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Productivity metrics in dynamic LCA for whole buildings: Using a post-occupancy evaluation of energy and indoor environmental quality tradeoffs

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ABSTRACT

The IEQ + DLCA framework, which integrates indoor environmental quality (IEQ) and dynamic life cycle assessment (DLCA) at the whole-building level, was revised and expanded to consider non-chemical health impacts and productivity/performance impacts. The complete framework was evaluated for a case study of a LEED gold rated university building, supplemented with a post-occupancy evaluation (POE) designed to elicit qualitative feedback on IEQ and productivity impacts specific to the building. Most non-chemical health impacts (e.g. sick building syndrome (SBS), asthma) were not able to be included in the framework, due to potential overlaps with chemical-specific impacts already included in LCA. However, productivity impacts were able to be included in the framework for the purpose of comparing different design and operational choices for a given building. Occupants were also asked to evaluate the anticipated effects on their individual productivity due to IEQ changes associated with hypothetical energy-saving strategies. Results of the POE showed occupants were generally satisfied with IEQ, and considered that increasing summer cooling temperature set points would enhance productivity. Energy savings were calculated using an empirical energy and IEQ model calibrated with sensed data from the building. Evaluation of the full IEQ + DLCA framework suggested potentially significant energy savings potential and possible productivity enhancement, but indicated tradeoffs between internal chemical impact categories related to building ventilation, indoor pollutant generation and outdoor pollutant intake. The tradeoffs and overlaps between internal chemical impact categories themselves, as well as between chemical and non-chemical impact categories such as (SBS) are a challenge for LCA of whole buildings.

1. Introduction

Life cycle assessment (LCA) of the built environment is increasingly incorporating indoor environmental quality (IEQ) impacts [1–3]. The procedure for LCA is outlined by ISO and incorporates environmental impacts of a product or process throughout all stages of its life cycle [4]. The steps in LCA are goal and scope; life cycle inventory (LCI) of resource uses and environmental stressors; categorization and characterization of these stressors into environmental impact categories, known as life cycle impact assessment (LCIA); and interpretation. Green building rating systems, such as the United States Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) Version 4 are increasingly integrating LCA into their rating methods [5]. Evaluations of buildings rated "green" have shown measureable improvements from baseline in a number of LCIA categories [6]. LCIA impacts on human health and well-being are traditionally limited to toxicology-based effects of certain chemicals [7,8], although some current research in LCA has included social and economic metrics beyond the scope of traditional chemical impacts [9,10]. For buildings, IEQ impacts are broader than exposure to individual chemicals, including toxicity symptoms not traceable to specific chemical agents, communicable diseases, and work performance impacts [11]. IEQ is sometimes considered as a separate evaluation criterion in multi-criteria evaluations of buildings [12]. However, no widely accepted framework for holistically integrating

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IEQ with LCA exists. In a previous paper, the authors reported on the inclusion of indoor chemical impacts into LCA at the whole-building level [13]. Here, we turn our attention to other aspects of IEQ impacts, focusing on work performance or productivity, while exploring potential future work related to health impacts not traceable to specific chemicals.

Techniques to elicit health and performance effects of IEQ include controlled experiments to develop quantitative relationships, and post-occupancy evaluations (POE) to provide qualitative feedback on a broader range of topics [14]. Health impacts have usually been categorized into sick building syndrome (SBS), representing "eye, nose, or throat irritation, headache, and fatigue, that are associated with occupancy in a specific building" [15]; building related illnesses (BRI), used to describe illnesses caused by infectious agents such as bacteria or viruses transmitted or harbored by building systems [16], and allergies and asthma symptoms. Quantitative relationships have been developed to relate SBS with several whole-building level variables such as ventilation and temperature [15,17]. Symptoms of SBS, allergies and asthma, as well as some chemical triggers of allergies and asthma, are similar to toxic impacts reported by current life cycle impact assessment methods such as USE-Tox [18], making it difficult to include these effects in LCA due to potential overlap with existing categories. Other impacts such as BRI and non-communicable, non-inhalation illnesses such as stress and mood effects of lighting, acoustics or other aspects of IEQ, have not been studied sufficiently to develop quantitative relationships. Further research on these topics would be beneficial to LCA, because potentially significant effects from plausible pathways exist which do not correspond to any impact category in conventional life cycle impact assessment (LCIA).

Productivity or work performance (hereafter productivity) has been related to ventilation rates [19], indoor temperatures [20], and lighting quality [21–23]. Productivity in office work has typically been measured separately from absenteeism (i.e. sick leave), which is a potential proxy for multiple IEQ effects in workplaces, though it seems plausible that absenteeism more strongly represents acute illnesses, particularly respiratory illnesses, e.g. colds, influenza - than long term conditions such as SBS [11]. Though productivity impacts require different measurement units than health impacts, and may accrue to different entities, there is potential to include productivity impacts in LCA of buildings. When comparing different design or operational decisions, the relative impacts on productivity and the internal and external environment can be simultaneously evaluated and tradeoffs can be identified. However, our literature review did not find any existing methods that incorporate productivity information into a life cycle assessment framework.

Productivity has also been qualitatively related to improvements in general IEQ through the use of POE [24,25]. POE, also known as occupant satisfaction surveys, are used to provide feedback about the occupants' perceptions of a building's performance, generally focusing on indoor comfort and satisfaction aspects [26]. These surveys are used to help evaluate the performance of individual buildings as well as for more basic research, and are often coupled with physical measurements of indoor conditions [14]. Surveys have the advantage of being less expensive and easier to implement than physical data collection, as well as a focus on outcomes; however, they are subjective, reflecting differences in occupant's perception due to factors which may not be controllable or related to the building under study. Extensive POE data collection has been done by the UC Berkeley Center for the Built Environment (CBE) [26]. The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) has developed commercial building performance measurement protocols in the categories of energy use, water use and IEQ assessment [27]. ASHRAE recommends using the CBE survey alongside detailed physical measurements to assess a building's performance in these key categories.

A key focus area for POE research has been evaluating the differences between buildings identified as "green" or high-performance and standard buildings, particularly with respect to IEQ. Altomonte and Schiavone found that occupants of LEED buildings were insignificantly more satisfied with IEQ than occupants of non-LEED buildings, though satisfaction with air quality was significantly higher and satisfaction with lighting was significantly lower [28]. Menadue, Sobarto and Williamson reported similar findings related to the Australian Green Star rating system [29]. Likewise, Liang et al. find generally good IEQ in green buildings in Taiwan, but some dissatisfaction related to thermal comfort [30]. Other findings related to thermal comfort have been mixed, including instances of over-cooling [31,32]. Within office, academic or mixed-use buildings, results vary by floor plan type (e.g. open plan, private offices) [33,34] and occupants' gender [35]. Several studies have investigated the tradeoffs between occupants' perception of thermal comfort and building energy management [36–38], with warm weather cooling an area of focus. Negative impacts of poor IEQ on self-assessed productivity have been documented in at least one recent study [39]. Challenges remain in interpreting the results; POE's have been criticized for their subjectivity, including failing to correlate with measured data across multiple buildings [40]. Proposals for improvement have included insights from comparison of different POE methods [41] and development of standardized benchmarks [42]. Few if any studies appear to have assessed the potential for improvement on individual buildings by coupling POE and physical analysis; we provide an example herein.

In this paper, we expand on our previous work developing the Indoor Environmental Quality + Dynamic LCA (IEQ + DLCA) model and using the Mascaro Center for Sustainable Innovation (MCSI) building at the University of Pittsburgh in Pittsburgh, PA (US) as a case study [13,43]. We implemented a POE designed to elicit occupants' feedback on IEQ and its impact on their self-assessed productivity. Using the POE results as a guide, we developed a scenario analysis using the IEQ + DLCA model, along with empirically-derived energy and IEQ relationships for the MCSI building, to explore the tradeoffs or synergies resulting from hypothetical energy efficiency measures applied to the building. The main research question addressed by the POE and coupled analysis was "How can qualitative data related to occupant perceptions be synthesized with physical measurements in an LCA framework?"

2. Methods

The overall procedure is summarized in the following steps: 1) First, a literature review was conducted to determine feasibility of incorporating non-chemical related health impacts and productivity impacts into LCA for whole buildings; 2) Second, a POE was developed and administered to determine building-specific user preferences related to IEQ and productivity for a case study building; 3) Third, physical data on the case study building was used to develop an empirical energy model for the case study building; and 4) Fourth, responses from the POE were used to crease building-specific scenarios oriented toward the goal of energy savings, and the empirical model was used to evaluate the LCA impacts of these scenarios.

2.1. Incorporating productivity into the IEQ + DLCA framework

A general framework for incorporating IEQ into DLCA was introduced by Collinge et al. [13]. This paper expands on that