CONSIDERING SUSTAINABILITY IN THE SELECTION OF STRUCTURAL SYSTEMS

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SUMMARY

A structural design engineer knowledgeable in the life cycle characteristics of materials can significantly reduce the ecological damage resulting from the construction of a building. Athena^{TM}, a life cycle analyses tool developed in Canada, was used to compare the environmental impact of a cast-in-place concrete system with a structural steel system for the Queen's University Integrated Learning Centre in Kingston, Canada. The case study showed that the concrete system had less impact on global warming, toxicity, solid emissions, and energy consumption, but required greater resource use than the structural steel system. Overall, the concrete system had less environmental impact than the structural steel system.

Key Words: Sustainability; Structural Systems; Life Cycle Analyses; Embodied Energy; Greenhouse Gases

1. INTRODUCTION

The objectives of sustainable development are to minimize the ecological damage resulting from infrastructure creation, operation, and maintenance. To date, sustainable building design has focused largely on a building's in-service energy efficiency. With continued improvements in this area, in-service non-renewable energy consumption continues to fall, and construction material selection becomes a more significant part of the overall environmental impact. This article will investigate the relative effect of the choice of different structural systems on embodied energy, and other environmental impacts.

In the construction of a typical building, the structural elements may represent about 20% of the total construction cost but about 80% of the mass. The structural design engineer, if aware of the embodied energy and other environmental impacts associated with different materials, may make a significant contribution to reducing the overall environmental impact of a new building.

The Integrated Learning Centre at Queen's University in Kingston, Canada is 3-story, 2300 m^2 footprint facility scheduled for occupancy in January 2004 (See Drawing S1). The structure is to seamlessly incorporate sustainable design concepts, and live building features (building components used for demonstration purposes from which students can learn about engineering). The goal is to have the building itself employed as a tool to educate engineering students. As part of the sustainable design process, life cycle analyses (LCA) of a cast-in-place concrete and structural steel system were compared.

Drawing S1: Queens University Integrated Learning Centre Rendering

2. BACKGROUND INFORMATION

Infrastructure development can negatively impact the environment by consuming resources and energy, contributing towards global warming, increasing air and water toxicity, and releasing solid wastes. LCA is a method in which these factors are quantified, allowing different building systems to be compared from an ecological standpoint. Through LCA, structural systems can be selected which minimize environmental impacts.

Athena™ is a life cycle analyses tool developed by the Athena™ Sustainable Materials Institute in Canada. Through computer modeling, environmental measures are calculated and presented for structural assemblies for the first three stages in a building's life cycle (resource extraction, processing, and installation) including transportation within and between stages. The model, drawing on databases within the program, presents a set of summary results including:

- weighted resource use;
- global warming potential;
- air toxicity index;
- water toxicity index;
- solid waste emission; and
- embodied energy inputs.

These outputs can be used to judge the relative environmental impact of different building structures.

2.1 Embodied Energy

Embodied energy is the measure of the amount of energy used to extract, process, transport, install, maintain, and dispose of a product, expressed in units of energy.

Values of embodied energy for a given product can be separated into initial, and recurring components, with "initial" containing all energy use from material extraction to installation. Building structures are typically very robust and tend to require few inputs (repairs or modifications) over the life of a structure. As a result the recurring component of their embodied energy is typically insignificant. This is in contrast to building envelope components and interior finishes where, over time, recurring embodied energy can more than double the initial component. This paper does not consider recurring embodied energy.

2.2 Resource Use

Resource use measures all the natural resources consumed in the procurement of building materials. It includes both the materials existing in the end product, plus all material required to install and manufacture the product. For example, resource use includes products such as formwork and falsework for cast-in-place concrete.

Since the environmental impacts of extracting various raw materials are not the same, an ecologically weighted system is defined in order to compare construction products when conducting a life cycle analysis. Resource use does not include energy feedstocks used as raw materials as this impact is included in energy use. Resource use is expressed in a ecologically weighted mass of raw material consumption.

2.3 Global Warming

Global warming is expressed as the equivalent mass of CO_2 (carbon dioxide) released into the atmosphere resulting from the manufacture, transportation, installation, and operation of a building component. Gases other than CO_2, such as NO_2 (nitrous oxide), CH_4 (methane), and CFC's (chloroflorocarbons), have the similar property of trapping heat within the earth's atmosphere. These gases all vary in there ability to trap heat, and are therefore expressed as an equivalent mass of CO_2.

The life cycle analyses in this report include the release of greenhouse gases from both the combustion of energy (major source), and from manufacturing processes. For example, the CO_2 released during calcining of raw material in the manufacture of cement is included in the total greenhouse gas emissions.

2.4 Air and Water Toxicity

Air and water toxicity quantifies the health effects of substances emitted throughout the life cycle of building materials. The toxicity indices in this paper are based on the volume required to dilute the single most contaminating by-product to acceptable levels. Only one by-product is used in the index because it is believed, in most cases, that a volume of air or water can simultaneously dilute several pollutants.

2.5 Solid Waste Emissions

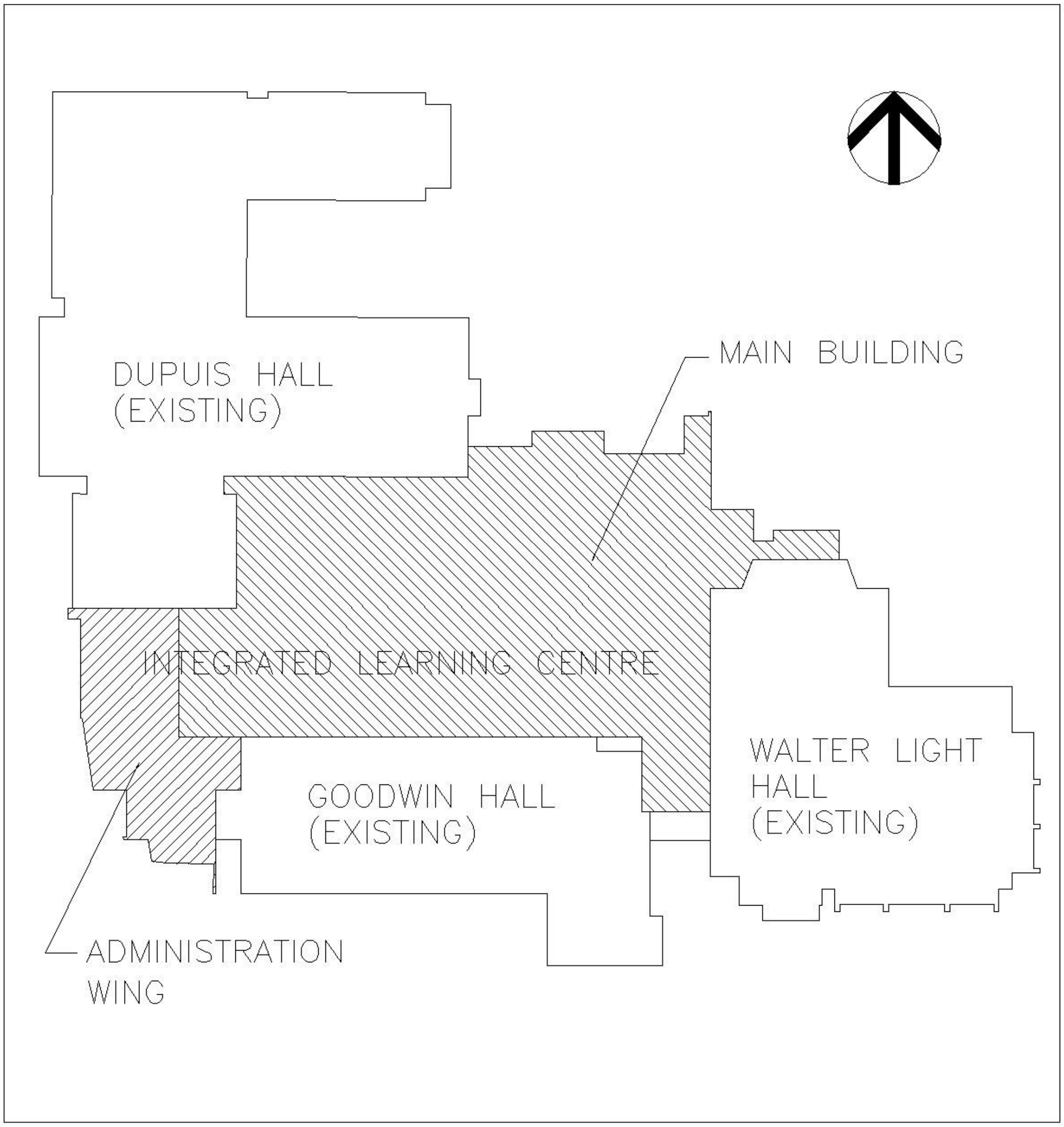
Solid waste emissions represent the total mass of emissions deposited to land as a result of using various building materials. The analyses in this paper do not distinguish between hazardous and non-hazardous wastes, as neither steel nor cast-in-place concrete have any appreciable amount of hazardous solid waste.

3. CASE STUDY: STRUCTURAL SYSTEMS AT THE INTEGRATED LEARNING CENTRE

The structure of the Integrated Learning Centre (ILC) can be broken up into two sections. The administration wing, located on the west end of the site, is 3 storeys tall and has a footprint of approximately 500 m^2, while the main building is 3 storeys and has a footprint of 1800 m^2 (See Drawing S2). The columns are generally laid out at 9 metre spacings in the east west direction, and range from 5 to 15 metre spacings in the north south directions.

In order to maximize the benefits of "live building" concepts, the design team planned to incorporate both cast-in-place concrete framing in some areas of the building, and structural steel supporting composite deck in others. Other structural systems, such as precast concrete and wood framing systems, were not used in any significant way because they were judged not the most appropriate for this type of facility.

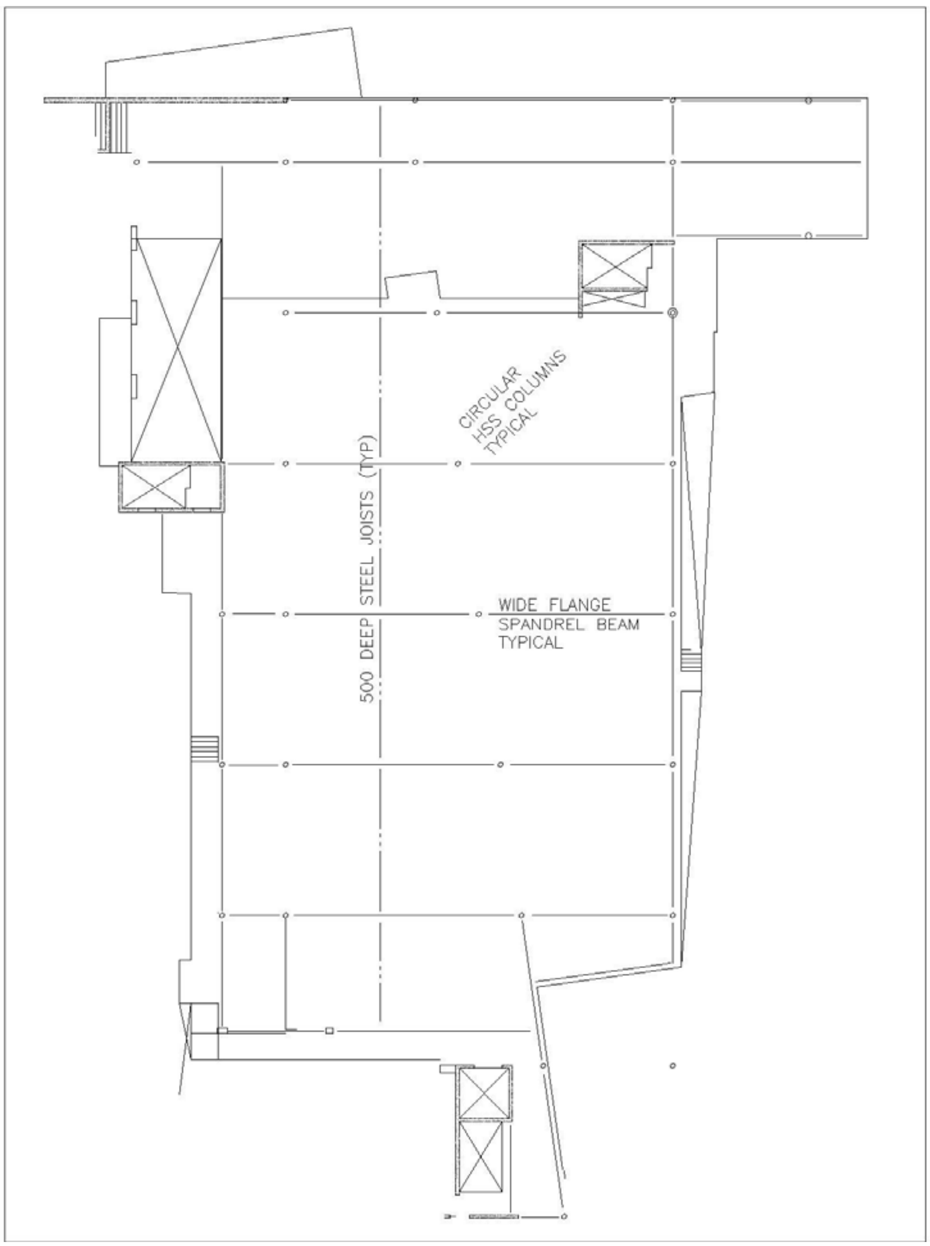
Athena^{TM} was used to model both the concrete system and the structural steel system for the main building. The system with the least environmental impact would be used in the larger main building, and the other system used in the smaller administration wing. Through this exercise, both the "live building" and sustainability requirements could be met.



Drawing S2: Case Study Queen's University ILC - Building Layout

3.1 Description of Structural Steel System

The layout of the structural steel system consisted of circular HSS columns, wide flange spandrel beams spanning in the north south direction between columns, and open web steel joists spanning in the east west direction between spandrel beams (See drawing S3). Conventionally reinforced concrete spread footings were used to support columns, and strip footings used to provide frost protection around the perimeter of the building. A 38 mm deep steel deck acting compositely with a 90 mm concrete slab was placed above the joists. 90 mm of concrete was selected because, with joists at 2m spacing, it provides a 1-hour fire rating between the floor levels without spray fireproofing. The roof consisted of a 38mm deep corrugated deck supported on open web steel joists and wide flange spandrel beams. Weights or materials used in the structural steel model were estimated based on a preliminary design of the system.

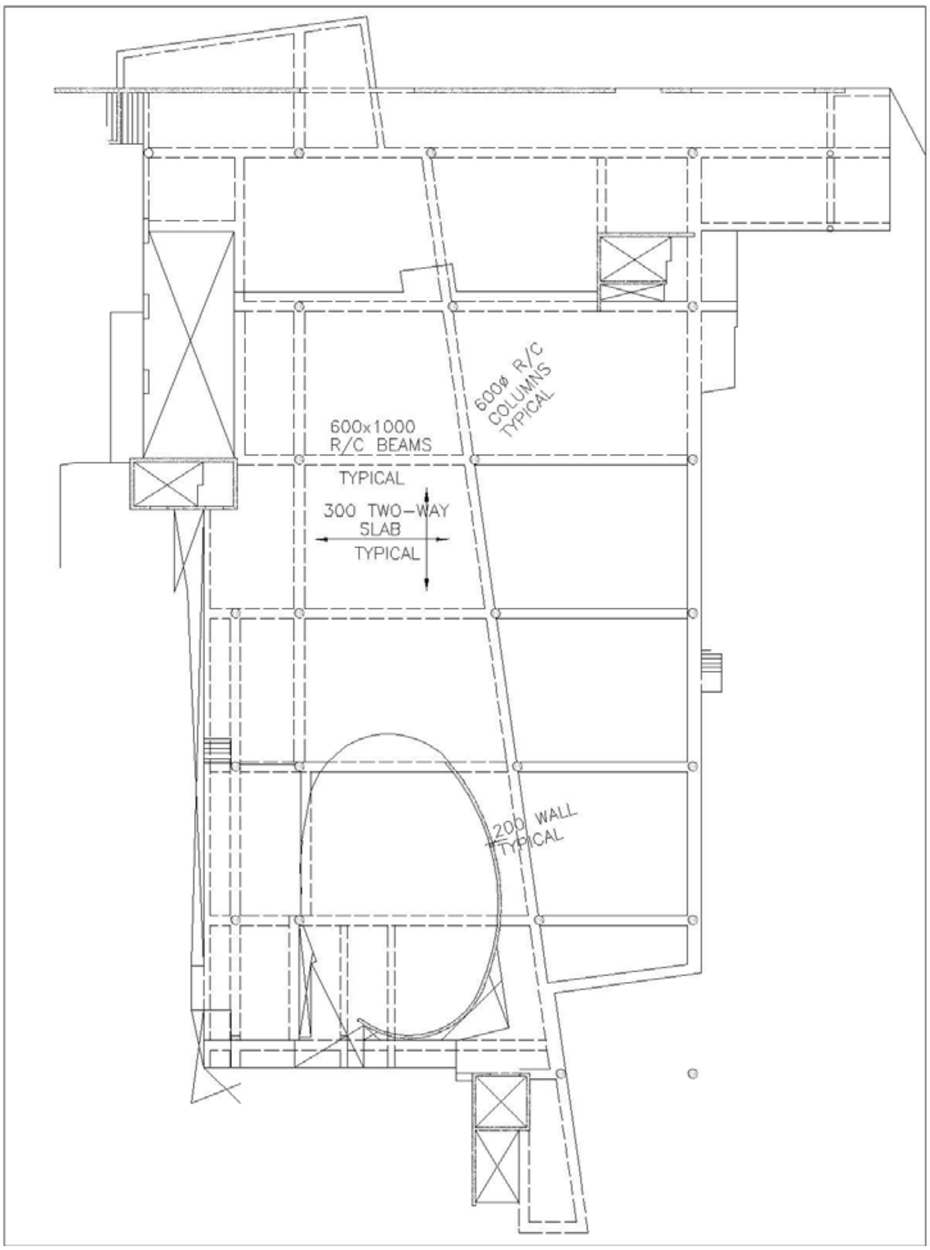


Drawing S3: Queen's University ILC - Steel System

3.2 Description of Cast-in-Place Concrete System

The layout of the cast-in-place concrete system consists of circular reinforced concrete columns, conventionally reinforced concrete beams spanning between columns in the north-south and east-west directions, and a 300mm two way reinforced slab designed as per CAN/CSA A23.1-94 Appendix E: Two way slabs on stiff supports, (See Drawing S4). Conventionally reinforced concrete spread footings were used to support columns, and strip footings were used to support walls and provide frost protection around the perimeter of the building. The roof consisted of a 38mm corrugated deck supported on open web steel joists and wide flange spandrel beams.

Weights of materials used in the cast-in-place concrete model were estimated based on a preliminary design of the system.



Drawing S4: Queen's University ILC - Concrete System

4. CASE STUDY RESULTS

The results of the life cycle analyses of the above structures are shown in tabular form on Figure 1. The concrete structure has significantly lower energy consumption, air and water toxicity, and global warming potential. Solid waste emissions for both systems are roughly equal. Resource use for the concrete system is more than double that of the structural steel system. Based on the data compiled by Athena™, it is the author's opinion that the concrete system has less environmental impact than the structural steel system.

Given the surprising results of the ILC analyses, a second set of analyses was completed for a single storey building, which seems intuitively well suited to steel framing. A technology shop at Cambrian College in Sudbury, Canada was used as a model for this analysis. The roof was modeled as wide flange beams supporting 38 mm deep corrugated steel deck for the structural steel system, and as a flat plate slab for the concrete system. In both systems, the floor was a 150 mm thick slab on grade, and the framed structure was supported on spread footings. In this second set of analyses steel framing had less environmental impact than concrete in all categories.

5. CONCLUSIONS

The environmental impacts of a building structure can vary dramatically depending on the type of system selected. Reinforced concrete appears to have significant benefits over structural steel for the Queen's University Integrated Learning Centre. However, structural steel systems can have less environmental impact than concrete structures for certain types of buildings. More research is required to better define what type of structural system will minimize environmental impact for a given building type. Athena™ does not include the impact of disposal at the end of the building's service life which may effect the results from life cycle analyses.

A number of Life Cycle Assessment tools are coming to market; structural engineers are advised to consider them as another tool for evaluating structural systems on their projects.

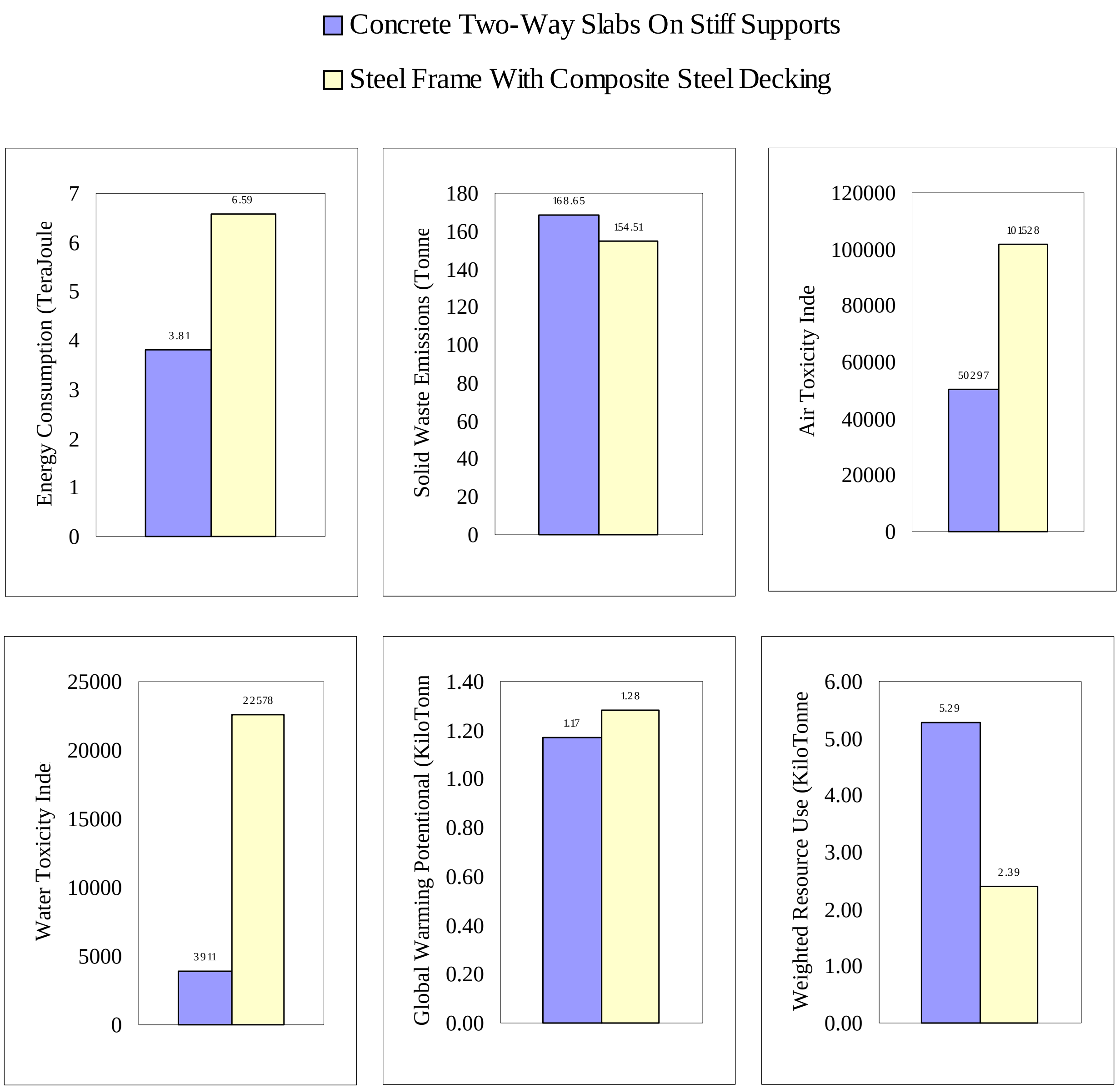


Figure 1: Environmental Impacts of Structural Steel vs. Cast-in-Place Concrete at Queens University – Integrated Learning Centre