# Measuring whole-building performance with dynamic LCA: a case study of a green university building

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## Abstract

This paper presents initial results of an ongoing project to monitor energy consumption and indoor environmental quality in a green university building, and to include the measured data in a dynamic life cycle assessment (DLCA) of the building. DLCA can be defined as an approach to life cycle assessment (LCA) that explicitly incorporates dynamic process modelling in the context of temporal and spatial variations in the surrounding industrial and environmental systems. DLCA has been suggested to be important for buildings due to their long lifetimes, during which they may undergo significant operational changes. An important part of the dynamic process modeling component is the measurement of actual data to validate or refine predictive models. A static LCA of the building was completed, including construction materials and a whole-building energy model. An initial DLCA was conducted incorporating estimates of future industrial and environmental factors, exemplified by energy mixes and emissions factors from energy production. Partial data from the building's operations were compared to energy model predictions and then incorporated into the DLCA model. Results showed substantial differences between impacts due to estimated actual energy consumption and energy model results, suggesting that that monitoring of buildings' actual performance over time is crucial to the accuracy of building LCA.

# 1. INTRODUCTION

## 1.1 A dynamic life cycle assessment (DLCA) method for buildings

Commercial and institutional buildings consume large amounts of energy and materials [1, 2], but have the potential for large improvements in performance in sustainability-related categories [3-5]. Life cycle assessment (LCA) can aid in quantifying the environmental impacts of buildings while identifying areas for potential improvement [6, 7]. However, the long lifetime of buildings and the complexities of their construction and operations, particularly in the use phase, require further method development [8, 9].

The lack of temporally specific data has been identified as a key need in LCA [10]. One approach to resolving this problem is to aggregate temporal and spatial variability into more general uncertainty terms and use probabilistic (e.g. Monte Carlo) analysis to overcome it [11]. Another approach is to link a level of explicit systems modelling with traditional aggregated LCA datasets, and use additional probabilistic analysis to reduce uncertainty [12, 13]. This approach may utilize dynamic models of primary systems (e.g. a building or industrial plant), but uses the models in the same steady-state industrial and environmental context as the preceding approach. Additional recent studies have explored temporal issues in LCA [14-19]. However, few studies combine dynamic process modelling with temporally explicit LCI data and LCIA methods.

We have previously developed a general equation for a DLCA model [20]:

$$h_t = \sum_{t0}^{te} \mathbf{C}_t \times \mathbf{B}_t \times \mathbf{A}_t^{-1} \times f_t \qquad (1)$$

where $t$ represents a point in time at which the values in the various terms are known; $t_0$ and $t_e$ represent the beginning and ending time points of the analysis, usually the beginning and end of the product life cycle; $h$ is a vector representing the total environmental impacts of the studied system; $f$ represents the quantities of goods or services required for a specified function of the studied system; $\boldsymbol{A}$ is a matrix representing each unit of output as a function of the input processes; $\boldsymbol{B}$ is a matrix representing the life cycle inventory (LCI) - the emissions and resource consumption generated by each process in the supply chain; and $\boldsymbol{C}$ is a matrix of the life cycle impact assessment (LCIA) characterization factors (CFs) in each impact category. Eq. 1 builds on the approach outlined for static LCA by Heijungs and Suh [21] and further elaborated by Mutel and Hellweg [22]. Additional information is presented in our previous work [20, 23, 24].

In the current study we used this approach to evaluate a new green university building, the Mascaro Center for Sustainable Innovation (MCSI) building at the University of Pittsburgh, described in the following section. The remaining sections of the paper (Section 2 - Section 5) outline our approach in terms of equation 1, as follow:

- Section 2 - Static LCA of construction materials and estimated annual energy use.
- Section 3 - Dynamic LCA including $\mathbf{A_t}$ (temporal changes in energy and material supply chain) and $\mathbf{B_t}$, (temporal changes in emissions / resource consumption). Due to the lack of dynamic CFs in the literature, static values for $\mathbf{C}_t$ were used throughout.
- Section 4 - Dynamic LCA including estimated actual data from initial building operations ($f_t$).

- Section 5 - Discussion of initial conclusions and plans for enhanced future monitoring.

Each section describes the applicable method for that section in additional detail, then presents results for that portion of the analysis.

### 1.2 Case study description

The MCSI building is a 4,200 m$^2$ facility consisting of 1,900 m$^2$ of new construction and 2,300 m$^2$ of renovations, and was occupied in November, 2009. The building currently achieved the US Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) certification process at the Gold level. The renovated area comprises the 2$^{nd}$ floor of the 12-story tower of Benedum Hall, the existing engineering school building. The addition is a 3-story annex to the tower, providing an aboveground connection from the tower to the adjacent auditorium complex. Constructed in 1971, the tower and auditorium share two underground floors which are joined together under an aboveground plaza; the annex is also above the original basement floors, but has a separate foundation structure. The MCSI building houses both wet and dry laboratory spaces, individual offices for faculty and staff, open office/cubicle areas for graduate students, conference rooms. Heating and cooling are provided by centralized natural gas steam heating and electric chilled water systems. Two ducted variable air volume (VAV) HVAC systems supply conditioned air to the space; the wet lab is supplied with 100% outside air with energy recovery, whereas the remaining spaces are supplied with mixed return/outside air. At this time, only the 1,900 m$^2$ new addition was selected for the DLCA modeling effort.

## 2. PRELIMINARY STATIC LCA METHODS AND RESULTS

A static LCA was conducted using the general framework outlined by ISO 14046 [25]. System boundaries for the LCA included the extraction and manufacturing of building materials, but excluded transportation to the site, on-site construction effort, and building end-of-life. The life cycle inventory (LCI) was compiled from as-built construction drawings and specifications, using material and energy processes from the ecoinvent and USLCI databases [26, 27].

Major material categories in the LCI were the structural system (reinforced concrete and structural steel); building envelope (steel stud walls, insulation, windows, curtain walls, and exterior paneling); interior finishes (walls, ceilings, flooring and paints) ; and mechanical and electrical systems. For the LCIA, the US EPA's Tool for the Reduction and Assessment of Chemical and other Environmental Impacts, Version 1 (TRACI) method [28] was used for all impact categories, except nonrenewable energy consumption, for which Impact 2002+ was used [29].

To estimate energy consumption, a geometric model of the building was developed in Design Builder version 2.2.5.004 and 2.3.5.036. Energy performance was simulated with the US DOE's Energy Plus software, Version 6.0.0.023 [30]. Parameters used in the Energy Plus model are presented in the Appendix, Table A1. Results of construction materials and one year of estimated operating impacts are shown in Figure 1. A breakdown of mass and energy usage by construction materials is included in Table A2 in the Appendix.

## 3. INITIAL DYNAMIC LCA METHODS AND RESULTS

To assess the impact of future variations in external industrial and environmental systems, energy consumption from the Energy Plus model was combined with temporally specific unit processes and emissions factors constructed from available industry and environmental data [31, 32]. To project variability in the future electrical supply mix, the Energy Information Administration (EIA) Annual Energy Outlook (AEO) Reference Case was used [32]. Variability in the electricity mix represents a key element of $\mathbf{A}_t$ from eq. 1. Although the AEO projects only annual generation mixes, an estimate of future seasonal variation was made by combining AEO projections with recent monthly generation mixes from the EIA's Monthly Energy Review (MER) [33]. Variability in future emissions factors from electrical power generation - a key component of $\mathbf{B}_t$ in eq. 1 -was assessed for each fuel type by incorporating the EPA's analysis of its proposed Transport and Toxics Rules, which has the potential to significantly curtail emissions of criteria and hazardous air pollutants (CAPs and HAPs) by 2016 if enacted in their current form [31]. EPA emissions data were available on an annual basis by generation type ; thus an implicit assumption is that emission factors do not have significant seasonal variation. Future variability in heating supply and emissions were considered to be minimal, as district heating is provided by one new and one recently remodeled natural gas-fired steam plant.

The DLCA model was initially evaluated for 10 years of building operations. The use of a 10-year period allowed consideration of substantial changes in energy mixes and emissions factors, while avoiding the need to assume a service lifetime for the building. Results of the dynamic background analysis are compared against static estimates in Figure 2. The relatively larger footprint of building systems compared to energy use in the toxicity categories (carcinogens, non-carcinogens and ecotoxicity) is generally due to higher water emissions than energy processes, though it may also reflect greater chemical coverage of the ecoinvent processes used for materials than the EPA emissions data used for energy processes. The domination of the ozone depletion category by the building envelope represents tetrafluoroethylene production for use in the composite exterior cladding panels.

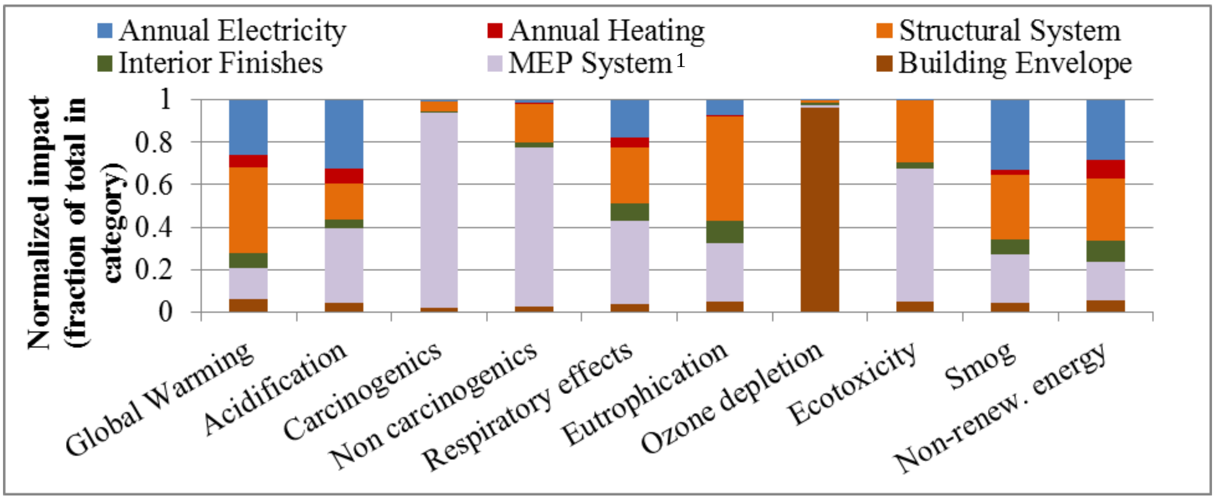


Figure 1: Static LCIA results for MCSI (construction materials and one year of operations) - [1]MEP - Mechanical, Electrical and Plumbing

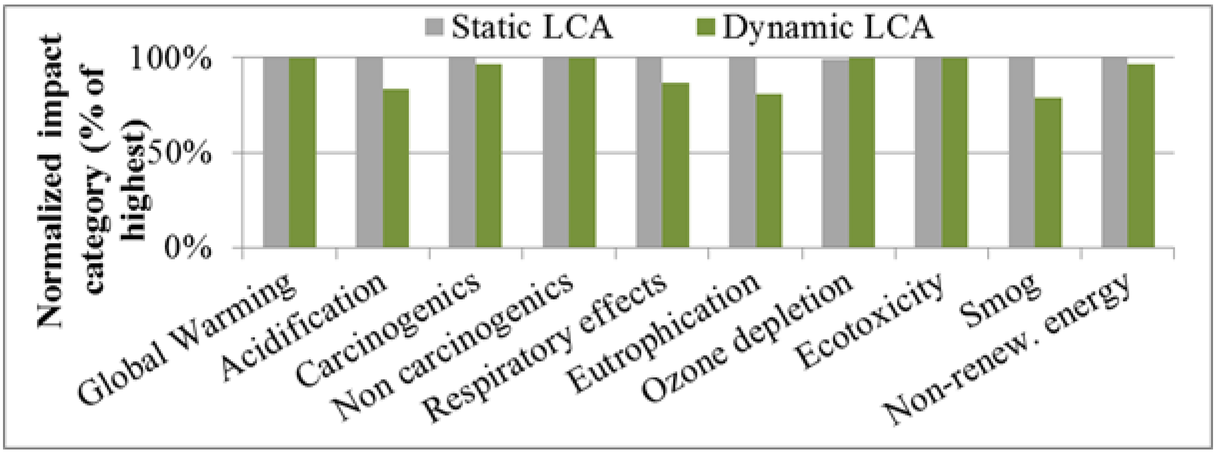


Figure 2: Comparative results of static and dynamic LCA of first 10 years of operations.

## 4. DYNAMIC LCA UPDATED WITH ESTIMATED ACTUAL BUILDING DATA

Since the MCSI building was opened in November 2009, several sources of data have been available to help track its energy performance. Initially, MCSI was not metered separately from the overall Benedum Hall complex, though electrical and steam meter readings were available for Benedum Hall for the entire period. These meter readings provided some context for assessing the energy use of MCSI. However, the electricity data did not cover the cooling load because the chilled water is generated off site, and chilled water meter data were unavailable at the building. At a more detailed level, data for heating and cooling at the HVAC units from the existing Building Automation System (BAS) were recorded for the period January 1 through December 31, 2011. Data from the BAS included temperature and relative humidity for the air streams at the two main air-handling units (AHUs), including ventilation (outside) air, return air and mixed supply air. Enthalpy change calculations were performed on the BAS data in accordance with the 2009 ASHRAE Handbook [34].

Beginning in February, 2012, end-use specific energy meters were deployed in the MCSI building. These meters included steam and chilled water flow meters at the AHUs; hot water meters at the loops feeding radiators and variable air volume (VAV) air reheat devices; and panel-based electric meters. The data from this limited time period were used to supplement the HVAC data for 2011 to help refine the heating and cooling load estimates. Due to the lack of specific electricity use data, two separate estimates were made. First, the building-wide electricity use was pro-rated to MCSI from the entirety of Benedum Hall on a unit floor area basis. Second, the electrical use characteristics of the period from February 1 to March 18, 2012 were used to predict non-cooling electrical loads for 2011. Lighting and miscellaneous loads were pro-rated based on daily usage, while fan loads were pro-rated based on fan volumetric flow data, which were available for all of 2011. Figures 3 and 4 compare the estimated heating and cooling data, and estimated electrical data, respectively, with the Energy Plus model results.

From Figure 3, the heating and cooling loads were qualitatively similar to the Energy Plus model results, though estimated actual loads were higher during months with more extreme temperatures in either direction. Several factors may be responsible for the differences. Weather conditions in the Energy Plus model are from an idealized weather file, which may differ significantly from actual conditions during the study period. Additionally, the 2011 data are lacking information on hot water used at the radiators and VAV reheat terminals. Because no sensor data was recorded at these locations during 2011, they were projected using data from a short time frame during February and March 2012, representing only a moderate range of outdoor temperatures. Total estimated annual heating load for the 1,900 m2 addition was 310,000 kWh (585 MJ/m2) and cooling load was 275,000 kWh (520 MJ/m2) for 2011.

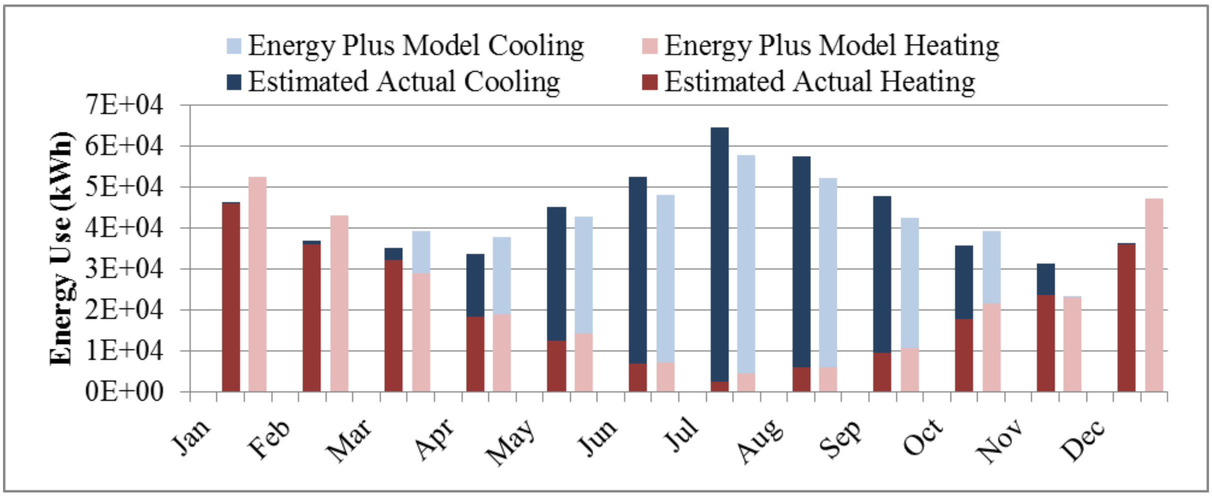


Figure 3: Estimated actual end-use energy for heating and cooling at MCSI compared to results of the Energy Plus model.

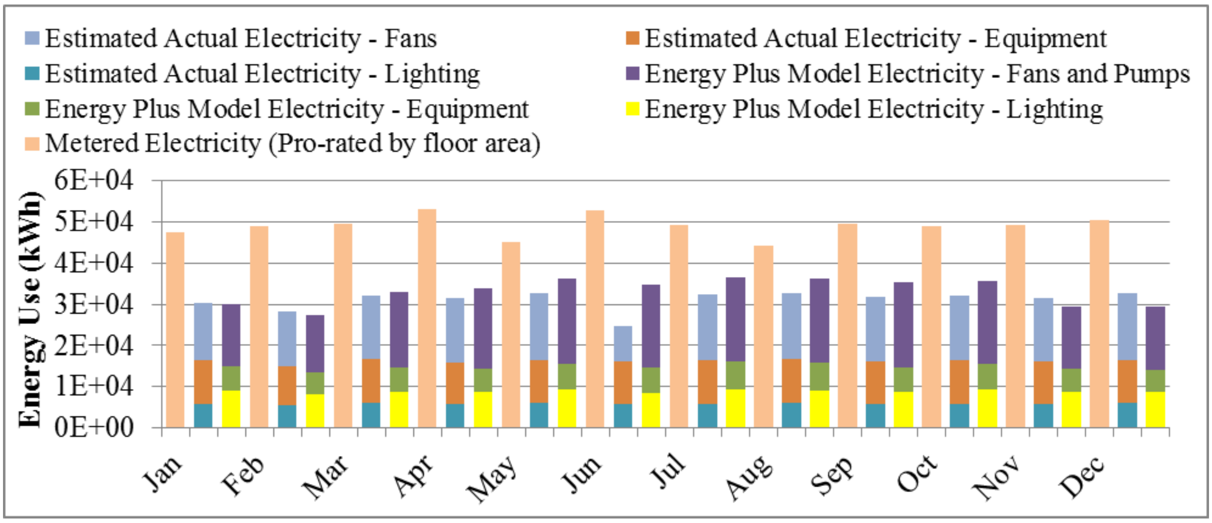


Figure 4 - Pro-rated building-wide, estimated actual and Energy Plus model end-use electrical energy for fans, lighting and equipment (including plug loads) at MCSI.

From Figure 4, the estimated actual electricity use projected from the February-March 2012 data were similar to the Energy Plus model results, while the building-wide electrical use pro-rated by floor are was substantially higher. The annual total pro-rated usage was 589,000 kWh (1115 MJ/m2), whereas the Energy Plus model showed 398,000 kWh (753 MJ/m2), and the estimated actual usage was 372,000 kWh (706 MJ/m2). Although efforts were made to reflect the actual equipment and lighting devices in the Energy Plus model, the distribution of loads between lighting and miscellaneous/plug loads differed from the Energy Plus model to the estimated actual data. The difference may also be affected by actual versus assumed operating schedules. The difference between the pro-rated and estimate actual data may be explained by lower energy intensity of the new addition, but also the presence of high electrical loads elsewhere in the building which may or may not be justifiably pro-rated to the MCSI space. Examples of these types of loads include elevators and heating/cooling system pumps in the 12-story tower, which reflect the greater energy use required to move materials and persons in a tall building. Calculations to determine which building-wide loads should be pro-rated to the MCSI space will be done as part of future work. .

Figure 5 shows the results of combining the DLCA model with the estimated actual building data. Cumulative time series are shown for three selected TRACI impact categories, plus non-renewable energy use from Impact 2002+. For comparison, results are shown for each of 1) all energy use from the Energy Plus model, 2) estimated actual energy use for heating and cooling, with estimated actual electricity for remaining loads, and 3) estimated actual energy use for heating and cooling, with pro-rated building-wide electricity for remaining loads. Scenario 3) is shown with the higher emissions factors representing no new EPA rules, as a probable upper bound on both energy use and emissions. The three impact categories selected are broadly representative of the different patterns shown in the results, with one category dominated by construction materials (carcinogens), one category with substantial reductions in future impacts due to environmental controls (respiratory effects), and one category dominated by energy use with little long-term change (global warming potential). Results for the remaining categories are shown in Figure A2 of the Appendix.

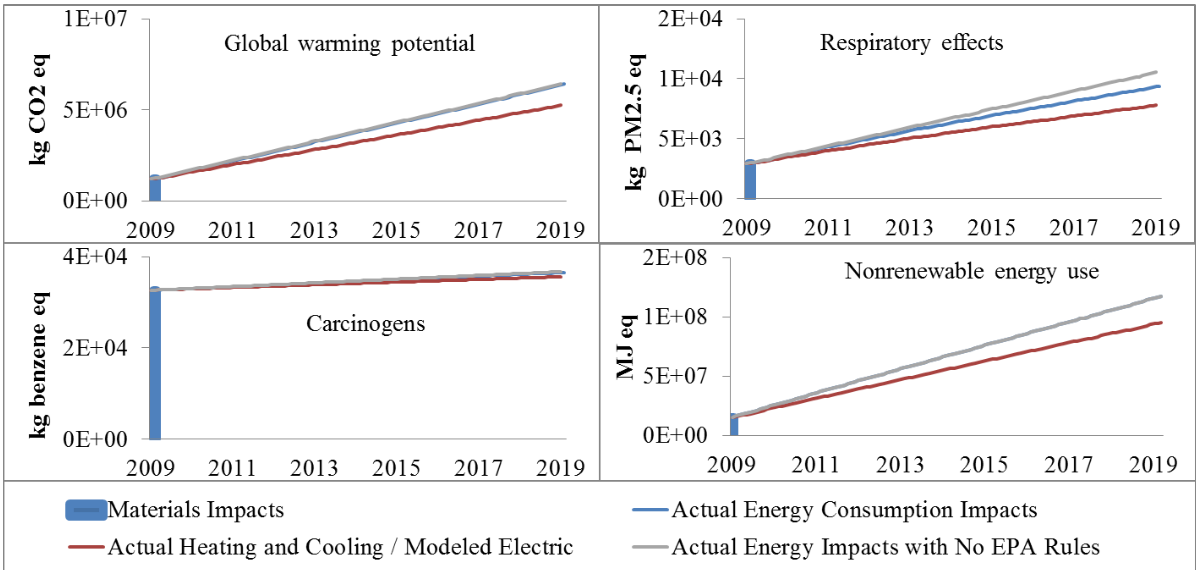


Figure 5 - Cumulative time series results of DLCA model for selected TRACI and Impact 2002+ categories. Additional TRACI categories are shown in Figure A2 of the Appendix.

## 5. CONCLUSIONS AND FUTURE WORK

Dynamic LCA (DLCA) can make a noticeable difference in the evaluation of buildings, due to their long lifetime and potential to undergo changes. Combining post-construction building monitoring with DLCA modeling can result in improved accuracy for estimation of building impacts. However, in this paper only seasonal and annual variations in energy mixes, and annual variations in emissions factors were considered. Future efforts will include matching hourly and weekly variations in end-use load profiles with hourly variations in electrical supply mixes, and the development of temporally variable characterization factors for some impact categories, as well as continued refinement of data gathering techniques. Additional information will be gathered regarding indoor air/ environmental quality (IAQ/IEQ) in consideration of a potential IAQ/IEQ metric for inclusion in building LCA.

## ACKNOWLEDGEMENTS

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**APPENDIX**

Table A1 - Key Input Variables for Energy Plus Model of MCSI

<table>
<tr><th colspan="3">Variable</th><th colspan="3">Value</th></tr>
<tr><td colspan="3">Climate Zone</td><td colspan="3">Humid Continental (Pittsburgh, PA)</td></tr>
<tr><td colspan="3">Type of HVAC System</td><td colspan="3">Variable Air Volume (VAV)</td></tr>
<tr><td colspan="3">Heating Setpoint / Cooling Setpoint</td><td colspan="3">20 °C / 22 °C</td></tr>
<tr><td colspan="3">Cooling Plant</td><td colspan="3">District electric chillers, C.O.P. 3.0</td></tr>
<tr><td colspan="3">Heating Plant</td><td colspan="3">District steam, 80% eff.,<br>natural gas fired</td></tr>
<tr><td colspan="6">Envelope Characteristics - New Construction Wing</td></tr>
<tr><td colspan="2">Element</td><td colspan="2">Construction</td><td>Thickness (mm)</td><td>U-Value ($W/m^2$-K)</td></tr>
<tr><td colspan="2">Sloped curtain walls</td><td colspan="2">Low E double pane sheet glass with aluminum framing</td><td>24.2</td><td>1.634</td></tr>
<tr><td colspan="2">Vertical curtain walls</td><td colspan="2">Low E double pane sheet glass with aluminum framing</td><td>24.2</td><td>1.676</td></tr>
<tr><td colspan="2">Walls</td><td colspan="2">Glass fiber reinforced concrete</td><td>117.5</td><td>.312</td></tr>
<tr><td colspan="2">Roofs</td><td colspan="2">Concrete slab with sealer and glass fiber slab insulation</td><td>513.7</td><td>.131</td></tr>
<tr><td colspan="6">Envelope Characteristics - Renovated 2nd Floor Tower</td></tr>
<tr><td colspan="2">Element</td><td colspan="2">Construction</td><td>Thickness</td><td>U-Value</td></tr>
<tr><td colspan="2">Vertical curtain walls</td><td colspan="2">Low E double pane sheet glass with aluminum framing</td><td>24.2</td><td>1.676</td></tr>
<tr><td colspan="2">Walls</td><td colspan="2">Limestone paneling</td><td>117.5</td><td>.312</td></tr>
<tr><td colspan="6">Space Characteristics - New Construction Wing</td></tr>
<tr><td>Area Type</td><td>Area ($m^2$)</td><td>Occupant Density ($m^2$/person)</td><td>Ventilation Rate (air changes/hour)</td><td>Lighting Intensity ($W/m^2$)</td><td>Equipment Intensity ($W/m^2$)</td></tr>
<tr><td>Corridor</td><td>341</td><td>8.3</td><td>.75</td><td>6.8</td><td>0</td></tr>
<tr><td>Open Office</td><td>567</td><td>25.0</td><td>1.47</td><td>7.0</td><td>8.4</td></tr>
<tr><td>Dry Lab</td><td>629</td><td>25.0</td><td>1.42</td><td>7.7</td><td>7.9</td></tr>
<tr><td>Offices</td><td>167</td><td>11.1</td><td>1.76</td><td>6.6</td><td>11.1</td></tr>
<tr><td colspan="2"></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="6">Space Characteristics - New Construction Wing</td></tr>
<tr><td>Corridor</td><td>380</td><td>8.3</td><td>.85</td><td>10</td><td>0</td></tr>
<tr><td>Offices</td><td>187</td><td>8.3</td><td>1.46</td><td>5.0</td><td>10</td></tr>
<tr><td>Wet Lab</td><td>1253</td><td>8.3</td><td>.94</td><td>10</td><td>10</td></tr>
</table>

Table A2 - Material and Energy Results for Initial (Static) LCA of the Mascaro Center for Sustainable Innovation

| Floor area | 4,200 m$^2$* | |
|---|---|---|
| | Mass/area (kg/m2) | Energy/area (MJ/m2) |
| Structural system | | |
| Total concrete | 680 | 470 |
| Cement | 92 | ---- |
| Sand | 200 | ---- |
| Gravel | 340 | ---- |
| Water | 40 | ---- |
| Concrete reinforcing bars (rebar) | 19 | 440 |
| Steel framing | 5.9 | 160 |
| Galvanized decking for floors | 6.1 | 170 |
| Building envelope | | |
| Window glazing | 6.9 | 88 |
| Aluminum window frames | 0.42 | 47 |
| Fiberglass insulation | 0.63 | 29 |
| Rigid insulation | 0.19 | 20 |
| Exterior cladding - aluminum | 0.18 | 21 |
| Exterior cladding - polyethylene | 0.34 | 27 |
| Exterior cladding - glass fiber reinforced concrete | 0.35 | 1.3 |
| Interior finishes | | |
| Steel studs, doors, and frames | 11 | 300 |
| Gypsum board | 5.4 | 31 |
| Mechanical systems | | |
| Galvanized steel ductwork | 4.8 | 130 |
| Stainless steel ductwork | 2.3 | 180 |
| Steel piping and conduit | 3.5 | 97 |
| Cast iron piping | 6.7 | 160 |
| Copper tubing and wire | 4.5 | 140 |
| HVAC multizone units | 5.0 | 140 |
| **Total materials** | **760** | **2700** |
| | | |
| **Total operating energy** | | **3,920** |
| Electricity | | 3,340 |
| Heating | | 580 |

*2,300 m$^2$ renovation; 1,900 m$^2$ new construction

Figure A1 - Photos of case study building. Upper Left - MCSI addition (constructed 2009). Upper Right - Benedum Hall tower (constructed 1971; renovated 2009). Lower - cutaway view showing MCSI addition and renovation of tower 2$^{nd}$ floor.

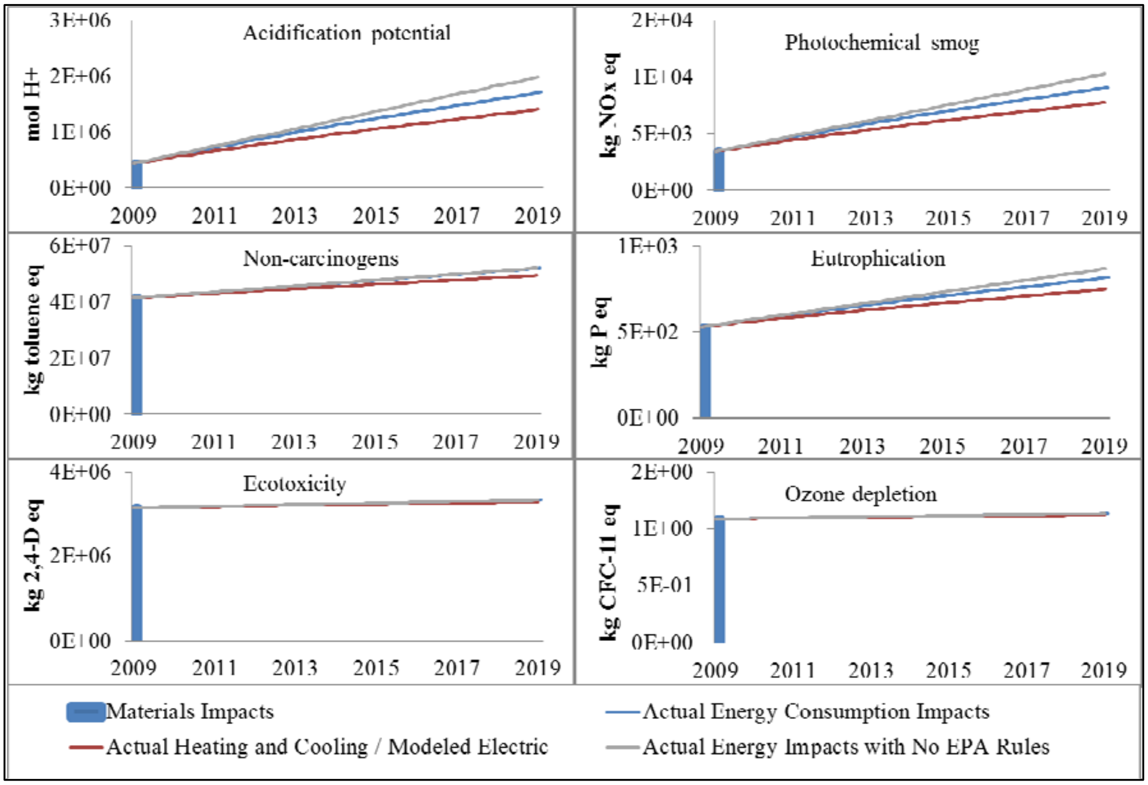


Figure A2 - Cumulative time series results of DLCA model including both actual building data and dynamic LCI factors. Remaining TRACI impact categories not selected for Figure 5.