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Differential Durability, Building Life Cycle and Sustainability

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ABSTRACT

An extensive stock of high-rise housing in Canada was constructed in response to post-war immigration to large urban centres. The building technology enjoyed the benefit of well-engineered reinforced concrete structural systems, however, advanced building science concepts were not applied to the building envelope design. For the first three decades of this building typology's service life, the envelope performed acceptably and the low cost of energy did not place economic burdens on owners and tenants. With much of this high-rise housing stock now reaching some 40 years of service, deterioration of the building envelope is widely evident and the cost of energy is becoming increasingly significant. Conventional solutions to envelope energy efficiency and durability are often producing unacceptable aesthetic outcomes.

This paper is based on research into façade retrofit technologies that extend the service life of the building envelope while optimizing thermal performance and maintaining, if not enhancing, the traditional aesthetic character of the building stock. Roof, opaque wall and glazing retrofit measures are assessed for their economic viability to owners, and these indicators are compared with life cycle cost analyses of the buildings from the perspective of housing as a social and cultural resource.

The social and environmental value of high-rise housing in large urban centres is a relevant issue in many parts of the world where post-war development occupied prime building sites with inferior building technology. The legislative and technical solutions needed to sustain this housing stock are discussed within the broader context of urban landscapes and sustainable cities.

INTRODUCTION

Canadian cities, along with most large urban centres in North America, have an extensive inventory of post-war high-rise housing. These buildings have envelopes and services that are nearing the end of their useful service lives. Owners of these buildings will soon have to make decisions for renewal and this implies they will require assistance from designers and building science specialists. New methods and materials of façade retrofit along with sophisticated tools for performance prediction improve the odds of appropriate remedies, however, larger questions and issues will influence the transformation of this pervasive building typology.

This paper begins with a brief survey of the existing building condition and then explores available retrofit strategies that are suited to this building typology. A life cycle assessment of a retrofit scenario then presents the cost effectiveness of a "facelift" followed by a discussion of the opportunities and barriers to renewing this extensive form of housing stock. The paper concludes with insights on differential durability and how lessons learned from existing buildings can improve new building design.

EXISTING BUILDING CONDITION

A vast majority of high-rise housing constitues rental housing predating the condominium form of tenure. The structural system employed was steel reinforced cast-in-place concrete arranged in a series of parallel shear walls including end walls, some of which were clad in brick veneer. Spanning perpendicular to the shear walls were one-way steel reinforced cast-in-place concrete floor slabs. This seemed to be in keeping with the arrival and development of flying form technology. Roofscapes indicated poured concrete elevator cores and stairwells. Later versions of the typology began to articulate the end walls with more punched openings. Earlier, lower-rise versions utilized poured columns and beams often displaying corner windows. Contemporary versions tended to display a hybrid system of shear walls throughout the body of the building and flat plate slabs with concrete columns at the ends providing opportunities for corner and end wall glazing.

FIGURE 1
These high-rise apartment buildings located in Toronto, Ontario are typical of this extensive form of housing stock constructed predominantly during the 1960s and 1970s in Canada.

The predominant form seemed to be linear buildings, followed by "Y" shaped and point towers. No matter what the plan geometry, all forms displayed common structural and envelope characteristics. The predominant envelope system was 100 mm (4") brick veneer with a 100 mm (4") concrete block back-up tied together by a regular rhythm of continuous header courses, an early version of mesh reinforced interior gypsum board on wood strapping and plaster with oil based paint finish. The solid non-load bearing masonry envelope more often than not simply sat on top of the exposed exterior floor slab perimeter

In many cases, buildings indicate exposed shear wall edges some of which actually projected +/- 1.2 m (4ft.) to 1.5 m (5ft.) beyond the exterior face of the masonry envelope to support balconies. About half of these shear walls continued down to grade while others cut back to the envelope at angles approximating 45°. These balconies were simple extensions of the interior structural concrete floor slab. Virtually all buildings from this era featured exposed balconies, most of which were linear in geometry and extensions of the structural floor slabs. Some were cantilevered while others were supported as noted previously. Balcony guards were predominately painted steel frame with varying configurations of painted steel infill in the form of steel pans, pickets, etc., attached directly to the top or edge of the balcony slabs.

Openings in the envelopes were handled in different ways depending on their context. Glazed openings which addressed balconies tended to sit upon a typical masonry plinth and extended to the underside of the slab above. Glazed openings through the envelope not occurring at balconies were handled in one of three ways: 1) they were simple punched openings occurring in the body of the envelope sitting on masonry with loose steel lintels above carrying masonry to the underside of the slab above; or 2) they sat on masonry and extended to the underside of the slab above; or 3) or they occurred in an opening which spanned from top of slab to underside of slab with a metal panel above the glazing, below or both.

The condition of Canadian high-rise housing has been widely studied and published. Recent research conducted by graduate students at the University of Toronto confirms what has already been published on this building typology's condition.[1,2,3]

Most envelope related failures appeared at the junctures of exposed structure and masonry envelope, balcony/envelope interface and window/envelope interface. Deterioration was also noted at balcony/guard interface, underside of exposed balconies, mechanical vents and miscellaneous breaches in the envelope. Roof access was not available so roof membrane condition, parapet/membrane interface, etc., were not reviewed or documented. Roofing condition is expected to vary from recently replaced to nearly failing condition.

The most drastic masonry deterioration was evident wherever a brick façade with glazed exterior finish was used. The glazed face typically had popped off and efflorescence was present. Most brick deterioration was evident below window sills or at slab edges with associated mortar joint failure. Wherever the brick veneer of the masonry envelope came in contact with grade, deterioration of the brick was evident.

Other areas which indicated envelope stress seemed to be at the junctures of concrete structure and envelope where a sealant was used to fill the joint. Sealant integrity appeared to be compromised due to either a lack of adhesion or a surpassing of the applied sealant's stress/strain capabilities. Many such junctures specifically between the masonry envelope and concrete structure had no sealant at all, nor soft joints at the underside of slab/envelope juncture.

Inadequate flashings, or lack thereof, also indicated localized areas of envelope failure. These were most evident at window sills, but rarely observed at base flashings between the foundation and masonry envelope, or at the top of balcony slab and masonry wall junctures. Window openings were, however, consistently associated with localized envelope stress materializing in efflorescence, staining and masonry deterioration. Many of the buildings studied had yet to undergo a window retrofit and still possessed the original single gazed units, not to mention perhaps the original sealant about their perimeter.

Balconies in general represented a location where deterioration was evident. The junctures of steel balcony guards and slabs usually required immediate attention and often displayed exposed and corroded anchors and deteriorating concrete. The underside of said balconies often displayed surface and finish deterioration. Drip edges were inadequate or had been compromised by successive finish applications. Corrosion was also often evident wherever painted steel balcony guards had been employed.

FIGURE 2

Defects in high-rise housing range from structural problems to cosmetic staining. Cantilevered balconies enhance amenity but cause thermal bridging and are highly susceptible to deterioration – yet they represent enormous potential for innovative envelope retrofit strategies. This feature has become notably absent in contemporary condominium tower designs.

There are several interesting observations regarding the condition and performance of this building typology. First, and most remarkable, is the the ability of this "primitive" material assembly to survive cumulative cycles of heat, air and moisture movement with such minimal deterioration. Being so energy inefficient, the generous space heating delivered to the envelope perimeter effectively drove out accumulated moisture from the masonry back-up and brick veneer wall assembly (hygric buffer) which was minimal due to limited cooling (air conditioning) during the summer months. Thus, these air and vapour permeable environmental separators remain largely safe and sound. Second, and quite unacceptable, is the thermal comfort of these buildings during extreme weather periods, both hot and cold. Thermal bridging at balconies produces perimiter floor and wall areas that are near outside temperatures during all seasons, and the thermal mass of these buildings promotes sustained overheating during summer heatwaves, especially for west and south facing exposures. Third, the single glazed window assemblies, while providing ample daylight, do not contribute to environmental control, especially natural ventilation due largely to the single sided exposure of most suites. Finally, the energy performance of this building typology is approaching critical levels in terms of housing affordability, accounting for a growing proportion of annual rental increases. For all of the above reasons, this building typology is both ideally positioned for, and greatly in need of, envelope rehabilitation.

Understanding post-war high-rise housing stock leads to speculation about the future performance of contemporary high-rise building envelopes, which offer a minimal hygric buffer and remain highly dependent on sealants to achieve control of air leakage and moisture migration. Unlike the "primitive" building envelopes of post-war high-rise housing, where the durabilities of the various components were somewhat similar (and if they were not, the envelope systems were forgiving), many of today's high-rise housing typology exhibits components with significantly different durabilities. It would be unfortunate if the rehabilitation of post-war high-rise housing adopted envelope retrofit strategies that inherently exhibited a high degree of differential durability. This paper now turns to a discussion of differential durability concepts and their relationship to retrofit strategies presented later.

DIFFERENTIAL DURABILITY CONCEPTS

Differential durability is a term used to describe how the useful service life of building components, such as structure, envelope, finishes and services, differs - both between components, and within the materials, assemblies and systems comprising the components.[4] The term may also be used to describe the whole building system by comparing between the service life of the building and its functional obsolescence.

An important term that is often absent in durability literature is service quality. This term goes beyond the purely functional performance of a product, component, assembly or construction to include attributes such as aesthetics. For example, two different roofing materials may have an identical service life, but exhibit different visual deterioration. One may appear unsightly after a fraction of its service life has expired, while the other may preserve its appearance until only a few years before becoming unserviceable. Functionally both keep out the water for as long a period of time, but the service quality of the latter is higher for longer, as depicted in Figure 3.

A review of contemporary research generally indicates that with exception to structural elements, all of the other components require varying levels of maintenance, repair and replacement during the life cycle of the building. The extent and intensity of these recurring embodied energy demands vary significantly, depending on how appropriately the durability of materials, assemblies and systems are harmonized, and how accessible they are for periodic maintenance, repair and replacement.[5]

Figure 4 depicts the key characteristics and relationships associated with differential durability concepts. As discussed earlier, durability may be expressed as a function of service quality and service life. There are three critical service quality thresholds related to durability: 1) the specified quality, established by the designer and/or minimum codes and standards, representing the typical new service condition; 2) the minimum acceptable quality indicating the need for replacement or retrofit; and 3) failure, where the material or assembly is considered completely unserviceable.

Failure may occur suddenly, as in the case of a lamp, pump or similar type of equipment, or it may result after gradual deterioration. Maintenance or restoration taking place prior to failure can extend the service life, whereas deferred retrofit or replacement beyond the minimum acceptable quality threshold can accelerate total failure. It is important to note that in some cases, the initial service quality of the material or assembly may exceed the specified quality based on codes and standards.

FIGURE 3
Service Quality X Service Life = Durability

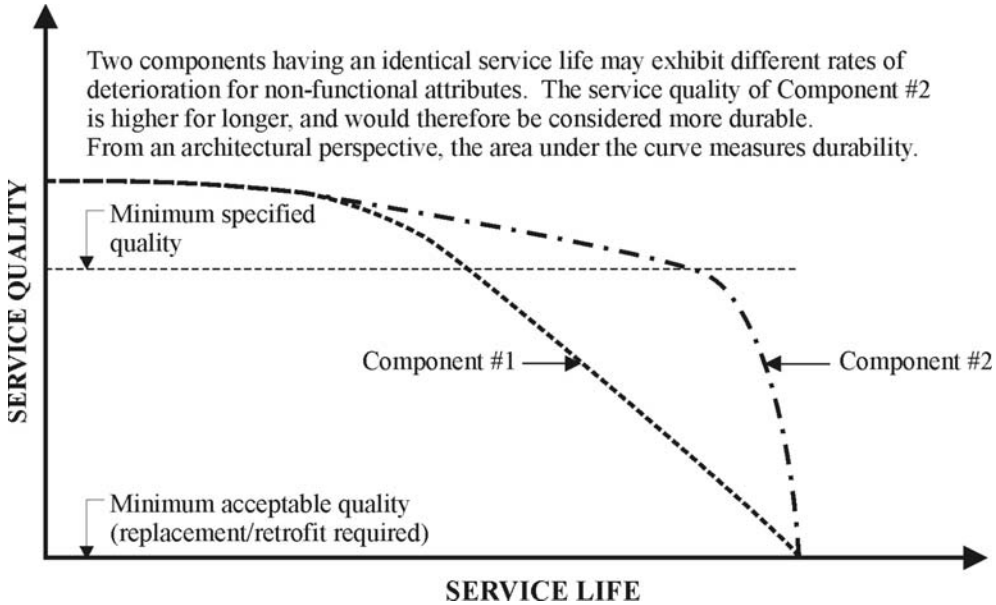
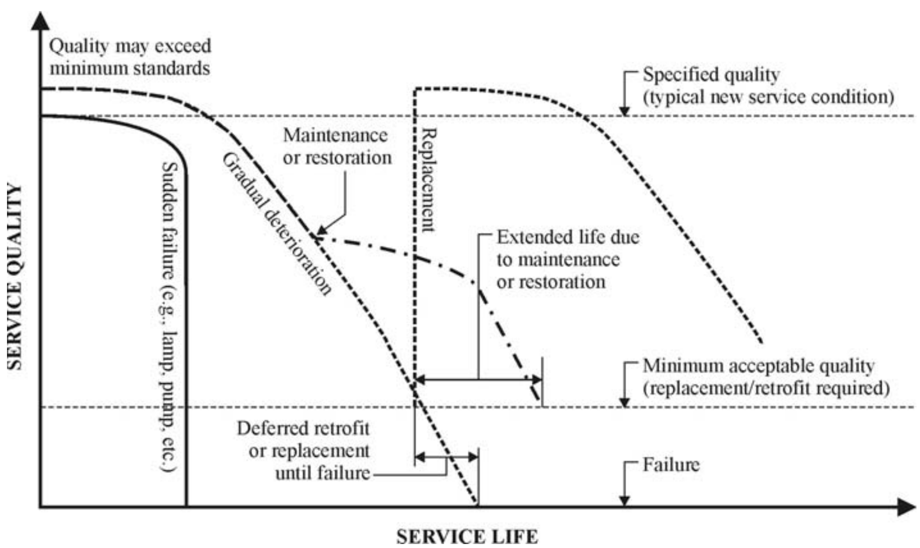
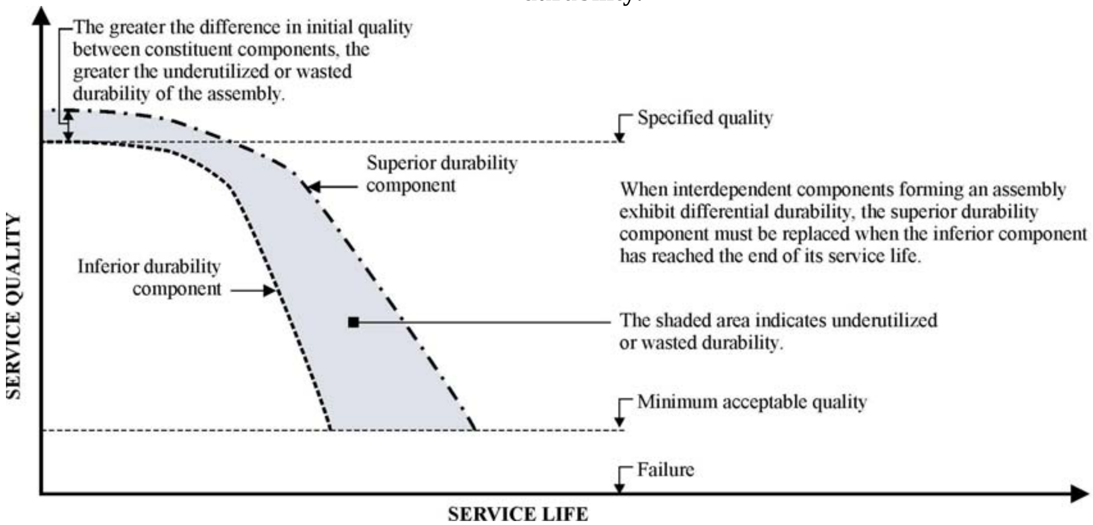


FIGURE 4
Durability characteristics and relationships as a function of service quality and service life.



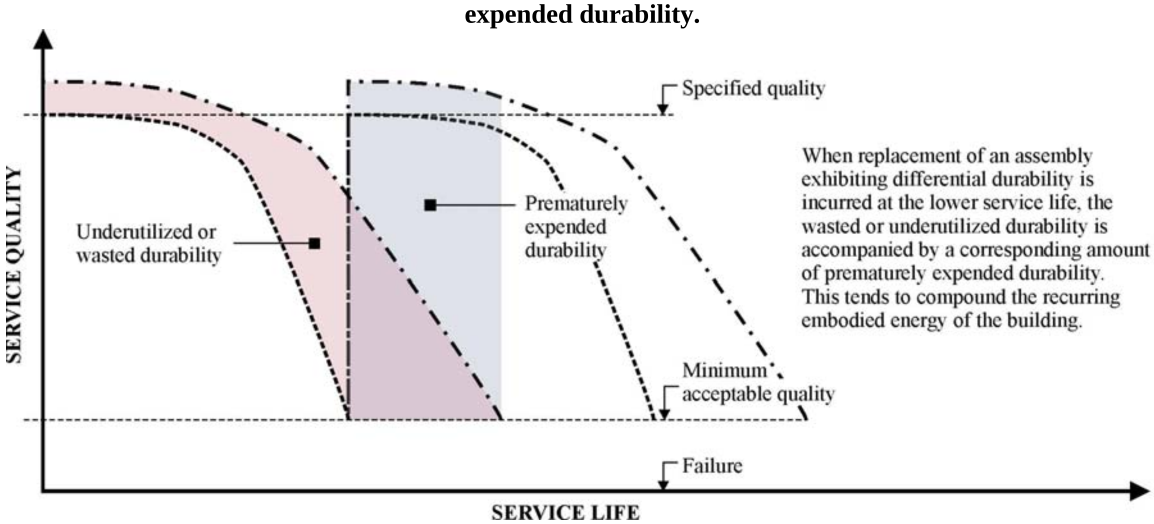
Given these basic characteristics and relationships, it is possible to explore various aspects of differential durability. Figure 5 depicts the underutilization of durability in assemblies with interdependent components exhibiting differential durability. A practical example of interdependent durability is the case of bricks and brick ties, where the former often deliver a longer service life than the latter. When the inferior durability component reaches the end of its useful service life, the superior durability component is often replaced at the same time, resulting in an underutilization of its durability. The lesser the degree of durability harmonization, and the greater the degree of difference in initial service quality between components, the greater the underutilized or wasted durability (embodied energy) of the assembly. This underutilization has a direct impact on the recurring embodied energy demand over the building life cycle.

FIGURE 5
Underutilization of durability in assemblies with interdependent components exhibiting differential durability.



The magnitude of recurring embodied energy is compounded when the assembly is replaced at the end of the inferior component's service life, as depicted in Figure 6. This prematurely expended durability must be added to the underutilized durability when assessing the impacts of differential durability. This type of accounting is not normally conducted in durability research related to the recurring energy content of buildings. At this time, it is difficult to accurately assess the magnitude of these compounding effects due to the scarce availability of verifiable data. However, a tour through any typical building demolition/reclaim yard indicates that many of the materials and components are serviceable. In the case of old windows where the glazing is serviceable long after the frames have deteriorated, the compound recurring energy for the glazing may easily approach 50%.

FIGURE 6
Compounding of recurring embodied energy due to underutilized (wasted) and prematurely expended durability.



The high-rise housing stock examined in this paper exhibits differential durability among its primary systems: structure, envelope and building services. However, there is a remarkable harmonization of durability among the envelope components. Further, the envelope system chosen for this housing stock continues to provide a structurally sound substrate for the envelope rehabilitation strategies which are presented next.

BUILDING ENVELOPE RETROFIT STRATEGIES

Strategies for retrofit of building envelopes range from the purely cosmetic to the entirely integrated systems approach. Required maintenance, such as caulking, painting or repointing is not discussed in this paper, but it is acknowledged these measures may affect durability and performance significantly. For the purposes of this paper, a building envelope retrofit is ideally defined as a process that improves the energy efficiency *and* durability of the building skin, notwithstanding its appearance. This reduces retrofit strategies into two alternatives: 1) an interior retrofit; and 2) an exterior retrofit. A third strategy is derived from a combination of these two approaches.

Interior retrofits have been demonstrated to be technically successful in cold climates, however, these are also disruptive to continuous occupancy, which is preferred by building owners from a cash flow perspective. Interior retrofits do not improve the public image of the building and nearly always imply a component of exterior retrofit work to manage moisture and air leakage.

Exterior retrofits are the most common approach because they are least intrusive for occupants and can more cost effectively address improvements in energy efficiency and durability. It is interesting to note that the need to re-condition balconies is a major factor tipping the balance in favour of exterior retrofit measures. Hence, this paper will shift its focus to exterior building envelope strategies.

Modern building science research has demonstrated that face seal or barrier approaches do not have a high likelihood of acceptable performance, except for relatively arid climate zones.[6] Pressure equalized rain screens, more correctly referred to as pressure moderated drain screens, manage moisture despite flawed workmanship and are commonly viewed as the most forgiving approach to building envelope design, especially for high-rise buildings. Within this context, overcladding in some form emerges as the preferred strategy for the envelope retrofit of post-war high-rise housing. Rather than deal with the wide range of available materials and methods specifically, this paper considers the larger selection and arrangement strategies for walls, noting that these represent the highest proportion of the overall building envelope surface area:

- **Basic Overcladding –** air barrier/insulation protected by an exterior cladding applied to opaque wall elements, excluding balconies, combined with window replacement;
- **Comprehensive Overcladding –** air barrier/insulation protected by an exterior cladding applied to the entire opaque wall area, including balconies, combined with window replacement and glazed enclosure of open balcony areas; and
- **Integrated Overcladding –** similar to comprehensive overcladding but incorporating a secondary framing system that enables the updating and integration of building services between the exterior insulation and existing façade, and the introduction of features such as double façade systems for natural ventilation and sound control.

Overcladding systems have the potential to significantly improve the hygrothermal performance of exterior wall assemblies. In the case of opaque wall areas, thermal insulation levels may be increased by up to RSI3.5 (R-20) effectively reducing the rate of heat loss to approximately 15% of the existing rate. Air leakage may also be reduced to conform with modern standards when a comprehensive overcladding strategy is employed. The application of new glazing systems can improve thermal and air leakage performance, and in the case of integrated overcladding systems, reduce cooling loads while promoting natural ventilation. All of this is technically possible due to the structural integrity of the original envelope system, however, economic viability must also be considered.

LIFE CYCLE COST ASSESSMENT

Investments in building improvements that are cost effective have the highest likelihood of adoption by building owners. The following example presents the case of a comprehensive overcladding system applied to an existing high-rise building. The rehabilitation includes a roofing retrofit such that all opaque envelope elements are insulated to an effective level of RSI 3.2 (R-14). Overcladding of the exterior walls consists of an air/vapour barrier applied over the existing façade, exterior insulation, a metal framing system attached to the masonry substrate and supporting clipped exterior façade panels. The glazing system employs metal thermally broken frames with double sealed glazing having a low emissivity coating, low conductivity edge seal and inert gas fill, yielding a thermal resistance value of RSI 0.6 (R-3.4). It is assumed the proposed overcladding system will have a useful service life exceeding 25 years for the façade panels, and 50 plus years for the air/vapour barrier, insulation and back-up framing.

This example is based on a typical 20-storey high-rise apartment building constructed in the 1970s. The building area is 1,661 m^2, the gross floor area is 33,212 m^2 and the gross envelope area of 11,834 m^2 consists of: roof, 1,661 m^2; opaque walls, 4,819 m^2; and windows. 5,354 m^2. Glazing represents 45.2% of the total building envelope surface area. EE4 Screening Tool software, developed by Natural Resources Canada to support the Canadian Building Incentives Program (CBIP), was used to roughly estimate existing and post-retrofit energy consumption. Accepting this software's limitations, the tool is well correlated to a number of common building typologies and also provides an estimate of greenhouse gas emissions.[7] Relevant data supporting the analysis are presented in Tables 1, 2 and 3.

TABLE 1
Breakdown of envelope retrofit areas and costs.

Envelope Element	*Area (m2)*	*Unit Cost ($/m2)*	*Total Cost*
Roof Area	1660.6	$120.00	$199,272.00
Exterior. Walls of Units			
Masonry	1380	$165.00	$227,700
Glazing	1860	$160.00	$297,600
Balcony Enclosures			
Exposed Shear Wall	1058.4	$165.00	$174,636
Glazed Enclosure	4838.4	$305.00	$1,475,712
Shear Walls			
Exposed Concrete	1969.2	$165.00	$324,918
Glazing Area	126	$160.00	$20,160
		TOTAL	**$2,719,998.00**
Note: Existing and post-retrofit scenario component areas differ due to the glazed enclosure of balconies containing portions of the original glazing area, and the overcladding of projecting shear walls.			

TABLE 2
Estimated annual energy consumption, costs and greenhouse gas emissions.

	Annual Energy (GJ)	Annual Energy Cost	Annual CO_2 (kg)
Existing	22,108	$491,289	1443215
Post-Retrofit	11,261	$250,244	735121
Savings (Costs)	***10,847***	***$241,044***	***708,095***

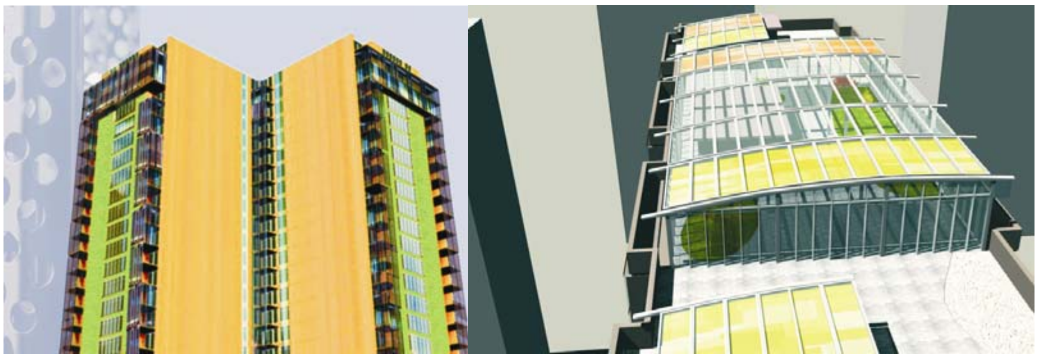
TABLE 3
Summary of life cycle cost assessment for comprehensive building envelope retrofit.

			Present Worth of Energy		**Present Worth of Energy + Capital Cost**	
Scenario	**Capital Cost**	**Annual Energy**	**Current Energy**	**High Energy**	**Current Energy**	**High Energy**
Existing Building	$0	$491,289	$16,972,319	$20,596,289	$16,972,319	$20,596,289
Post-Retrofit	$2,719,998	$250,244	$8,645,073	$10,490,990	$11,365,071	$13,210,988
				Savings	**$5,607,247**	**$7,385,301**
				Payback Period (years)	**9.04**	**8.25**
				Internal Rate of Return	**10.0%**	**11.7%**
Life cycle costing is based on ASTM E917-93 *Practice for Measuring Life Cycle Costs of Buildings and Building Systems.* 25 year study period used in this analysis, considering two economic scenarios: *Current*: Discount 4%, Energy Escalation 6.5%. *High*: Discount 6%, Energy Escalation 10%						

DISCUSSION

Acknowledging the limitations of the energy modelling and economic analysis peformed herein, it is evident that a comprehensive overcladding strategy for post-war high-rise housing typology is very cost effective, and delivers a reasonable rate of return. Additional benefits not accounted for in the analysis are reductions in vacancy rates (affordability, comfort, amenity and aesthetics), increased market value, reduced maintenance costs and possibly the economic valuation of greenhouse gas credits.

FIGURE 7
Examples of student work exploring innovative retrofit strategies incorporating green walls and enclosed rooftop amenity.



However, in order to fully realize these benefits the "facelift" must not exhibit significant differential durability among its vital components. The cost of staging alone needed to address envelope repair and maintenance for high-rise buildings is a significant expense that should be avoided during the useful life of the rehabilitated envelope. Further, the system should allow for ease of cosmetic improvement without the need to address critical performance components of the retrofit assembly. The "primitive" envelope system employed in post-war high-rise housing can accommodate such an approach, and in doing so sheds light on contemporary high-rise housing design. Can our new condominium towers be readily retrofit without major disruption to the occupants? Are contemporary envelope systems truly more innovative and sustainable than their "primitive" predecessors?

CONCLUSIONS AND INSIGHTS

Differential durability is normally not desired within building envelope components and assemblies, where it should ideally be harmonized, but it can form part of a staged building sustainability strategy between systems. Selection of an extremely durable structural system (armature) can accommodate a succession of building envelope assemblies (skins) provided their components exhibit harmonized durabilty and are designed for obsolescence (i.e., ease of replacement). Historically, architecture produced buildings with excellent durability characteristics. This was largely due to the traditional nature of the structural and envelope systems employed. As a prime example, load bearing masonry construction integrated armature and skin, hence the facade inherited the durability of the structure.[8] Modern buildings have departed from this traditional approach, but designers have not yet fully appreciated that with a separation between armature and skin, building facades should be designed as sacrificial layers that will be replaced or rehabilitated several times during the useful life of a building.

From the perspective of sustainability, albeit unintentionally, post-war high-rise housing employed a building envelope system with affordable first costs that could later accommodate retrofit strategies to upgrade performance. For social housing, it is especially important to consider the fairness of having one generation alone bear the economic burden of sustainability. Designing envelope systems that allow for a generational migration from affordability, through adaptability, onto sustainability may be a feasible strategy for future high-rise housing needed to accommodate immigration to Canada's large urban centres.

Looking to the immediate future, there is a genuine need for considerable research and development of appropriate building envelope retrofit strategies appropriate to high-rise housing. Performance, differential durability, ease of maintenance and subsequent retrofit are among the critical factors to reconcile. Sustainable retrofit solutions derived from technical research and development may further require government to formulate incentives for investments in building retrofits, possibly in the form of property tax credits and the brokering of greenhouse gas credits for building owners.

For designers and building science engineers, the challenges and opportunities are numerous. There are now many examples of published research on over-cladding systems issues and performance.[9,10] Durability guidelines have been developed that assist designers in setting appropriate benchmarks.[11] And as importantly, the economics of various building retrofit technologies and life cycle performance are being studied and communicated.[12,13] Further, case studies of emerging retrofit techniques of specific building typologies are available and continue to be developed and disseminated.[14] Beyond the technical issues, architectural and urban planning critiques provide valuable insights into the transformative potentials of high-rise housing retrofits.[15] It is essential that future rehabilitation efforts preserve the robust durability of post-war high-rise housing and provide us with a means of assessing contemporary design practices aimed at sustaining shelter in our communities. In doing so, it is not inconceivable that building envelope retrofits and contemporary building envelope designs may realize the vision that: "In 2020, building envelopes will be energy-positive, adaptable, affordable, environmental, healthy, intelligent, and durable."[16]

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