

Multi-performance retrofits to existing buildings: Increasing resiliency and reducing the environmental impact of buildings through simultaneous structural and energy retrofits

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ABSTRACT: Existing buildings consume 40 percent of the primary energy in the US. While new zero-energy buildings can gradually reduce this energy use, the existing building stock must be improved through deep energy retrofits to make a significant impact in this sector. Current energy retrofits and research in the US focus primarily on upgrades of mechanical and lighting systems to maximize energy reduction for minimal investment. This incremental approach is effective but limited in the overall energy savings it can generate, as major transformations to the fundamental operation of a building are cost prohibitive. Due to their disruptive nature, structural retrofits offer the physical and economic opportunity to completely transform how a building operates in terms of heating, cooling and lighting – the largest sources of energy use. Consequently, this paper proposes replacing current incremental strategies prevalent in most energy efficiency retrofits with transforming existing buildings through a multi-performance retrofit that (1) improves the structural response to extreme-event loading, (2) maximizes daylight to replace electric lighting, (3) uses low-temperature radiant systems to replace HVAC units, (4) deploys climate-appropriate thermal mass and (5) upgrades the envelope to (6) effectively maximize passive thermal and bioclimatic strategies. This paper documents a database of 25 commercial buildings, primarily from the Pacific Northwest region of the US that have undergone different types of retrofits. Overall, multi-performance retrofits are more expensive than a stand-alone structural or energy retrofits but provide benefits that are not easily quantified. Three multi-performance retrofits are described in more detail to highlight the strategies used and benefits of this approach.

KEY WORDS: Multi-performance retrofit; Integrated design, Resilience.

1 INTRODUCTION

1.1 Environmental Impact of Buildings

Existing buildings consume 40 percent of the primary energy and contribute 40 percent of CO₂ emissions in the US [1]. These numbers exclude the significant environmental impact of manufacturing, transporting, installing, maintaining and eventually demolishing materials used in building construction [2]. While every other sector has been reducing energy use over the last 30 years, commercial buildings have increased their energy intensity (energy use per square foot) by over 8%. Furthermore, the total square footage of these buildings has increased by almost 60% over the same time period. Only the recent recession temporarily blunted what had been the continual growth in energy use by the building sector [1]. It is well documented that deficiencies in building performance are ubiquitous, and if addressed nationally in the US could contribute to over \$18 billion in savings annually [3]. Thus, to mitigate climate change, there should be no higher priority than ensuring that residential and commercial buildings are created, adapted and retrofit to minimize energy use, resource consumption, and cost. While new resilient, zero-energy buildings (ZEBs) can gradually reduce the environmental impact of this sector, the existing building stock must be improved through energy retrofits to make a significant impact. In the US, buildings built before the year 2000 make up 78 percent of the commercial building stock and account for 77 of total building fuel consumption [4].

1.2 Conventional Energy Retrofits

Current energy retrofits and research in the US focus primarily on upgrades or commissioning of mechanical and lighting systems to maximize energy reduction for minimal investment [5, 6, 7, 8]. This incremental approach is effective but limited in the overall energy savings it can generate. It should also be noted that the majority of studies in the US use computer modelling instead of monitoring buildings that have undergone energy retrofits. Unfortunately, there is little to no funding in the US to measure the performance of existing buildings to assess the relative merits of deployed retrofit tactics or for researchers to take an active part in the design, construction, commissioning or operations of a recently renovated building. Stakeholder behaviour will not be shifted from current patterns of incremental energy efficiency upgrades unless measured performance data from real buildings is presented to them [9].

Major transformations to the fundamental operation of a building that could reduce energy use intensity (EUI) to levels associated with ZEBs are deemed cost prohibitive and miss the opportunities to “tunnel through the cost barrier” [10]. These major transformations are also inhibited by a desire for buildings to remain operational during an energy retrofit to avoid displacing occupants [11]. Consequently, an analysis by the author of New Building Institute’s “Getting to Fifty” database - which houses details and measured data on buildings that have undergone what NBI calls “deep energy retrofits” that use 50 percent less energy than conventional

buildings - shows that these minimally invasive energy retrofits that focus solely on equipment upgrades still have a site energy use intensity (EUI) of at least 20 kWhr/m²/yr (64 kBtu/sf/yr) [12], less than 20% better than the average US office building in 2012 [4]. While this level of energy savings is not insignificant, it is still over double the EUI of ZEBs.

1.3 Seismic context of the US Pacific Northwest

Episodic, greater than magnitude 9.0 earthquakes along the Cascadia Subduction zone were first discovered in the 1990s [13, 14, 15]. Consequently, building codes were updated throughout jurisdictions in the Pacific Northwest region of the United States – primarily in the states of Oregon and Washington – requiring new structures and existing buildings undergoing a change in occupancy to account for this new seismic risk. As the period between these earthquakes is hundreds of years with the last one occurring roughly 300 years ago [16], buildings constructed before 2001 lacked adequate structural capacity to deal with the ground acceleration from a Cascadia event. Consequently, unreinforced masonry (URM) structures make up a significant portion of the existing building stock in Oregon, particularly educational and apartment buildings. In a 2001 report that was recently updated, the City of Portland, Oregon identified over 1,750 URM buildings that are currently at risk during an earthquake [17]. These buildings also perform poorly in terms of energy use due to the lack of wall insulation and outdated mechanical and lighting systems, making them ideal targets for simultaneous energy and seismic retrofits. Modernist, steel framed buildings from the 1960s and 70s are also ideal candidates for similar reasons and have some of the highest EUIs compared to building of other eras [4]. Due to the simultaneous need to seismically upgrade and reduce energy use, a number of buildings in Oregon have undergone simultaneous retrofits yielding lower EUIs on average to conventional energy retrofits.

Outside of Oregon, existing buildings all along the west coast would benefit from these simultaneous energy and structural retrofits or *multi-performance retrofits*. As seismic hazards in other parts of the US and Europe are being re-evaluated in response to recent unusual seismic activity in the mid-west and east coast often related to hydraulic fracking [18], these strategies could be important as unforeseen structural retrofits are required while society strives to reduce energy use and carbon dioxide emissions.

1.4 Multi-performance Structures and Retrofits

In contemporary building construction, the selection of a structural system occurs early in the design process and is influenced by building codes, cost, scale of the project, and bay sizes required by the program [8]. Consequently, architects and engineers typically only consider structural performance in relationship to the cost of structure and the building program is considered. Selecting structural systems using a multi-performance set of criteria, including environmental impact, thermal mass, thermal conductance, increasing daylighting, acoustic transmission and fire-resistance, could offer considerable and largely untapped opportunities to reduce operational energy use and improve the indoor environmental quality of new and existing buildings while potentially lowering construction costs [19].

Preventative retrofits for earthquakes, hurricanes and other natural disasters also typically focus solely on improving the structural resilience of existing buildings. However, these retrofits could also radically reduce the energy use of existing buildings to the point where they could be transformed into ZEBs through an integrated design process [20]. Adapting strategies and technology used in the design and construction of new ZEBs to the retrofit of existing buildings is only possible when an event, such as a structural retrofit, allows for the significant disruption and alteration of the building's structure, enclosure, finishes and systems.

Unfortunately, there has been little research into the role the structural system or retrofit can have as part of an energy retrofit. A report on deep energy retrofits in the Pacific Northwest failed to list the structural engineer involved with the case studies highlighted even when a seismic retrofit was part of the renovation [11]. Consequently, the potential of using the existing structure and retrofit to improve other areas of performance, such as energy use, is neglected along with the economic advantages of leveraging funding for seismic retrofits. There is little existing research into the role of structural systems in energy retrofits with limited studies focused on housing in non-seismic zones, green roofs, and historic buildings [21, 22, 23, 24]. Only one paper could be found during a literature review that specifically looked at the environmental impact of seismic risk [25]. The paper concluded that structural retrofit of a non-building in a high seismic event is equally important to an energy retrofit in terms of environmental impact over the building's life cycle. However, the paper did not look at how the structural system or seismic retrofit might contribute to the proposed energy retrofit in the study.

This paper will investigate strategies for replacing current incremental structural and energy retrofits with radical transformations of existing buildings through multi-performance retrofits that:

- improves the structural response to extreme-event loading
- maximizes daylight to reduce electric lighting
- uses low-temperature radiant systems to replace conventional HVAC units
- deploys climate-appropriate thermal mass
- upgrades the envelope through increased insulation and airtightness
- effectively maximize passive thermal and bioclimatic strategies

Multi-performance retrofits by their nature focus on increasing the resiliency of existing buildings by increasing their lifespan and ensuring resources will not be lost in a natural disaster. At the same time, these building will be less resource dependent in terms of their operation, addressing the carbon dioxide emissions attributed to the building sector in the US that are a direct contribution to global warming and connected to the increased frequency of natural disasters [26]. The goal of a multi-performance retrofit is to not only regenerate existing buildings technically to reduce energy use and make it more resilient, but to regenerate the original spaces that are often badly compromised over time – to increase occupant comfort, ventilation, daylighting, and connections to the surrounding natural and built environment. Improving these architectural attributes is critical, as multiple

studies have shown a positive correlation between them and occupant health, productivity and satisfaction [27, 28, 29, 30, 31, 32].

2 METHODOLOGY

2.1 Overview

In order to better understand the advantages and potential disadvantages of multi-performance retrofits, a database of twenty-five buildings that had either a seismic, energy or multi-performance retrofit (simultaneous structural and energy retrofit) was developed by the author. This allows for comparisons of a number of performance criteria between the different types of retrofits. The three most promising examples of multi-performance retrofits were then researched in detail to provide case studies outlining lessons learned.

2.2 Building selection

As information on construction costs, measured energy use either before or after a retrofit, and details on specific retrofit tactics are seldom made public in the US, buildings were selected for this study based on the availability of detailed information about the retrofit. This study focuses on commercial buildings with total floor areas larger than 1,000 m² (roughly 11,000 ft²) up to 48,000 m² (roughly 515,000 ft²). Smaller buildings were excluded even though detailed information on the retrofits could be found as the systems and strategies used were not compatible with larger commercial buildings and were more comparable to residential retrofits. The buildings that had undergone an energy or multi-performance retrofit were selected primarily because measured EUI and construction cost data was publically available. 21 of the 25 buildings in the database are located in the US Pacific Northwest with 19 of those 21 in Oregon. The buildings in the database completed a retrofit between 2001 and 2013. These dates aligns with the change in seismic requirements for buildings due to a Cascadia subduction zone event. More recent retrofits are not included to allow at least one year of operations to collect EUI data.

2.3 Data collection

Data on each building was collected from a number of sources including public databases [12, 33, 34, 35] and white papers [11, 36, 37] on high performance buildings as well as datasets provided by the Oregon Department of Energy as part of the State Energy Efficiency Design (SEED) program that has been in operation since 1991 [38]. Data for projects that had only undergone a seismic structural retrofit were collected from published case studies as part of the State of Oregon's Seismic Rehabilitation Grant Program [39]. The following basic information was found for each building and its retrofit:

- location
- owner
- project team – architect, engineers, contractor
- type of retrofit – structural, energy or multi-performance
- year built and year retrofit was completed
- building type (occupancy)
- structural system
- floor area
- number of stories

- actual measured site EUI after retrofit (and before if available)
- construction cost (in 2013 US\$)

On top of this information, individual strategies used in each retrofit were documented and categorized, generating 24 strategies grouped into six major categories: structure, daylight and lighting, mechanical systems, thermal mass, envelope and passive strategies (natural ventilation, external shading devices, etc.).

2.4 Data limitations

There are several limitations to the data collected. Two of the most important pieces of information, EUI and overall construction cost, were self-reported by building owners to the various sources used here. Consequently EUI and cost data could have been calculated slightly differently introducing uncertainty in comparing one building's data to another. For example, many energy retrofits in the US qualify for grants, tax credits and other financial incentives that may or may not be accounted for in the construction cost data. Depending on the building, EUI data was collected during different years between 2005 and 2015, which is documented in the database. While some buildings offer multiple years of EUI, only one year of data was available for most of the buildings in the database. As weather can vary year to year, this makes comparing the EUI data between buildings more difficult. As is typical in the US, all EUI data is for energy used on site and does not account for losses at the source (i.e. electricity generation and transmission losses).

3 RESULTS AND ANALYSIS

3.1 Building characteristics

Due to the size and scope of the database generated for this paper, it is not possible to display it in its entirety. However, Tables 1 and 2 contain a brief summary of the buildings in the database.

Table 1. Characteristics of buildings in the database. EUI is site data post-retrofit.

Retrofit Type	No. of Buildings	Avg./Med. Cost (1,000,000 US\$)	Avg. EUI (kWh/m ²)
Structural	7	1.0/1.2	-
Energy	7	9.8/1.2	15
Multi.	11	26.8/13.1	13

As Table 1 highlights, 44% of the buildings in the database have undergone a multi-performance retrofit, with the remaining buildings split evenly between buildings that have either only had a structural or energy retrofit. The average and median costs for the multi-performance retrofits are significantly higher than those for individual structural and energy retrofits. The average EUI of the multi-performance retrofits is 20% lower than buildings that only underwent an energy retrofit. One reason the structural retrofits in this database are the least expensive is that on average they are smaller and shorter (Table 2). Another reason for the increased cost of the multi-performance retrofits is that on average they were originally built 30 years earlier and in many cases required more significant and expensive upgrades

to building systems, envelope and architectural finishes to bring these older buildings to same level of performance as the younger building set that only underwent energy retrofits.

Table 2. More characteristics of buildings in the database.

Retrofit Type	Avg. Stories	Avg. Floor Area (ft ²)	Avg. Year Built
Structural	1.7	50,000	1941
Energy	10.0	172,000	1954
Multi.	4.7	111,000	1924

In terms of ownership, 60% of the buildings in the database are publicly owned. Of the buildings that only underwent an energy retrofit, six out of the seven are privately owned. All but one of the public buildings in the database underwent a structural retrofit, either alone or as part of a multi-performance retrofit. This is a reflection of legislation providing funds for seismic retrofits in the State of Oregon as well as a lack of incentives for private building owners to provide seismic upgrades whereas there are financial incentives, often from utilities, for private buildings that undergo energy retrofits.

The structural systems of the buildings in the database (Figure 1) were representative of the commercial building stock in the Pacific Northwest where there are more light wood frame and timber structures in general. In cases of combined systems such as timber frame with exterior load bearing URM exterior walls, a single building would be recorded in both categories. As the structural retrofits in the database are smaller buildings, there are more light wood framed structures than the other types of retrofits. A little less than half of the multi-performance retrofits have URM.

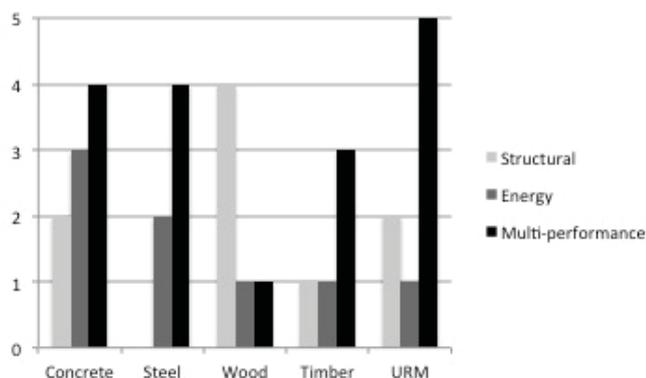


Figure 1. Types of structural systems represented in database buildings. Wood = light wood framing, URM = unreinforced masonry (load bearing)

3.2 Cost, size, EUI

To better understand the relationships between construction cost, building size and post-retrofit site EUI, Figures 2 and 3 show all of the buildings in the dataset grouped by retrofit type. The least expensive retrofits per unit of floor area were the structural retrofits – with all coming in under US\$50/ft². There is no correlation between lower EUI and higher cost as one might expect due to the need for more upgrades to reduce energy use – in fact the opposite is true for the buildings in the dataset that underwent just an energy retrofit. Without the EUI data before the retrofits occurred, it is difficult to understand

the relationship between cost and how much each building was improved, which would provide a more accurate picture of how effective each individual retrofit was.

Again, there is also no correlation between the size of building and cost per unit of floor area (Figure 2). At close to US\$500/ft², the most expensive retrofit is an outlier because that building was half multi-performance retrofit and half new construction. Other analyses comparing the age of the building before the retrofit to cost and the EUI to size of building also yielded no trends.

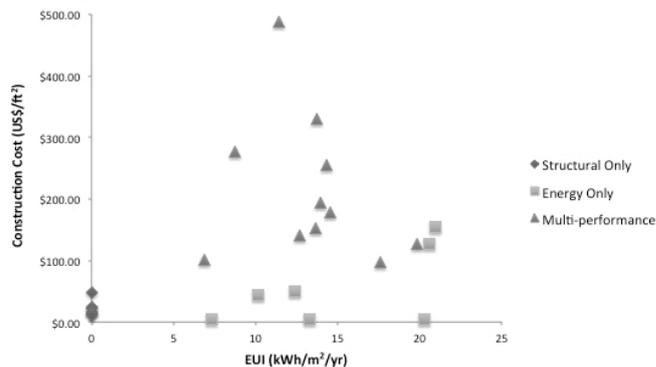


Figure 2. Post-retrofit site EUI versus construction cost per square foot of floor area.

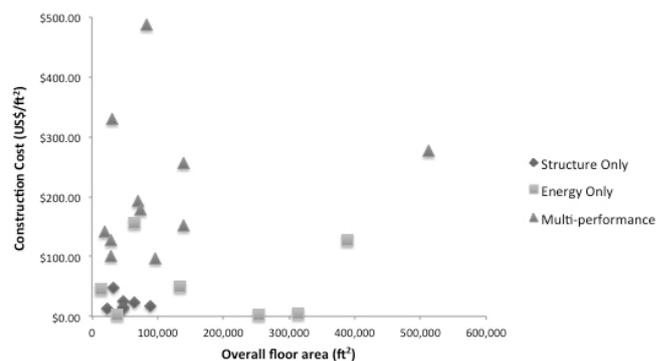


Figure 3. Building floor area versus construction cost per square foot of floor area.

3.3 Retrofit strategies deployed

An analysis of the strategies deployed in each type of retrofit yields more interesting results. In comparison to multi-performance retrofits, buildings that undergo just structural retrofits have three times as many structural strategies. As the entire budget is dedicated solely to improving structural performance in these retrofits, it is not surprising that more strategies would be deployed per building perhaps in a belt and suspenders approach. In contrast, simpler and more cost-effective structural strategies are required in a multi-performance retrofit when improving the structural response of the building is just one of many priorities.

Both the average energy and multi-performance retrofits focused approximately the same amount on mechanical and envelope strategies (Figure 4). Multi-performance retrofits showed a significant increase in daylighting strategies to complement new, more efficient lighting systems as well as deploying thermal mass and passive design strategies to reduce heating and cooling needs over energy retrofits. As

predicted, the ability for significant changes to be made to a building during a structural retrofit allowed for improved or new daylighting apertures and new thermal mass to be added. Almost half of the multi-performance retrofits also installed radiant systems for cooling or both heating and cooling. Overall, the average multi-performance retrofit deploys 8.7 strategies while a stand-alone energy retrofit only makes use of 4.9 strategies. The database doesn't account for improving the architectural quality through multi-performance retrofits that have additional benefits in terms of occupant health and productivity that extend beyond the first-cost of construction or energy savings studied here.

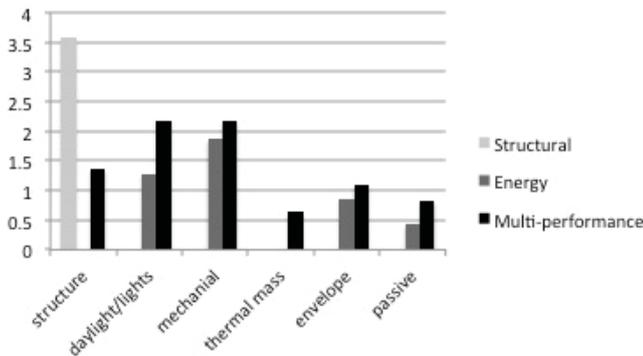


Figure 4. Average number of strategies deployed per type of retrofit.

4 CASE STUDIES

4.1 Shattuck Hall

Originally built in 1915 as an elementary school, Shattuck Hall is home to the School of Architecture at Portland State University (Figure 5). A multi-performance retrofit completed in 2008 included the addition of exposed concrete shear walls to the existing concrete column, joist and beam system.



Figure 5. Shattuck Hall Exterior, post-retrofit.

Many interior clay block non-load bearing walls and interior finishes were removed to create an open floor plan in spaces throughout the building and expose the concrete structure to serve as thermal mass (Figure 6). There was not enough height on the ground floor to increase the size of the ducts to meet current building code standard, so the existing duct system was used to provide ventilation air while heating and cooling is done by a new radiant panel system in the ceiling that also supports new lighting, fire suppression, ceiling fans and acoustic dampening. This decision turned out to be critical in significant reducing the energy used for thermal

comfort. Original lightwells that had been covered in previous renovations were restored and new skylights were added improving daylight in throughout the corridors and ground floor. Unfortunately, the existing uninsulated envelope was not upgraded.

- Post-retrofit EUI: 15 kWh/m²/yr (46 kBtu/ft²/yr)
- Floor area: 6830 m² (73,500 ft²)
- Construction cost per unit floor area: US\$178/ft²
- Total number of retrofit strategies: 10



Figure 6. Shattuck Hall studio interior, post-retrofit.

4.2 Lovejoy Building

The Lovejoy Building was originally built in 1910 as home to a hardware company and completed a multi-performance in 2004, one of the first in Oregon (Figure 7). The building is now office space for an architecture firm and retail/office tenants on the ground floor. The exterior walls were load bearing URM, and the interior structure was a timber frame with wood joists and decking for the diaphragm. The seismic retrofit consisted of applying shotcrete to the interior of the URM walls and adding a concrete slab on top of the existing wood floors. This new thermal mass was left exposed and radiant tubing was placed in the new concrete slabs to provide heating and cooling (Figure 8). Daylighting was significantly improved by increasing the height of window apertures and adding skylights. Operable windows and automated exterior sunshades allow the building to take advantage of outside air and sunlight when needed.

- Post-retrofit EUI: 13 kWh/m²/yr (40 kBtu/ft²/yr)
- Floor area: 1860 m² (20,000 ft²)
- Construction cost per unit floor area: US\$141/ft²
- Total number of retrofit strategies: 13



Figure 7. Lovejoy Building exterior, post-retrofit.



Figure 8. Lovejoy Building office interior, post-retrofit.

4.3 Edith Green Wendell Wyatt Federal Building

As the largest retrofit in the database, the Edith Green Wendell Wyatt Federal Building (EGWW) is one of the most unusual. Built in 1974, the office building for several federal offices was stripped back to its steel moment frame structure and given a completely new enclosure, mechanical and lighting systems (Figure 9). Removing the original precast concrete façade and replacing it with a significantly lighter curtain wall system significantly reduced the weight of the building so that additional strengthening of the lateral loading system was not required. The new envelope is optimised to provide maximum daylight while minimizing heat loss with insulated spandrel panels. The pattern of exterior shading devices are also optimised for each orientation to block unwanted solar gain. The new mechanical system is a combination of radiant ceiling panels for heating and cooling and a dedicated outdoor air system (DOAS) to provide ventilation – similar to Shattuck Hall. Daylighting was improved on the ground floor by removing portions of the structure in the lobby to create new double height spaces (Figure 10). In 2003, EGWW had an EUI of 20 kWh/ m²/yr (62 kBtu/ft²/yr) and the multi-performance retrofit reduced energy use by over 55%.

- Post-retrofit EUI: 9 kWh/m²/yr (28 kBtu/ft²/yr)
- Floor area: 47,600 m² (512,500 ft²)
- Construction cost per unit floor area: US\$276/ft²
- Total number of retrofit strategies: 14



Figure 9. EDWW exterior, before (left) and post-retrofit (right).



Figure 10. EDWW lobby interior, post-retrofit.

5 CONCLUSION

This paper has outlined the potential and need for more research into multi-performance retrofits that combine energy and structural retrofits to generate more benefits than either retrofit could accomplish alone. The initial database discussed in this paper is a starting point for more research into the advantages and potential disadvantages of multi-performance retrofits. Relying on publicly available information has limited the sample size of the database and potentially made comparisons more uncertain. Funding will be required to expand it as the time required to find and collect the information is a significant burden.

As this research is continued, the author feels strongly that academics and professionals cannot abandon in-situ measurements of buildings before and after retrofits to better understand which types of retrofits and strategies are most effective. There is a need for pre- and post-retrofit EUI data, which is seldom collected in the US. There is a place for computer modelling, but the limitations inherent in most energy simulations cannot allow them to account for the types of synergies that can be found in a multi-performance retrofit.

Finally, this paper briefly touched on the architectural implications of multi-performance retrofits beyond structural and energy performance. In commercial buildings, occupant health and productivity is increasingly valued by employers as salaries are the single largest cost in a business. If improving the daylight and ventilation of a building increases productivity and that productivity can be quantified, the higher cost of a multi-performance retrofit in comparison to stand-alone structural or energy retrofits could more easily be justified.

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