maintenance impacts, for Global Warming Potential.

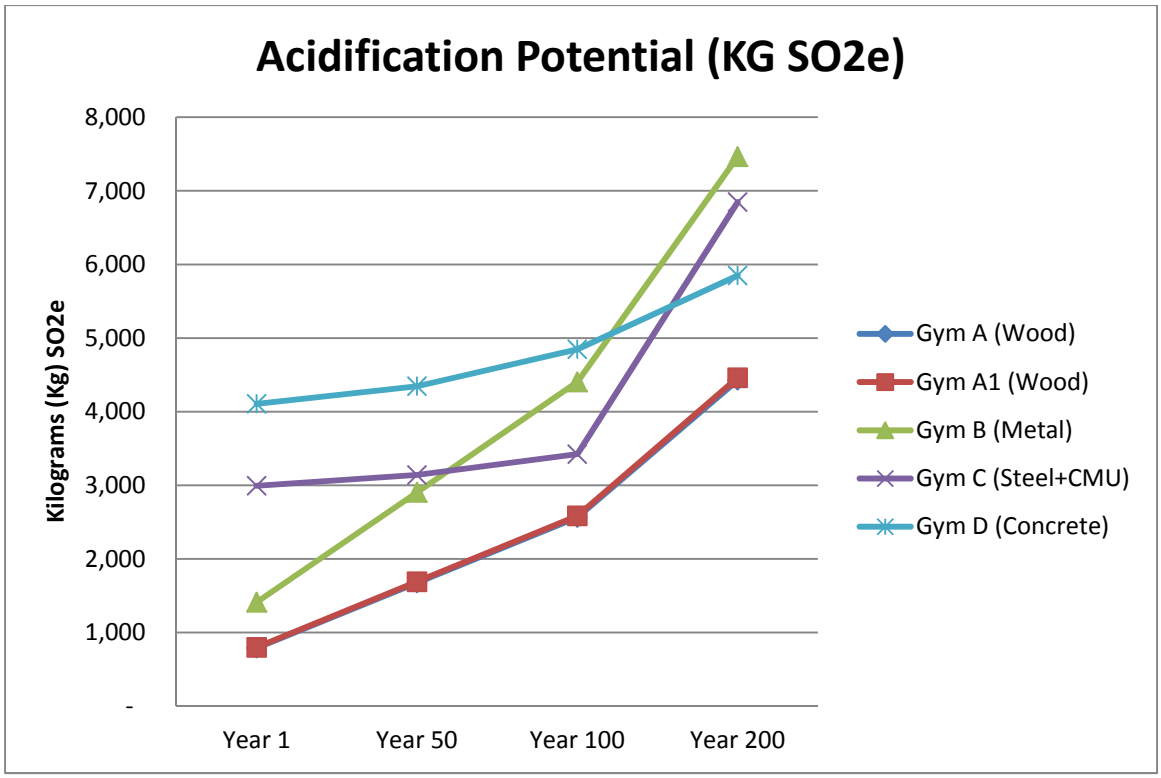

Figure 20: 200 year comparison of total impacts, including first impacts and maintenance impacts, for Acidification Potential.

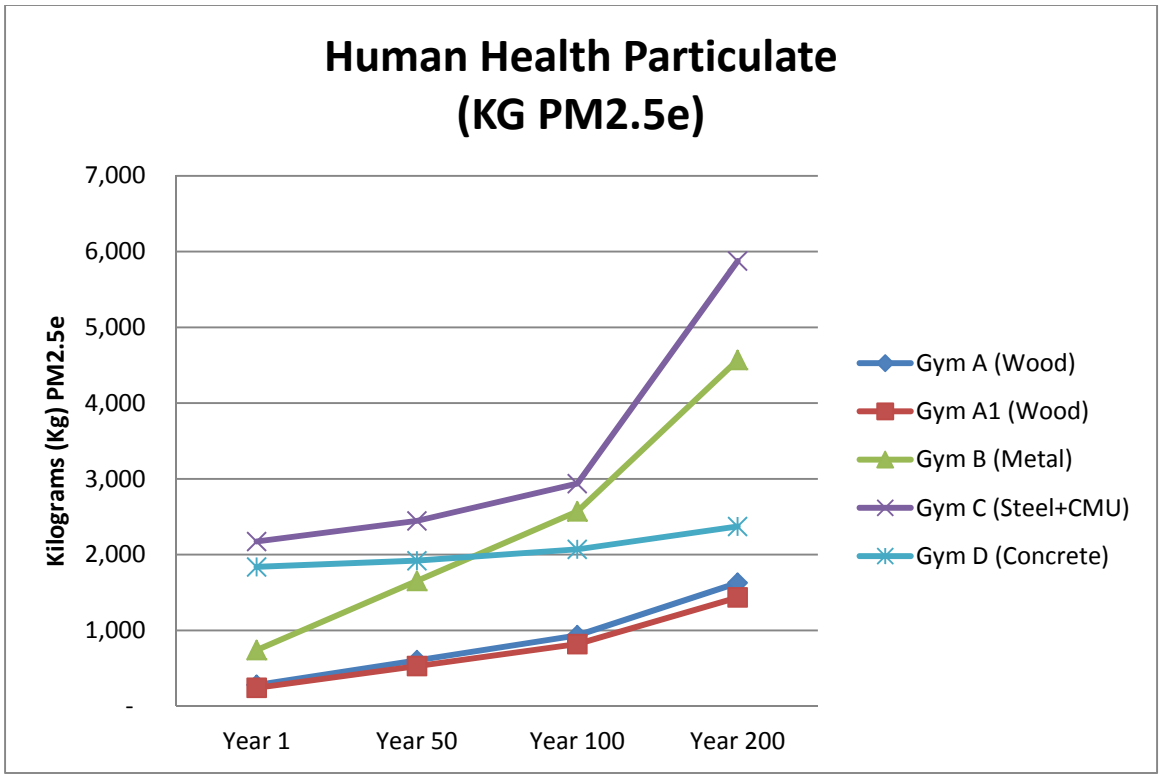

Figure 21: 200 year comparison of total impacts, including first impacts and maintenance impacts, for Human Health Particulate.

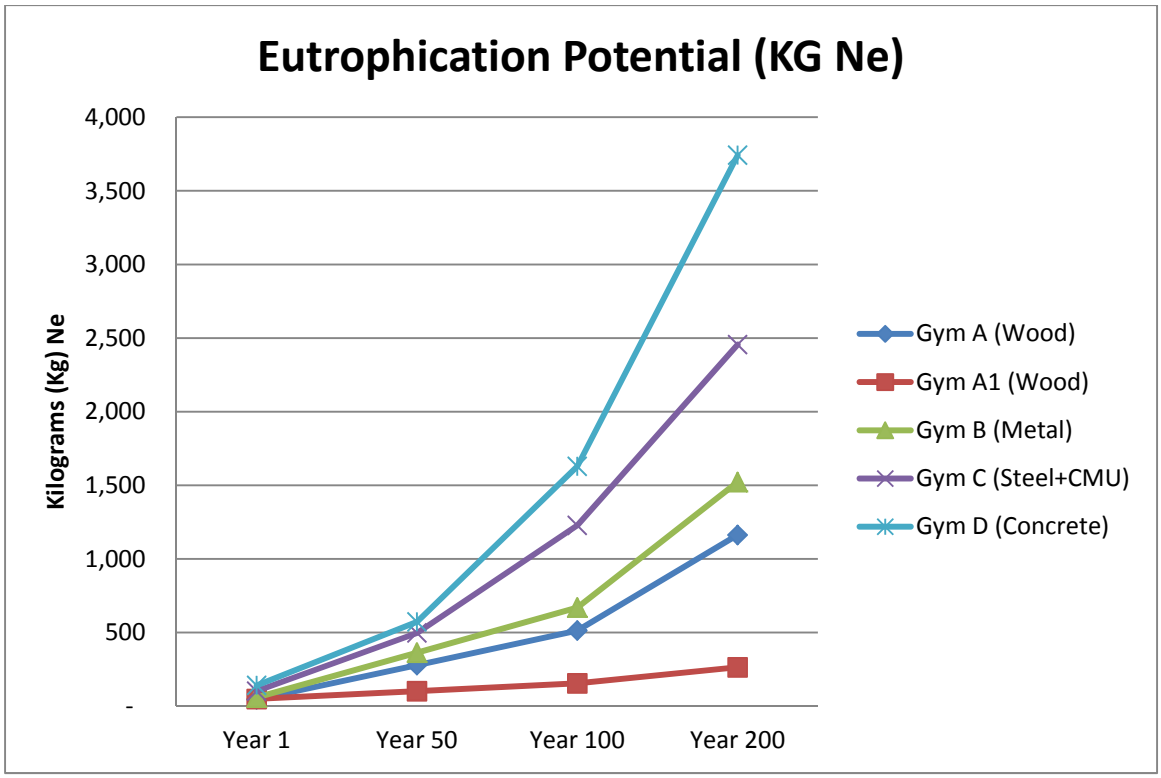

Figure 22: 200 year comparison of total impacts, including first impacts and maintenance impacts, for Eutrophication Potential.

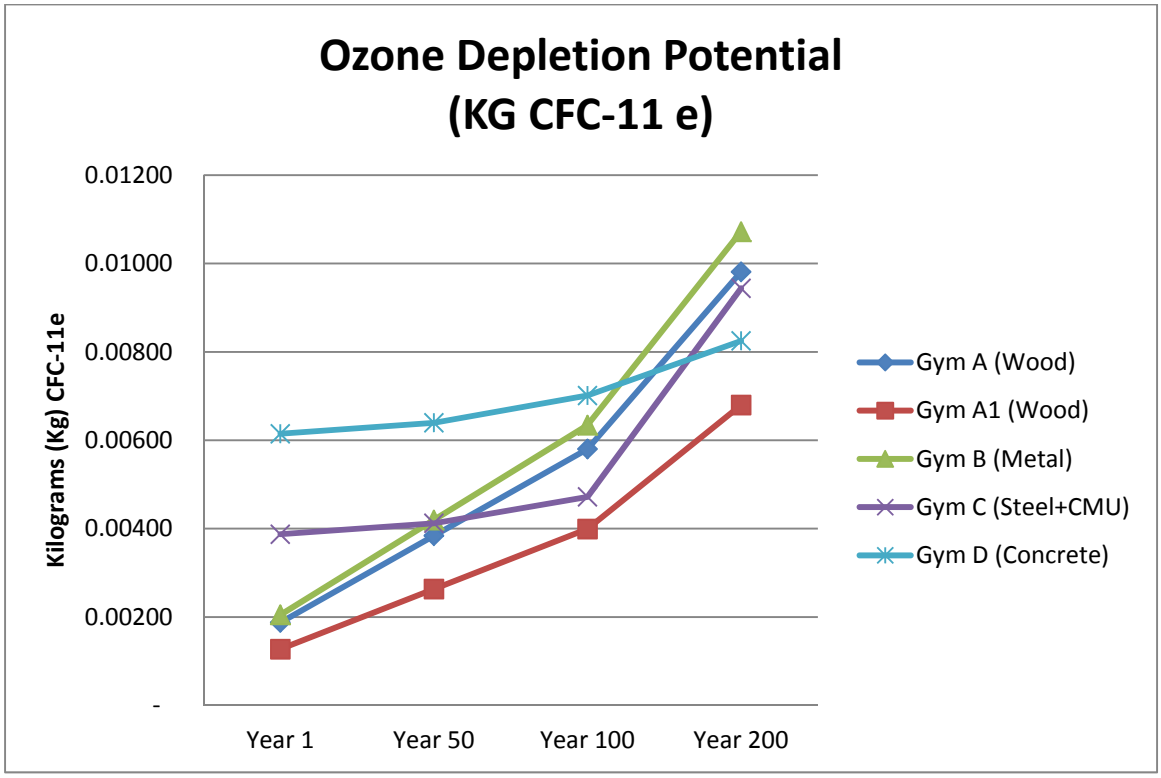

Figure 23: 200 year comparison of total impacts, including first impacts and maintenance impacts, for Ozone Depletion Potential.

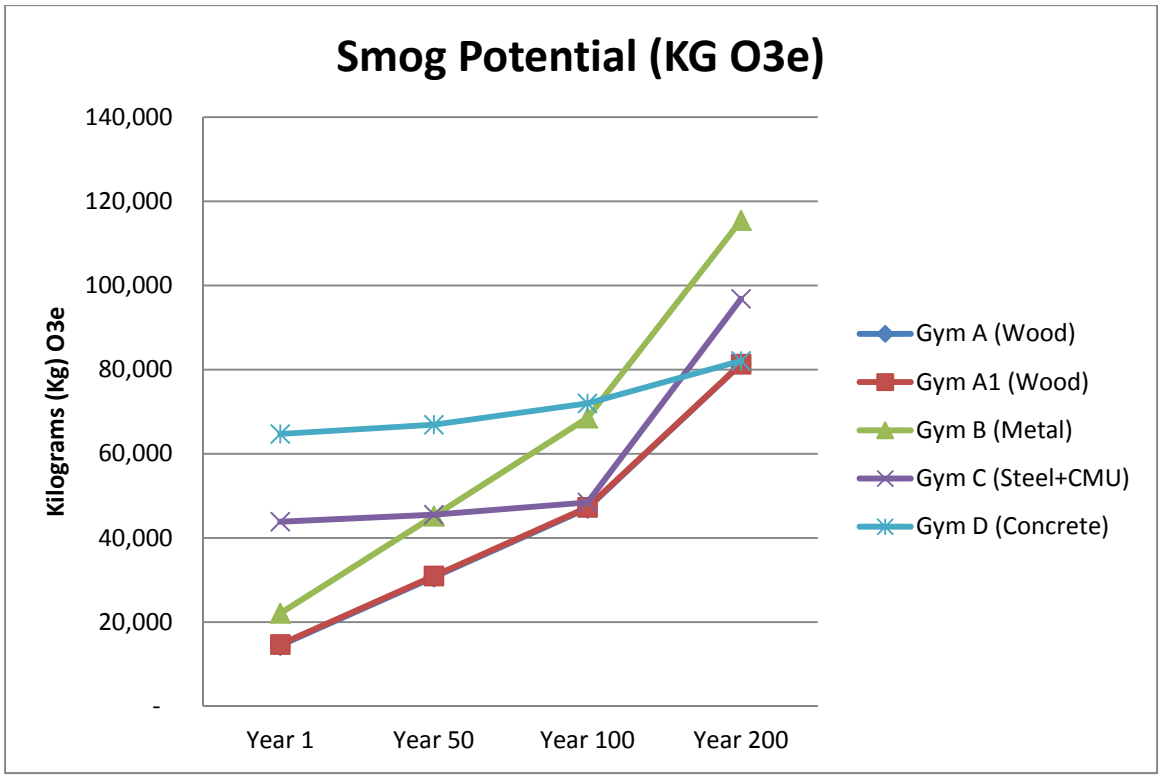

Figure 24: 200 year comparison of total impacts, including first impacts and maintenance impacts, for Smog Potential.

200 Year Comparison - New Gym A, A1 vs. Maintenance of Gym B, C, D

(Net Difference at Year 200)

	Gym A	Gym A1	Gym B	Gym C	Gym D
Fossil Fuel Consumption (MJ)	5,884,723	6,036,719	15,909,753	9,309,535	10,146,107
Global Warming Potential (kg CO2 eq)	185,048	268,017	1,124,766	754,547	275,618
Acidification Potential (kg SO2 eq)	1,908	1,910	6,052	3,853	1,744
HH Particulate (kg PM2.5 eq)	711	666	3,829	3,702	534
Eutrophication Potential (kg N eq)	1,678	95	1,464	2,353	3,601
Ozone Depletion Potential (kg CFC-11 eq)	0.00247	0.00187	0.00867	0.00557	0.00210
Smog Potential (kg O3 eq)	22,807	22,695	93,382	53,007	17,389

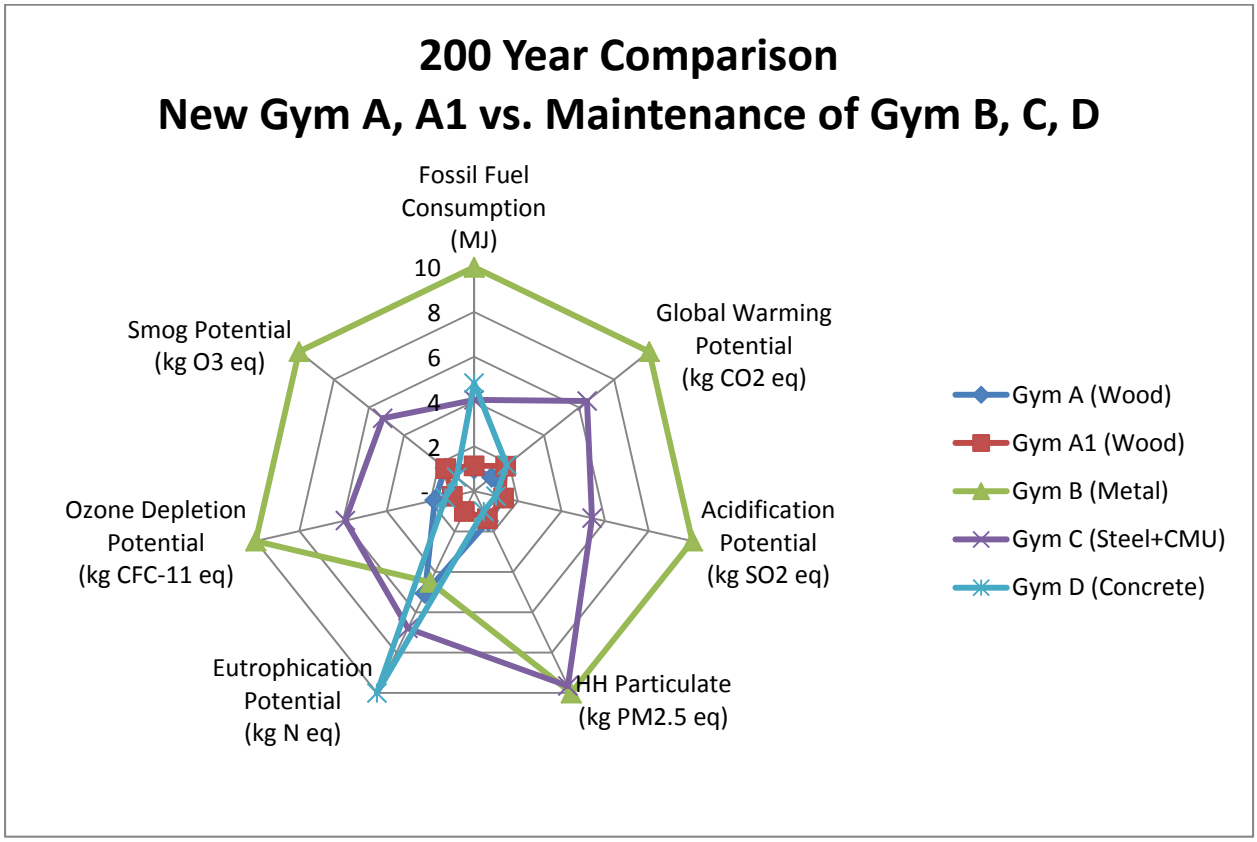

Figure 25: 200 year comparison of total environmental impacts, normalized on a scale of 10. This answers the question: If I am considering a new Gym, should I build a new wood gym or continue to maintain my existing concrete or masonry one? Note that there are many respects in which Gym A and A1 have lower impacts, Gym D has moderate impacts, and Gym B and C have the largest impacts.

200 Year Comparison - New Gym A, A1 vs. Maintenance of Gym B, C, D					
Summary Measures		Year 1	Year 50	Year 100	Year 200
Fossil Fuel Consumption (MJ)	Gym A (Wood)	1,709,681	2,478,923	3,614,190	5,884,723
	Gym A1 (Wood)	1,838,363	2,609,692	3,752,034	6,036,719
	Gym B (Metal)	-	3,894,457	7,806,715	15,909,753
	Gym C (Steel+CMU)	-	519,721	1,399,706	9,309,535
	Gym D (Concrete)	-	1,563,349	4,424,269	10,146,107
		Year 1	Year 50	Year 100	Year 200
Global Warming Potential (kg CO2 eq)	Gym A (Wood)	66,578	87,304	119,886	185,048
	Gym A1 (Wood)	125,431	149,120	188,753	268,017
	Gym B (Metal)	-	277,953	556,685	1,124,766
	Gym C (Steel+CMU)	-	22,341	64,795	754,547
	Gym D (Concrete)	-	37,258	116,711	275,618
		Year 1	Year 50	Year 100	Year 200
Acidification Potential (kg SO2 eq)	Gym A (Wood)	792	975	1,286	1,908
	Gym A1 (Wood)	800	981	1,291	1,910
	Gym B (Metal)	-	1,493	2,992	6,052
	Gym C (Steel+CMU)	-	147	429	3,853
	Gym D (Concrete)	-	239	741	1,744
		Year 1	Year 50	Year 100	Year 200
HH Particulate (kg PM2.5 eq)	Gym A (Wood)	282	359	476	711
	Gym A1 (Wood)	244	320	435	666
	Gym B (Metal)	-	914	1,831	3,829
	Gym C (Steel+CMU)	-	272	765	3,702
	Gym D (Concrete)	-	82	232	534
		Year 1	Year 50	Year 100	Year 200
Eutrophication Potential (kg N eq)	Gym A (Wood)	46	334	782	1,678
	Gym A1 (Wood)	49	57	69	95
	Gym B (Metal)	-	305	611	1,464
	Gym C (Steel+CMU)	-	395	1,125	2,353
	Gym D (Concrete)	-	432	1,488	3,601
		Year 1	Year 50	Year 100	Year 200
Ozone Depletion Potential (kg CFC-11 eq)	Gym A (Wood)	0.00188	0.00188	0.00206	0.00247
	Gym A1 (Wood)	0.00128	0.00128	0.00145	0.00187
	Gym B (Metal)	-	0.00214	0.00429	0.00867
	Gym C (Steel+CMU)	-	0.00025	0.00085	0.00557
	Gym D (Concrete)	-	0.00025	0.00087	0.00210
		Year 1	Year 50	Year 100	Year 200
Smog Potential (kg O3 eq)	Gym A (Wood)	14,441	14,441	17,748	22,807
	Gym A1 (Wood)	14,701	14,701	17,885	22,695
	Gym B (Metal)	-	23,095	46,405	93,382
	Gym C (Steel+CMU)	-	1,669	4,585	53,007
	Gym D (Concrete)	-	2,207	7,268	17,389

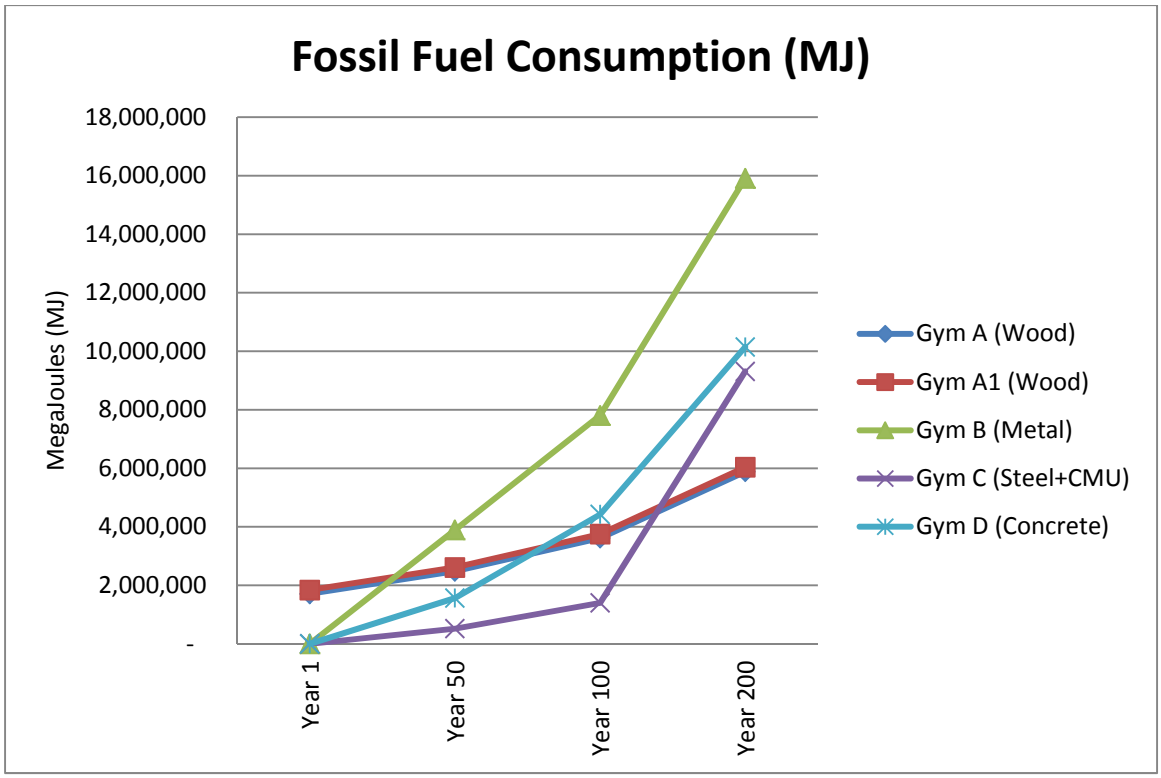

Figure 26: 200 year comparison of total impacts, including first impacts for Gym A and A1 and maintenance impacts for all gyms, for Fossil Fuel Consumption.

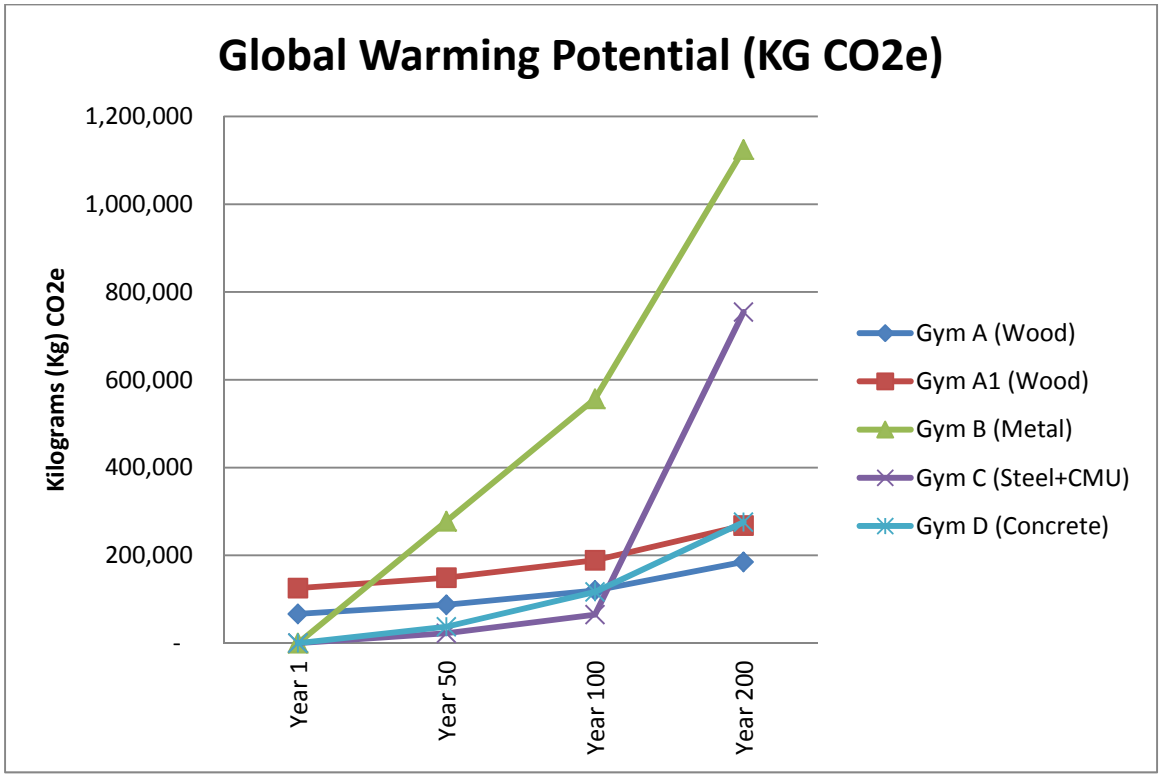

Figure 27: 200 year comparison of total impacts, including first impacts for Gym A and A1 and maintenance impacts for all gyms, for Global Warming Potential.

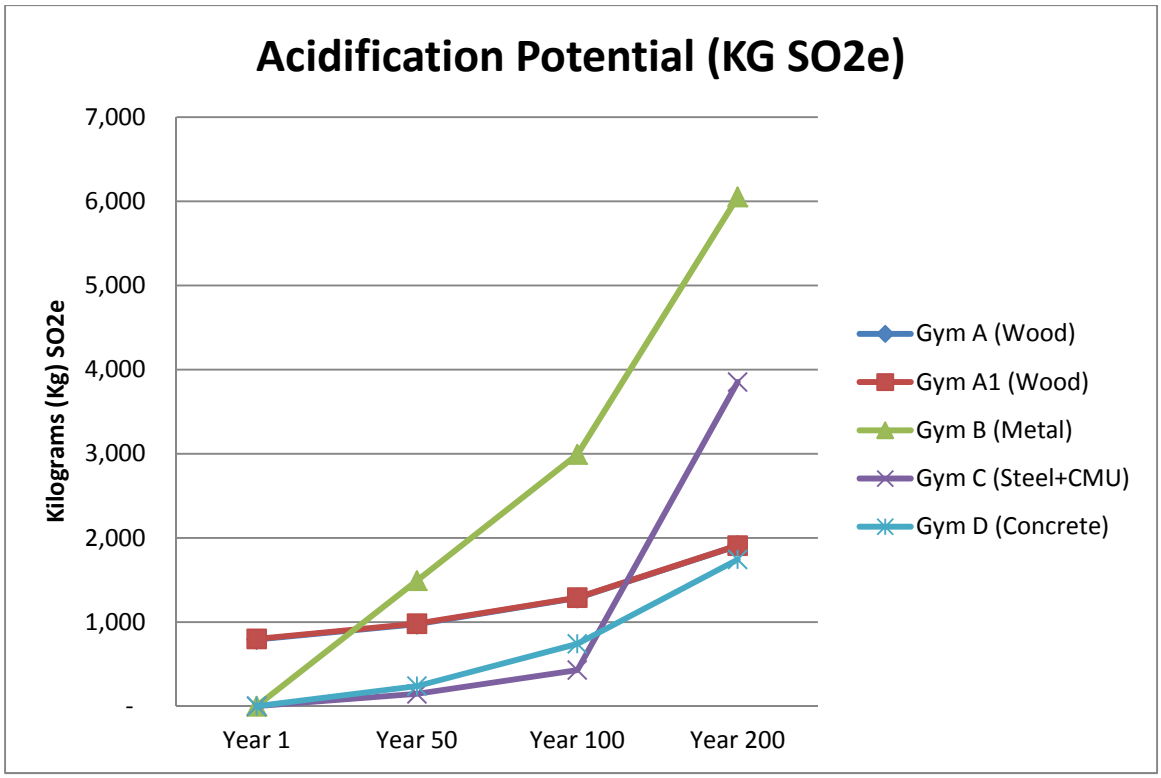

Figure 28: 200 year comparison of total impacts, including first impacts for Gym A and A1 and maintenance impacts for all gyms, for Acidification Potential.

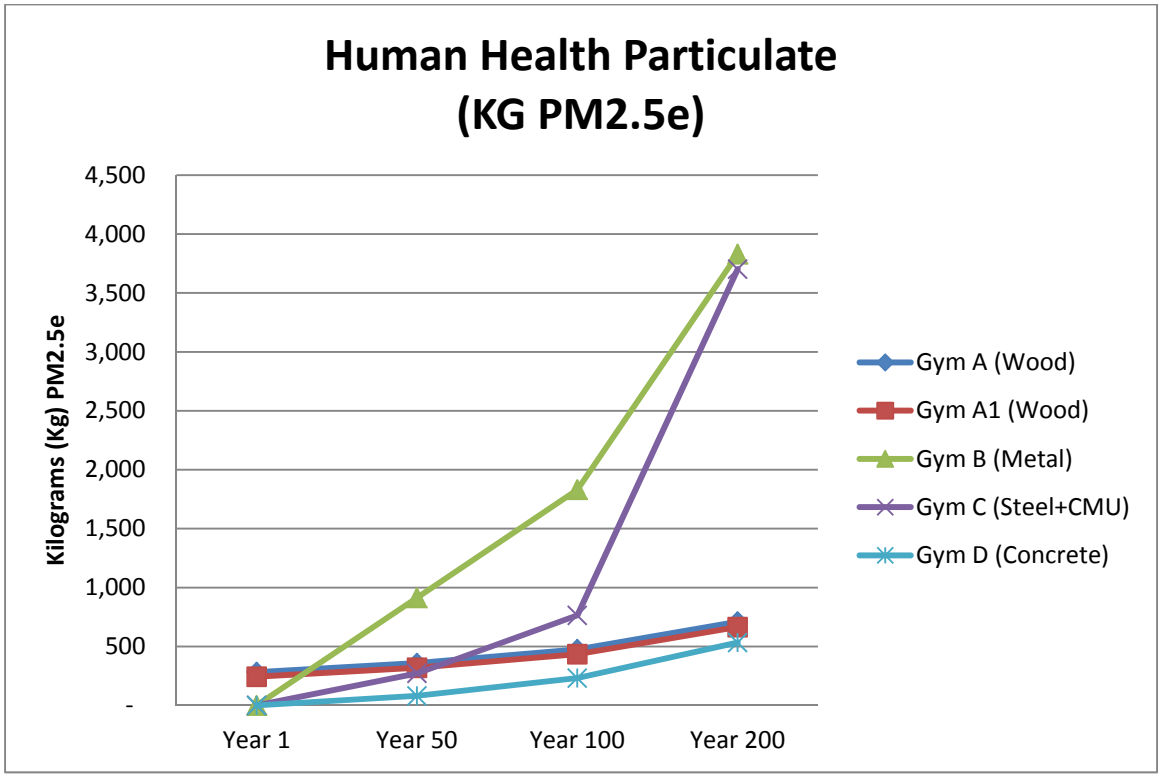

Figure 29: 200 year comparison of total impacts, including first impacts for Gym A and A1 and maintenance impacts for all gyms, for Human Health Particulate.

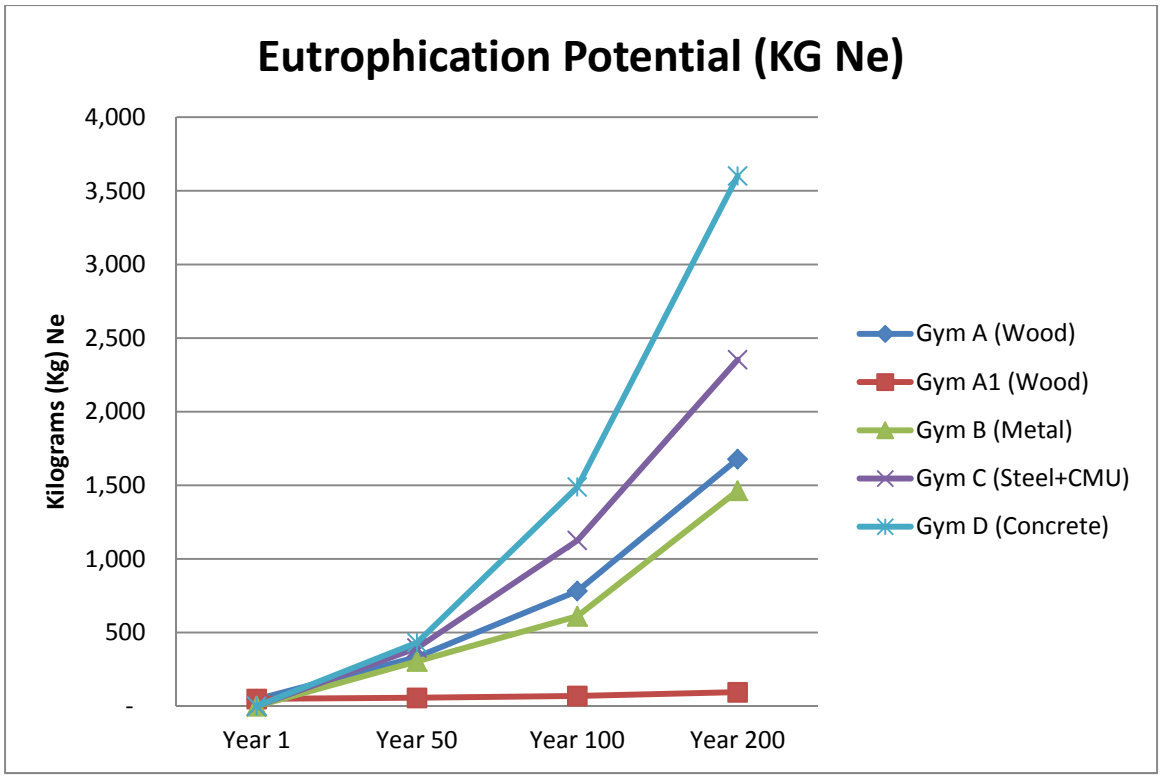

Figure 30: 200 year comparison of total impacts, including first impacts for Gym A and A1 and maintenance impacts for all gyms, for Eutrophication Potential.

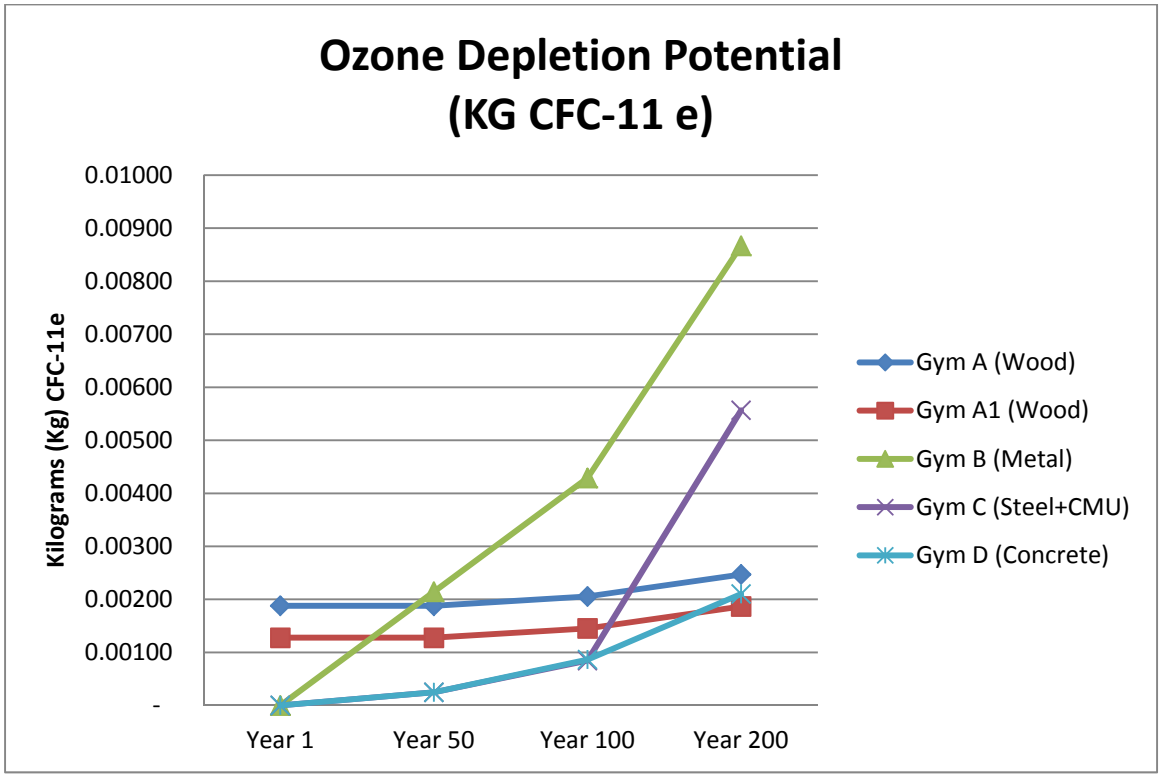

Figure 31: 200 year comparison of total impacts, including first impacts for Gym A and A1 and maintenance impacts for all gyms, for Ozone Depletion Potential.

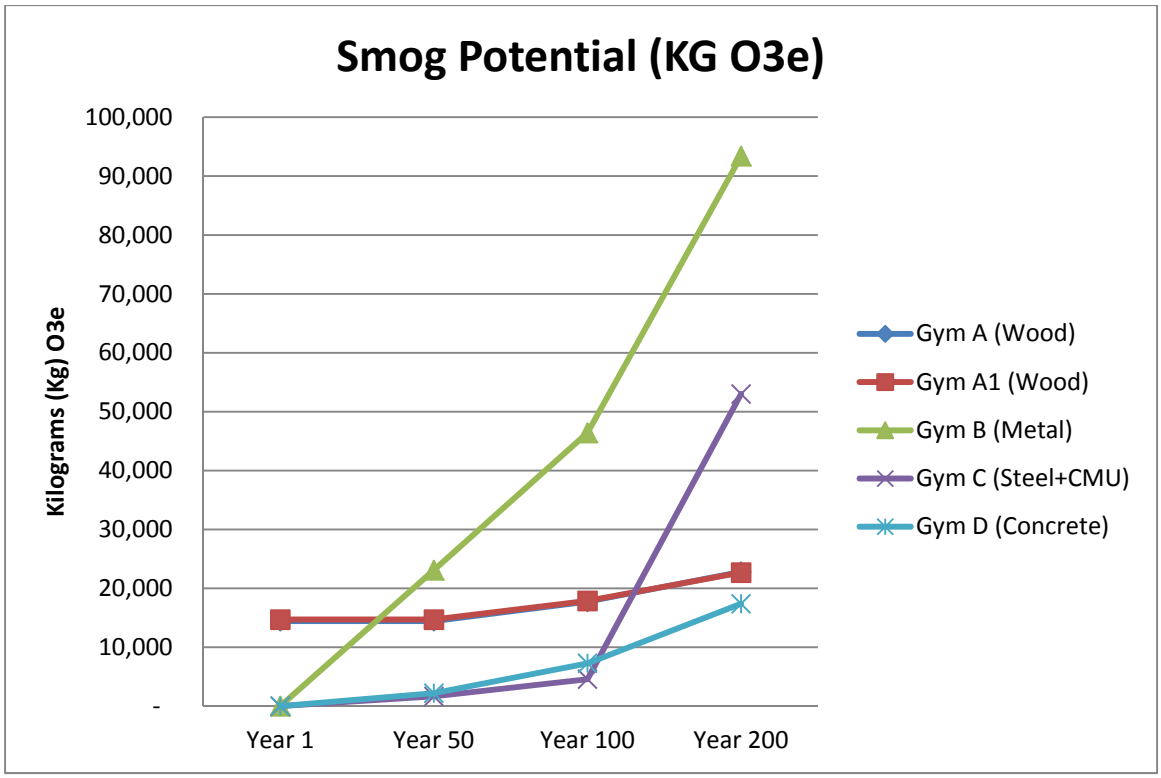

Figure 32: 200 year comparison of total impacts, including first impacts for Gym A and A1 and maintenance impacts for all gyms, for Smog Potential.

Life Cycle Analysis - 200 Year Comparison – Gymnasium - Bill of Materials

Gym A,B,C&D - Bill Of Materials Report - Quantity

Material	Unit	Quantity	Quantity	Quantity	Quantity	Quantity
Gym A		Year 1	Year 10	Year 20	Year 40	Net Change
Cedar Wood Bevel Siding	sf	15800	15800	15800	25281	9480
Double Glazed Hard Coated Argon	sf	1452	1452	1452	1936	484
#15 Organic Felt	100sf	277	277	277	554	277
Water Based Latex Paint	Gal (us)	128	128	167	334	206
Glass Based shingles 20yr	100sf	155	155	170	340	185
Gym A1		Year 1	Year 10	Year 20	Year 40	Net Change
Cedar Wood Bevel Siding	sf	15800	15800	15800	25281	9480
Double Glazed Hard Coated Argon	sf	1452	1452	1452	1936	484
#15 Organic Felt	100sf	277	277	277	554	277
PVC Window Frame	lbs	835	835	835	1097	261
Glass Based shingles 20yr	100sf	128	128	167	334	206
Gym B		Year 1	Year 10	Year 20	Year 40	Net Change
EPDM membrane (black, 60 mil)	lbs	4870	4870	4870	9740	4870
Double Glazed Hard Coated Argon	sf	1452	1452	1452	1936	484
PVC Window Frame	lbs	835	835	835	1114	278
Concrete 20 MPa (flyash av)	yd3	155	155	167	334	179
Concrete 30 MPa (flyash av)	yd3	84	84	155	249	165
Gym C		Year 1	Year 25	Year 50	Year 100	Net Change
EPDM membrane (black, 60 mil)	lbs	4870	6088	12175	13365	8495
Concrete Blocks	Blocks	16982	16982	16982	24350	7368
Triple Glazed Soft Coated Argon	sf	1452	1452	2421	4841	3389
5/8" Gypsum Fibre Gypsum Board	sf	13365	13365	13365	15800	2435
Aluminum Clad Wood Window Frame	lbs	940	940	1567	3133	2193
Gym D		Year 1	Year 50	Year 100	Year 200	Net Change
Polyiso Foam Board (unfaced)	sf (1")	101473	101473	101473	191235	89762
FG Batt R20	sf (1")	81499	81499	95617	167419	85919
Expanded Polystyrene	sf (1")	25571	47809	83709	101473	75902
Glass Facer	sf	25515	41855	81499	90288	64773
Modified Bitumen membrane	lbs	21992	25828	45144	81499	59507

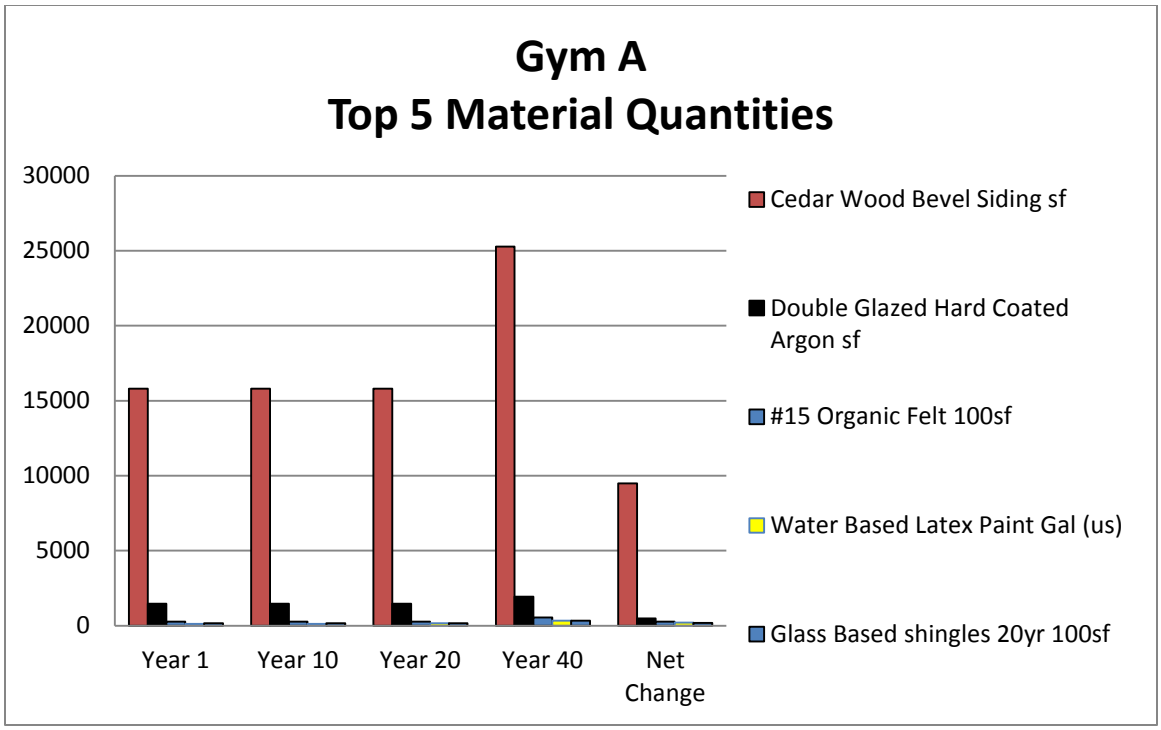

Figure 1: 200 Year Comparison – Gym A - Top 5 Material Quantities with the largest net change (maintenance or replacement).

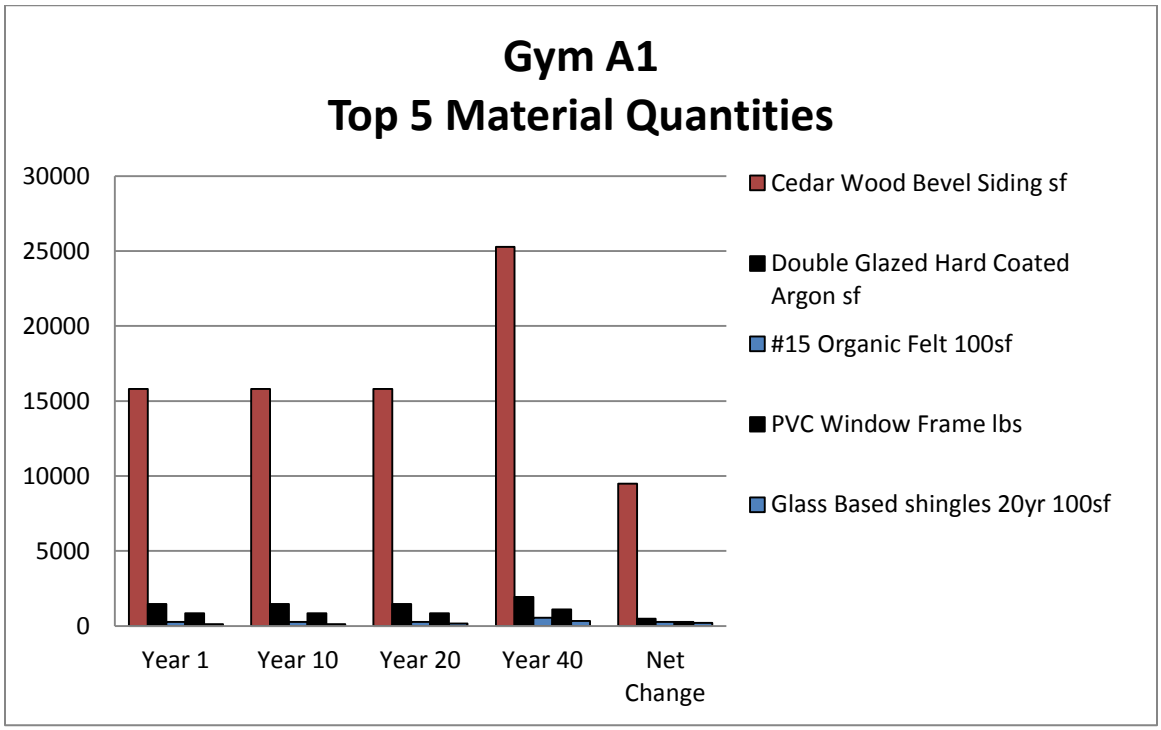

Figure 2: 200 Year Comparison – Gym A1 - Top 5 Material Quantities with the largest net change (maintenance or replacement).

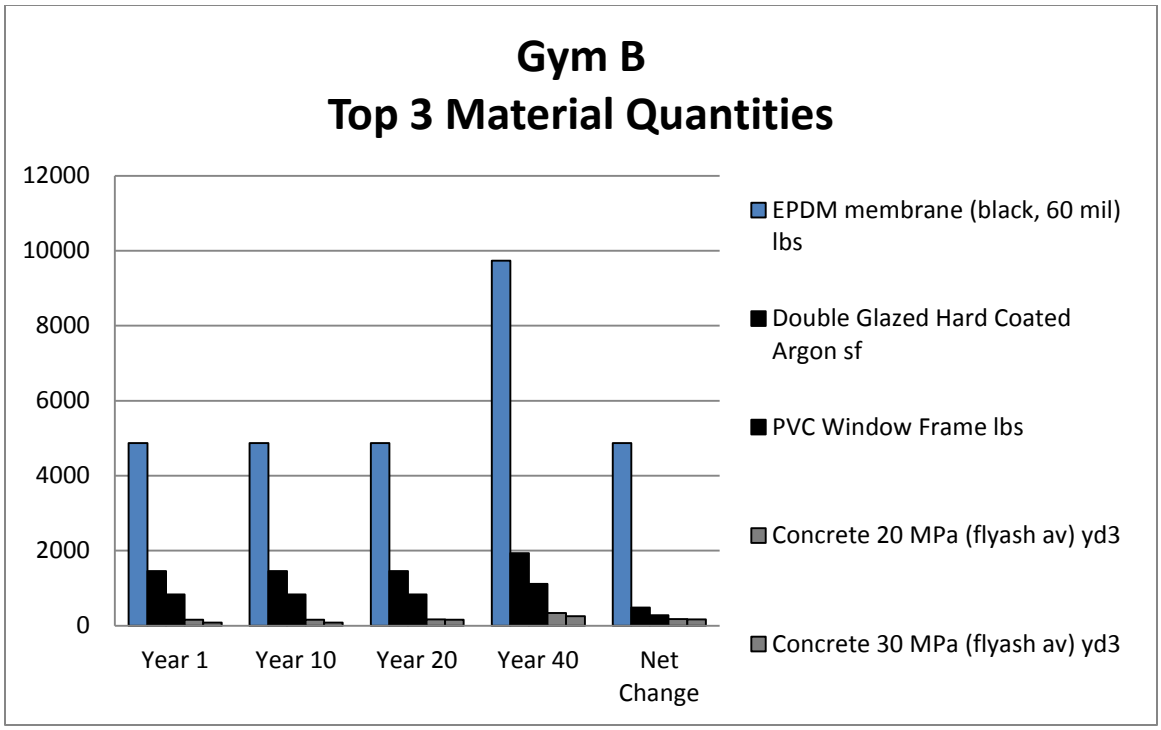

Figure 3: 200 Year Comparison – Gym B - Top 5 Material Quantities with the largest net change (maintenance or replacement).

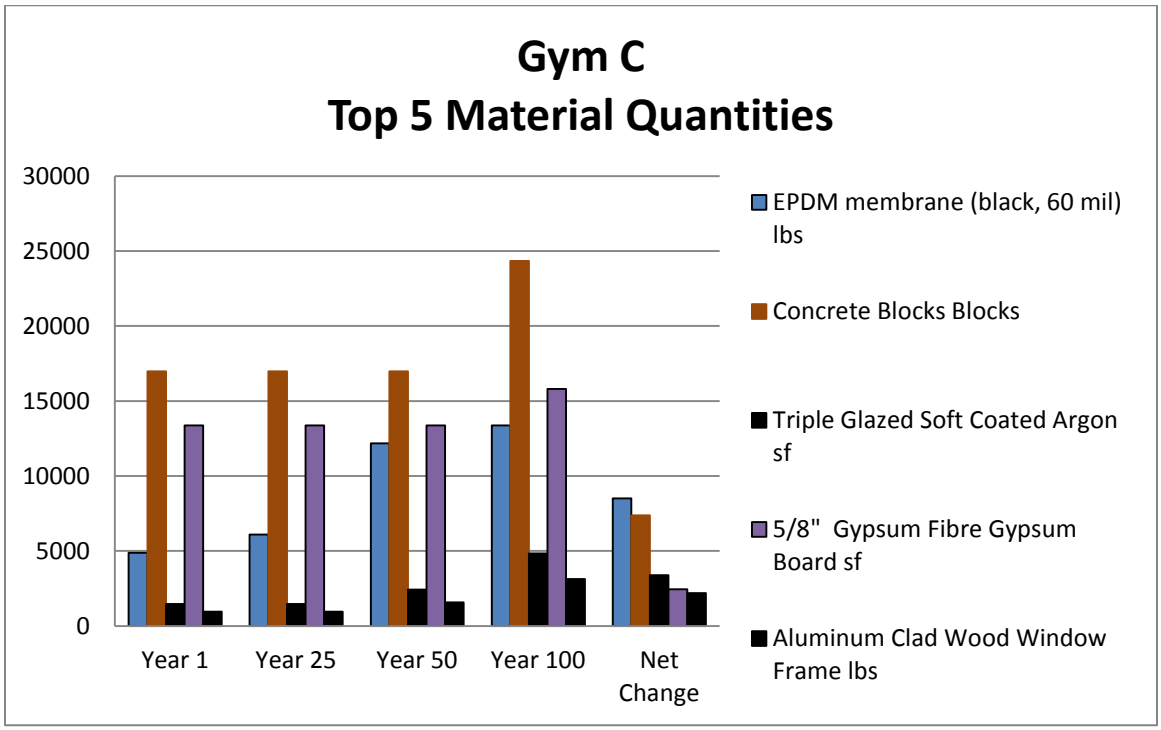

Figure 4: 200 Year Comparison – Gym C - Top 5 Material Quantities with the largest net change (maintenance or replacement).

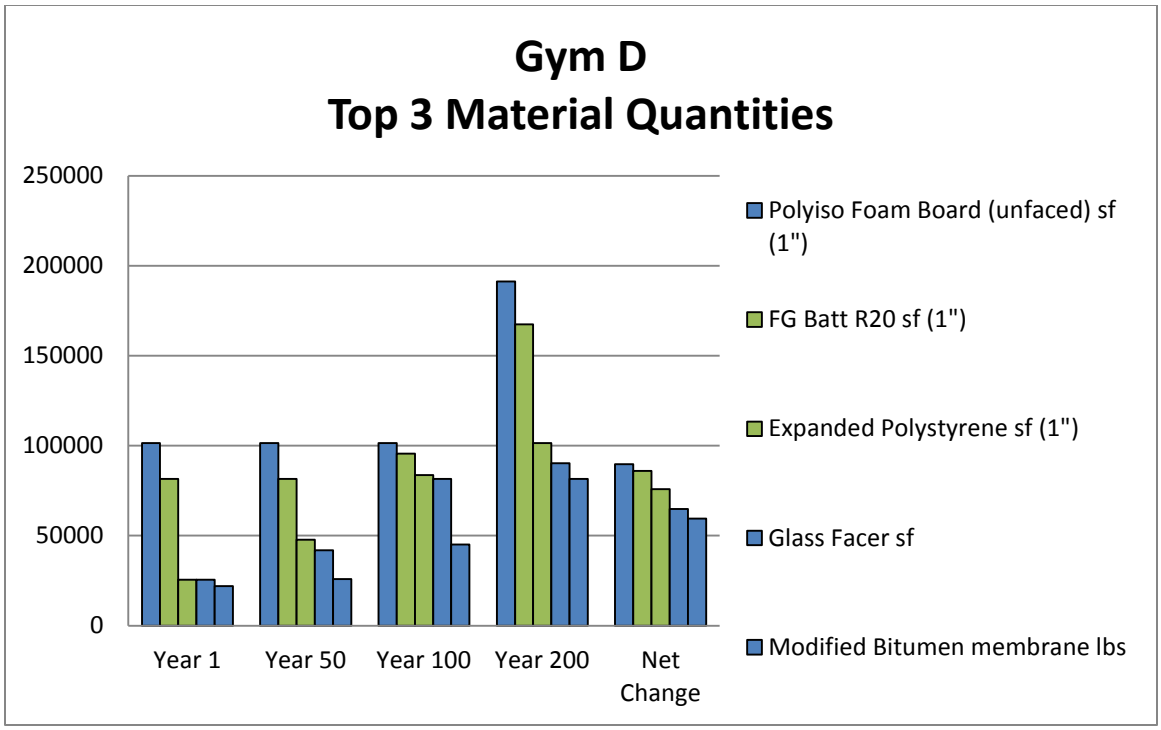

Figure 5: 200 Year Comparison – Gym D - Top 5 Material Quantities with the largest net change (maintenance or replacement).

Gym A,B,C&D - Bill Of Materials - Mass Value Comparison

Material	Mass Unit	Mass Value	Mass Value	Mass Value	Mass Value	Mass Value
Gym A		Year 1	Year 10	Year 20	Year 40	Net Change
Glass Based shingles 20yr	Tons	13.2	13.2	17.6	28.4	15.2
Cedar Wood Bevel Siding	Tons	6.8	6.8	6.8	11.0	4.1
Small Dimension Softwood Lumber, kiln-dried	Tons	28.4	28.4	28.4	31.4	2.9
5/8" Fire-Rated Type X Gypsum Board	Tons	31.4	31.4	31.4	33.7	2.3
Oriented Strand Board	Tons	33.7	33.7	33.7	35.2	1.5
Gym B	Tons	Year 1	Year 10	Year 20	Year 40	Net Change
FG Batt R30	Tons	3.3	3.3	3.3	4.6	1.3
EPDM membrane (black, 60 mil)	Tons	2.4	2.4	2.4	3.3	0.8
Double Glazed Hard Coated Argon	Tons	2.4	2.4	2.4	3.2	0.8
Galvanized Sheet	Tons	1.5	1.5	1.5	1.8	0.3
Glass Facer	Tons	0.7	0.7	0.7	1.0	0.3
Gym C	Tons	Year 1	Year 25	Year 50	Year 100	Net Change
Rebar, Rod, Light Sections	Tons	260.4	260.4	260.4	340.8	80.4
Triple Glazed Soft Coated Argon	Tons	3.7	3.7	6.2	12.2	8.5
Joint Compound	Tons	3.0	3.0	6.1	7.8	4.8
Polyiso Foam Board (unfaced)	Tons	7.8	7.8	7.8	12.3	4.5
Glass Facer	Tons	0.7	0.7	1.1	2.0	1.3
Gym D	Tons	Year 1	Year 50	Year 100	Year 200	Net Change
Ontario (Standard) Brick	Tons	186.9	186.9	186.9	332.9	146.0
Rebar, Rod, Light Sections	Tons	114.8	114.8	166.4	186.9	72.1
Stucco over metal mesh	Tons	58.3	83.2	114.8	114.8	56.5
Wide Flange Sections	Tons	36.0	36.0	47.8	83.7	47.7
Mortar	Tons	54.8	54.8	54.8	95.6	40.8

Note: Athena Version 4.2 does not provide Mass Info for A1 gym.

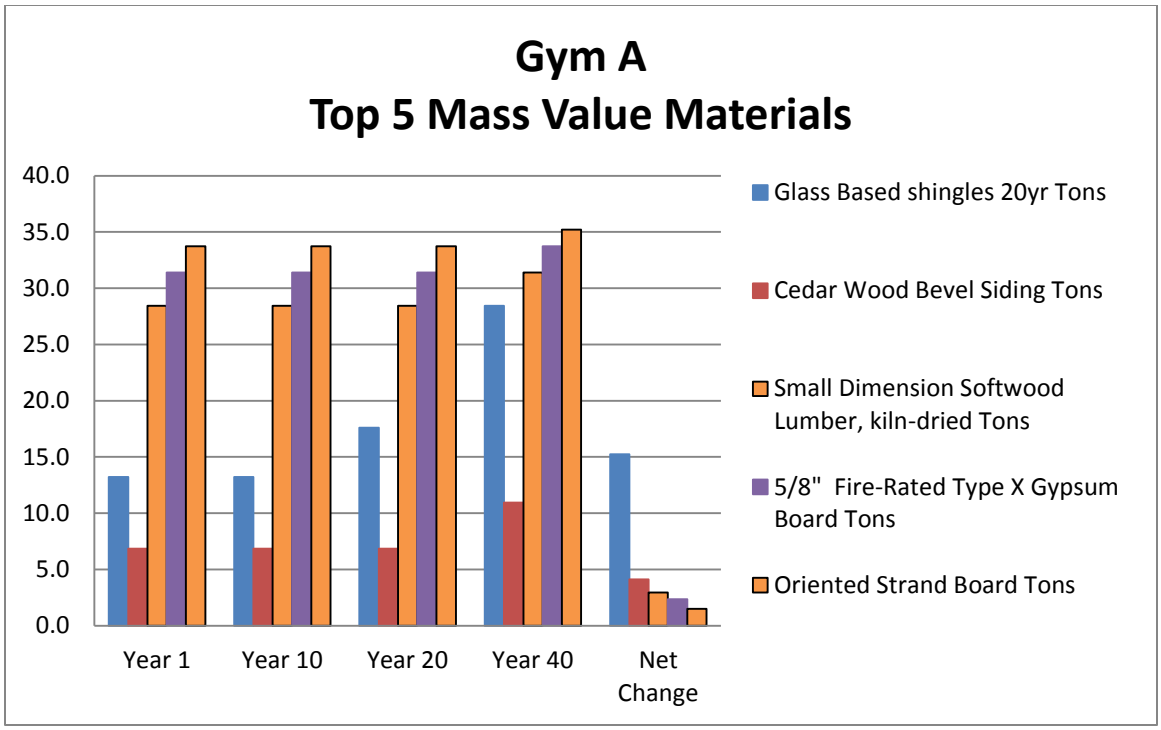

Figure 6: 200 Year Comparison – Gym A - Top 5 Mass Value Materials with the largest net change (maintenance or replacement).

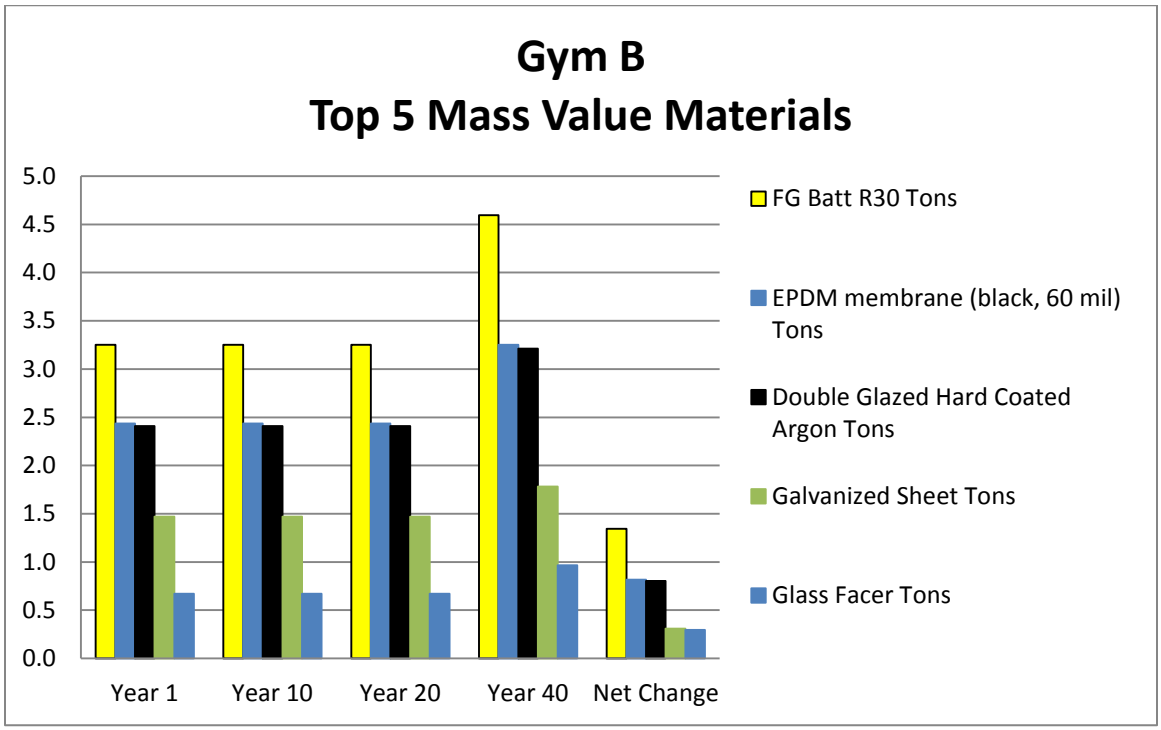

Figure 7: 200 Year Comparison – Gym B - Top 5 Mass Value Materials with the largest net change (maintenance or replacement).

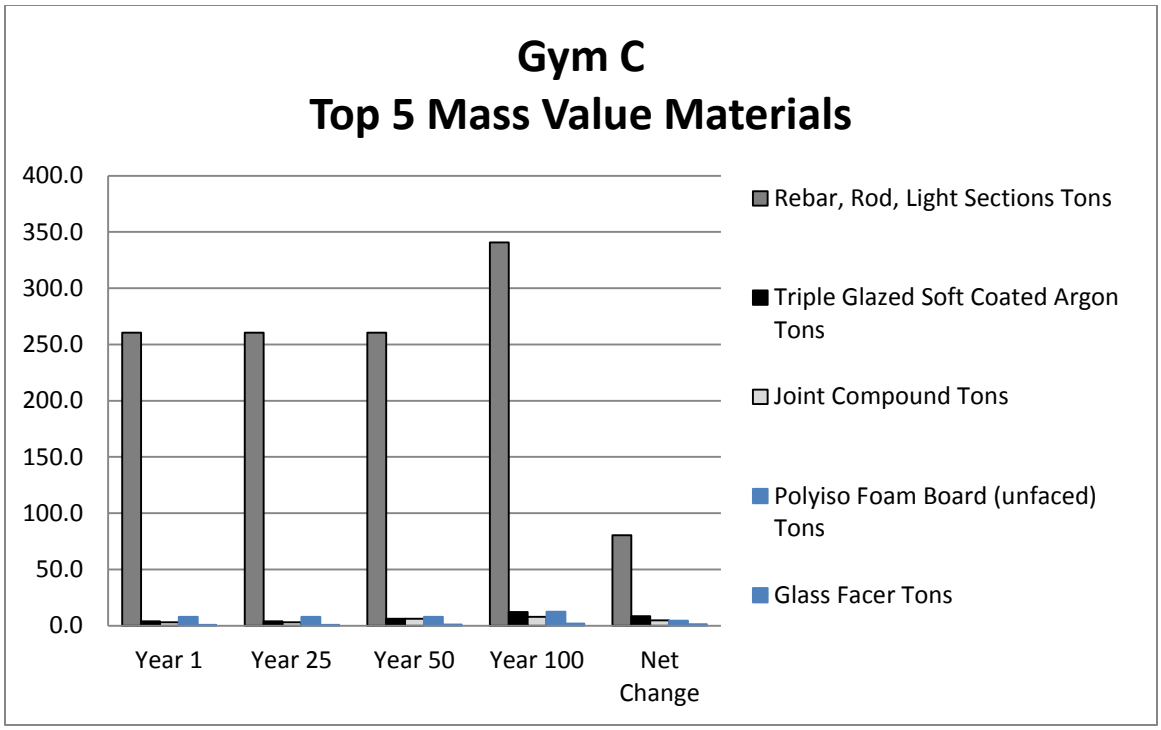

Figure 8: 200 Year Comparison – Gym C - Top 5 Mass Value Materials with the largest net change (maintenance or replacement).

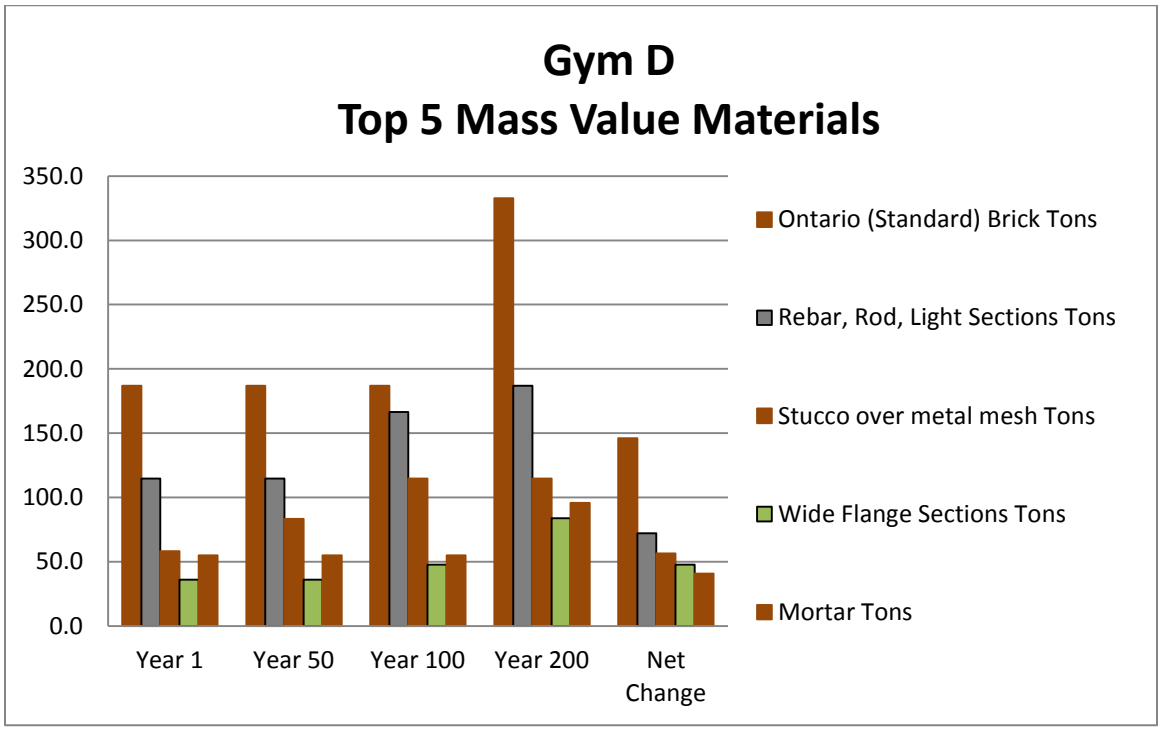

Figure 9: 200 Year Comparison – Gym D - Top 5 Mass Value Materials with the largest net change (maintenance or replacement).