Differential Durability and the Life Cycle of Buildings

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Abstract:

This paper presents findings from research conducted into the differential durability of major components comprising modern buildings, and how this impacts their life cycle energy demand, and hence their sustainability. The purpose of the research is to provide architects with better insights into the life cycle energy implications of material, assembly and system selections.

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. A fuller consideration of recurring embodied energy (maintenance, repair, retrofit and replacement) during the design process has the potential to realize significant opportunities for enhancing the life cycle sustainability of modern buildings.

A review of international 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.

Differential Durability and the Life Cycle of Buildings

Introduction

The life cycle of buildings includes design, construction, occupancy, maintenance, repair, renovation, alteration, retrofit and deconstruction. Occupancy, or operation, normally accounts for the largest proportion of the environmental impacts over the life cycle of the building, due to the relatively high non-renewable energy demands of most buildings. Maintenance, repair, renovation, alteration, and retrofit vary in degrees of impact depending on the durability of the building components, and the flexibility/adaptability of the building system.

As building technology gains sophistication in the integration of systems, it is important to consider the durability of constituent elements. In components such as walls and roofs comprised of multiple materials that are layered and/or overlapped, the resultant serviceability is limited by the least durable material. For building services, their accessibility for repair and replacement is critical, and when these are concealed within the fabric of the building, premature deterioration and failure, or obsolescence, imply the costly and disruptive deconstruction of well performing fixtures and finishes.

In all cases the value and importance of intelligent design is reinforced by contrasting the influence of this relatively brief, conceptual process on the life cycle outcome afforded the building.

Terminology

Before continuing with the body of this paper, the following terminology is presented to provide a basis of discussion [1]:

Durability - The ability of a building, its parts, components and materials to resist the action of degrading agents over a period of time.

Service Life - The period of time during which all essential performance characteristics of a properly maintained item (product, component, assembly or construction) in service exceeds the minimum acceptable values.

Design Life - The service life that the designer intends an item (product, component, assembly or construction) to achieve when subject to the expected service conditions and maintained according to a prescribed maintenance plan.

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 1.

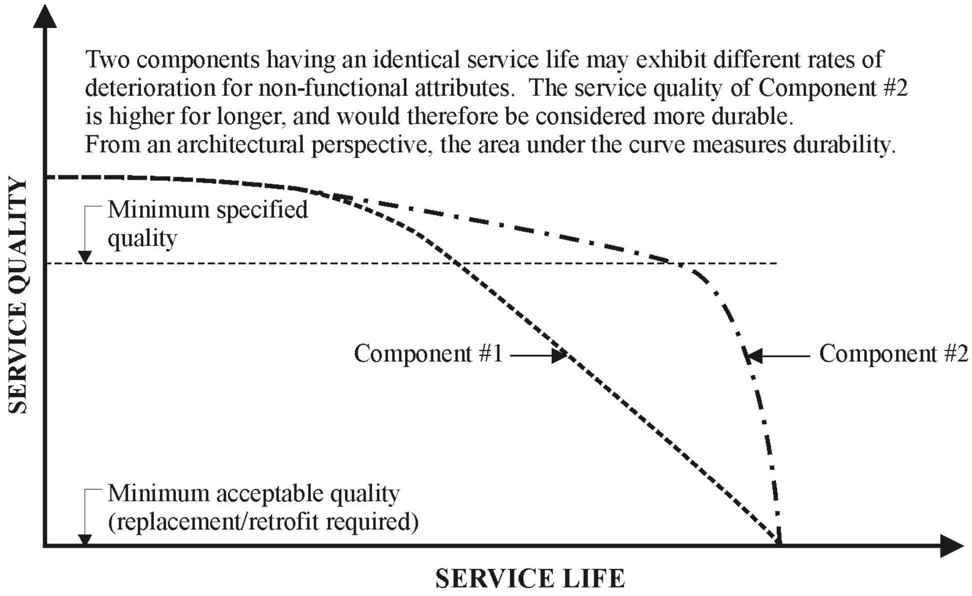

Figure 1. Service Quality X Service Life = Durability

Differential Durability Defined

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. 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.

A review of international 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.

Figure 2 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.

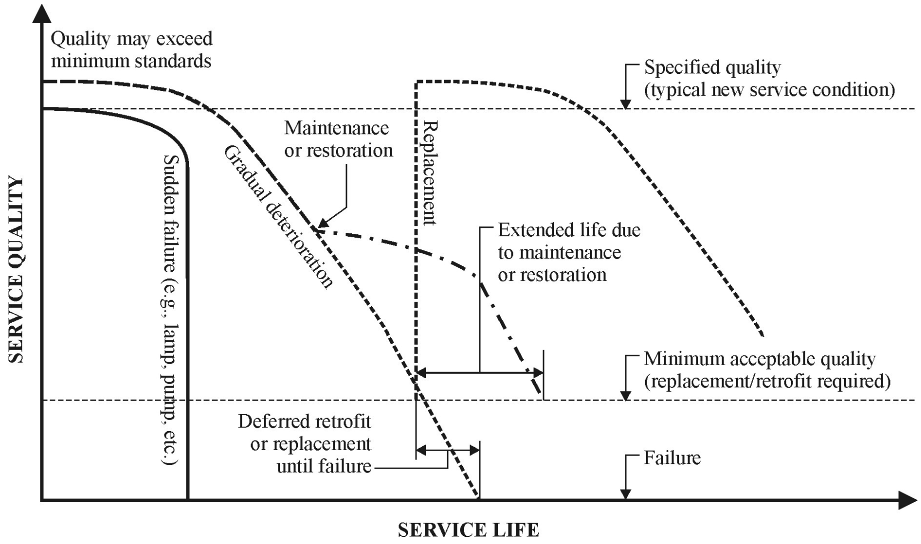

Figure 2. Durability characteristics and relationships as a function of service quality and service life.

Given these basic characteristics and relationships, it is possible to explore various aspects of differential durability. Figure 3 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 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.

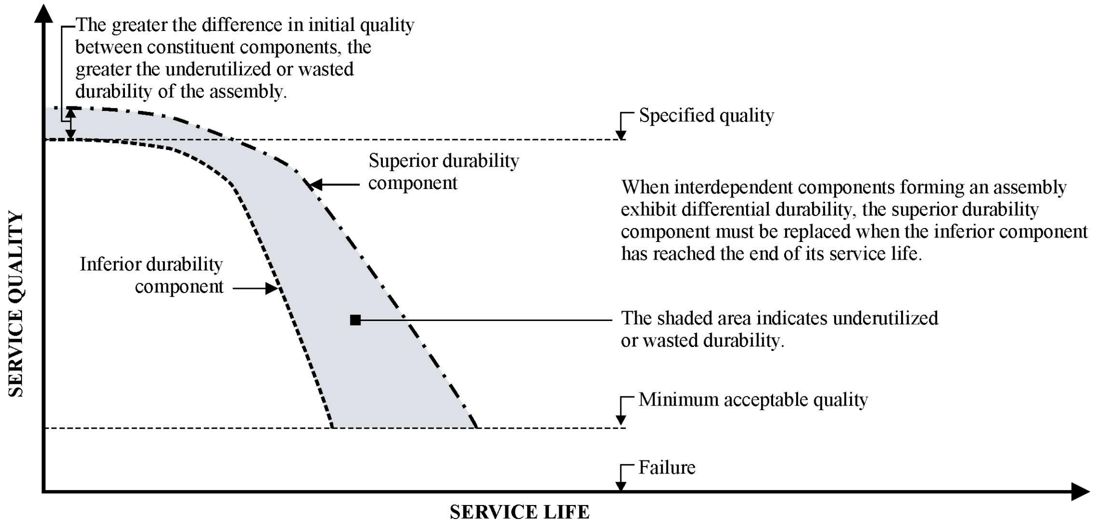

Figure 3. Underutilization of durability in assemblies with interdependent components exhibiting differential durability.

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 4. 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%.

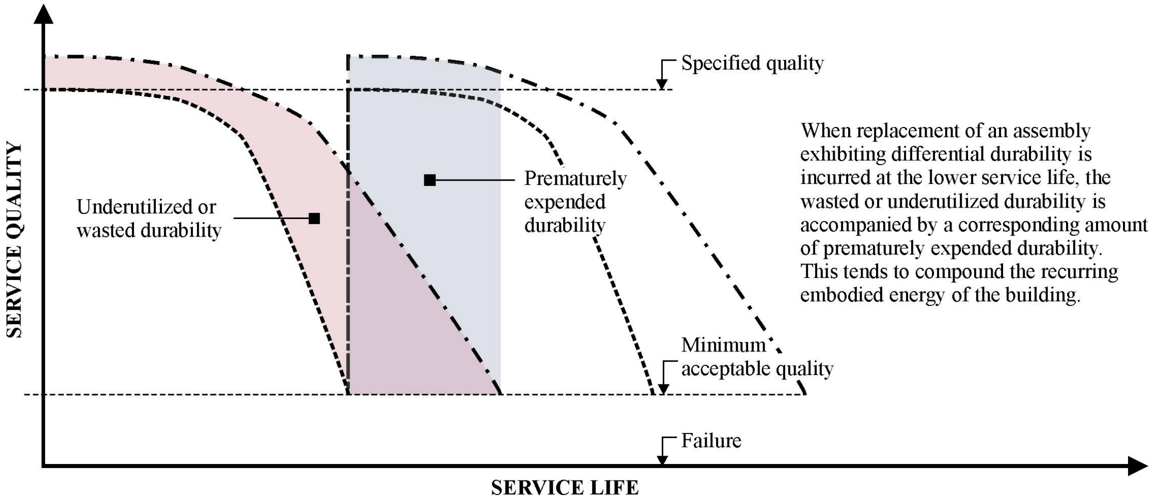

Figure 4. Compounding of recurring embodied energy due to underutilized (wasted) and prematurely expended durability.

Service Life of Building Components

In order to deal effectively with differential durability issues, it is important to examine the service life of components within the following context:

What is the acceptable amount of underutilized (wasted) and prematurely expended durability?

This is a difficult question to answer fully at this time, however, some insights may be gained by reviewing existing data. The service life of building components are reported in numerous publications, and vary significantly between countries, climatic regions, and among building types. Table 1 lists excerpts of recent service life estimates for wall elements in Canadian high-rise residential buildings [2].

		Average Range		
Building Element	**Type**	**Min**	**Max**	***Avg.***
Exterior Walls	Precast Concrete	39	44	*41.5*
	Brick Veneer	32	37	*34.5*
	Curtain Wall	32	38	*35*
	Stucco	20	22	*21*
	Avg.	30.75	35.25	*33*
Windows	Metal Casement	22	25	*23.5*
	Metal Double-Hung	21	23	*22*
	Vinyl Casement	18	20	*19*
	Vinyl Double-Hung	16	19	*17.5*
	Metal Sliding	21	24	*22.5*
	Avg.	19.6	22.2	*20.9*
Flashing	Sheet Metal	22	25	*23.5*
	Non-Metallic	16	19	*17.5*
	Avg.	19	22	*20.5*
Caulking	All Types	10	11	*10.5*

Table 1. Typical service life of high-rise residential wall elements.
[Source: *Service life of multi-unit residential building elements and equipment: final report.* Prepared by IBI Group for Canada Mortgage and Housing Corporation, May 2000.]

These estimates represent thresholds after which either repair/restoration, in the case of exterior walls, or replacement for the other elements is normally required. Walls exhibit the greatest variability in service life by almost a factor of two. The other elements exhibit relatively minor variability between types, particularly so for caulking. An interesting relationship may be noted between flashing and exterior walls where the durability of the flashing is not harmonized with three of the four wall types. Ideally, the flashing would remain serviceable until it was time to repair or restore the exterior walls.

This problem extends to many other building elements. The harmonization of durability, or rather the lack of it, has been identified in the area of building services for items such as piping [3]. It has been advocated that the life cycle of building sub-systems be prudently selected so that multiples of the typically shorter service life of these elements fit wholly within the overall building life cycle (e.g., three 25-year sub-system life cycles within a 75-year building life cycle).

Common outcomes of differential durability include:

1. ***Superfluous upkeep*** - the staging of excessively numerous maintenance, repair and replacement activities due to the differential service life of building components;
2. ***Deferral of upkeep*** – the staging of upkeep activities is costly and disruptive when activity cycles are not harmonized due to asynchronous differential durability, and when fewer than the required or recommended cycles are observed, accelerated deterioration may occur to neglected elements;
3. ***Prematurely expended upkeep*** - where staging is expensive, such as in the case of exterior elements on high-rise buildings, serviceable elements may be replaced at the same time as unserviceable elements to minimize staging expenses and disruptions, leading to prematurely expended durability.

The question of whether or not the typical service life of building components is appropriate, or sustainable, also deserves consideration. Based on the Canadian data in Table 1, most major building elements, except for the structure, tend not to survive much longer than 20 to 30 years. The incremental cost of providing greater durability should be closely considered within the building life cycle as for many components the marginal improvements are highly cost effective. Consider metallic flashing, a vital element where about a 50% increase in service life would better harmonize its durability with exterior wall claddings. The incremental cost of harmonizing its durability only applies to the material quality, assuming manufacturing and installation are price neutral.

Harmonized durability and "just in time" facilities management represent ideal constructs. Acceptable margins for underutilized and prematurely expended durability clearly require further study, but a reasonable target should observe economic and practical realities. Damage associated with a leaky roof may far outweigh premature replacement, but few owners would tolerate replacement midway through the predicted service life of building components.

Despite the international development of durability standards for buildings, and supporting programs of collaborative research, a major problem encountered when designing for durability has been identified:

> "*The principal barrier to the use of these standards has always been the fact that there are few quantitative methods for reliably predicting the service life of materials and components in a building. To overcome this problem, it is necessary to provide the designer either with quantitative information on the in-service properties of building materials and components or with a method for modeling their performance as a function of time* [4]."

Physical deterioration within and between materials and components remains a formidable challenge. An equally significant and complex aspect of durability involves the notion of obsolescence.

Obsolescence

Another facet of differential durability is associated with the degree of flexibility and adaptability in buildings, commonly referred to as obsolescence.

Figure 5. Demolition is more often the outcome of obsolescence rather than physical deterioration.

"*From a general point of view when the capacity of a property to perform the function for which it was intended declines, it becomes functionally obsolete. Functional obsolescence may originate from several sources following changes in the market, in equipment design or process or because of poor initial design* [5]."

Poor initial design leading to functional obsolescence is not normally considered in building durability, yet the recurring embodied energy implications may easily compare to those associated with physical deterioration. When the costs of retrofitting for adaptive re-use equal or exceed the construction cost of new facilities, the value of the original design is fairly questionable.

Software for building retrofit studies has been developed and implemented, enabling a more intelligent management of existing building resources to improve flexibility and adaptability [6]. There remains a genuine need for better predictive models of functional obsolescence. Eventually, it is reasonable to expect that such tools may generate invaluable insights that inform the design of new buildings.

It is important to appreciate the difficulty inherent in reconciling the two aspects of differential durability identified in this paper – physical deterioration and functional obsolescence. Even when these are balanced, factors such as "locational obsolescence" owing to shifting market demand and land value patterns may result in enormous expenditures of embodied energy. The incentive to address architectural aspects of differential durability is strengthened when their implications are better understood.

Implications of Differential Durability

Differential durability causes significant economic impacts, and can also affect sustainability in terms of environmental degradation, resource depletion, greenhouse gas emissions, and reduction in bio-diversity – the four commonly recognized environmental impacts of buildings.

First, this paper looks at an economic perspective on differential durability. The total value of investment in the Canadian housing sector was $42.7 billion in 2000, up 3.9% from 1999. The biggest contributor to the advance was the renovations component, which rose 5.9% compared with 1999. The cumulative value of residential repairs and renovations for the year 2000 was $18.2 billion. The total number of housing units in Canada was 11,908,049 in 2000. [7]

This represents an average expenditure of a little over $1,500 per housing unit, roughly equivalent to the annual purchased household energy. Durability, measured both as physical deterioration and functional obsolescence, ranged between 24% and 73% of these annual expenditures, depending on how the data are interpreted. Hence, it is reasonable to assume that differential durability, in its larger sense, is not insignificant when compared to operating energy in housing, which accounts for 15% of Canada's annual greenhouse gas emissions [8].

Second, the sustainability implications of differential durability are considered. Using durability as an indicator of sustainability is unavoidable because when other measures are employed, these typically attempt to quantify resource depletion and/or environmental degradation over the service life of the building. Interesting relationships have emerged when durability is considered in conjunction with other measures. For example, the sustainability of high embodied energy building components with a relatively long service life may be better than lower embodied energy alternatives with a shorter service life, especially if the former provide superior operating energy performance (e.g., thermal insulation, high performance glazing [9], etc.). Embodied energy and operating energy performance being equal, the relationship between durability and sustainability is linear – the more durable, the more sustainable.

Figure 6. Durability precedent based on sustainable yield of natural resources.
[Cedar shake-clad shed, Fruitvale BC, circa 1900.]

When sustainability parameters are properly considered, current standards for building durability become questionable. For example, some 100 years later, the shed depicted above remains serviceable long after the trees, now replacing those cut down to construct it, have grown back to maturity. From a sustainability perspective, a material, component or system can only be considered durable when its service life is fairly comparable to *the time required for related impacts on the environment to be absorbed by the ecosystem*. The service life of a shed suggested by current durability standards would fall far below any realistic threshold of sustainable yield.

The embodied energy implications of differential durability provide another perspective on sustainability. Figure 7 is based on the work of Cole and Kernan, 1996 [10]. Their research included a comparison of initial embodied energy content to recurring embodied energy content (maintenance, repair and replacement), for a wood-structure building over a 100-year life cycle. Periods of 25 years were selected to quantify the recurring embodied energy associated with 6 major components of a building. The sustainability implications of building durability are significant notwithstanding the exclusion of underutilized and prematurely expended durability (embodied energy) in their analyses.

First, to the credit of civil engineers, the structures of buildings normally do not expend recurring embodied energy, lasting the life of the building. By year 25, however, a typical office building will see an increase of almost 57% of its initial embodied energy due mostly to envelope, finishes and services. By year 50, recurring embodied energy will represent about 144% of the initial embodied energy, and it was projected that by year 100, this proportion would rise to almost 325%.

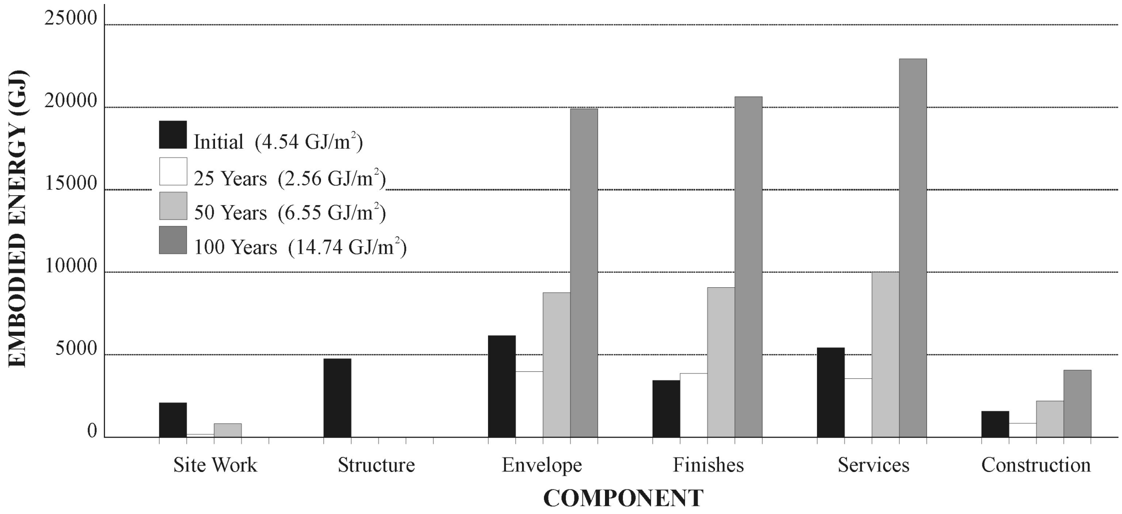

Figure 7. Comparison of Initial to Recurring Embodied Energy for Wood Structure Building Over a 100-Year Life Cycle [Cole and Kernan, 1996].

This relationship is a direct result of differential durability, where the service lives of the six major components comprising the building differ dramatically. Although difficult to quantify from available data, the significance of underutilized and prematurely expended durability cannot be ignored. The current preoccupation with lower first costs in buildings, coupled to misguided facilities management planning, reveals the widespread disregard for sustainability when viewed from a building life cycle perspective.

Another reason that the sustainability implications of recurring embodied energy consumption are not given the serious attention they merit is due to dramatically higher levels of non-renewable operating consumption in contemporary buildings. Figure 8 depicts the relationship between initial, recurring and operating energy for a typical office building. The recurring embodied energy accounts for 8.3% of the total life cycle energy consumed by the building.

Recent analyses for single-unit housing in Sweden indicate that over a 50-year life cycle study period, operating energy accounts for 83%-85% of the building life cycle energy consumption, embodied energy represents between 11%-12%, and recurring embodied energy for maintenance and renovation ranged between 4%-5% [11]. This compares favourably with the Canadian estimates for small office buildings as depicted in Figure 8.

Most building, however, tend to serve useful lives beyond 50 years and this is commonly identified in the current literature as a limitation in life cycle analyses. Potentially enormous recurring embodied energy expenditures can take place as buildings age beyond the 50-year horizon, especially when retrofit activities address both deterioration and obsolescence [12].

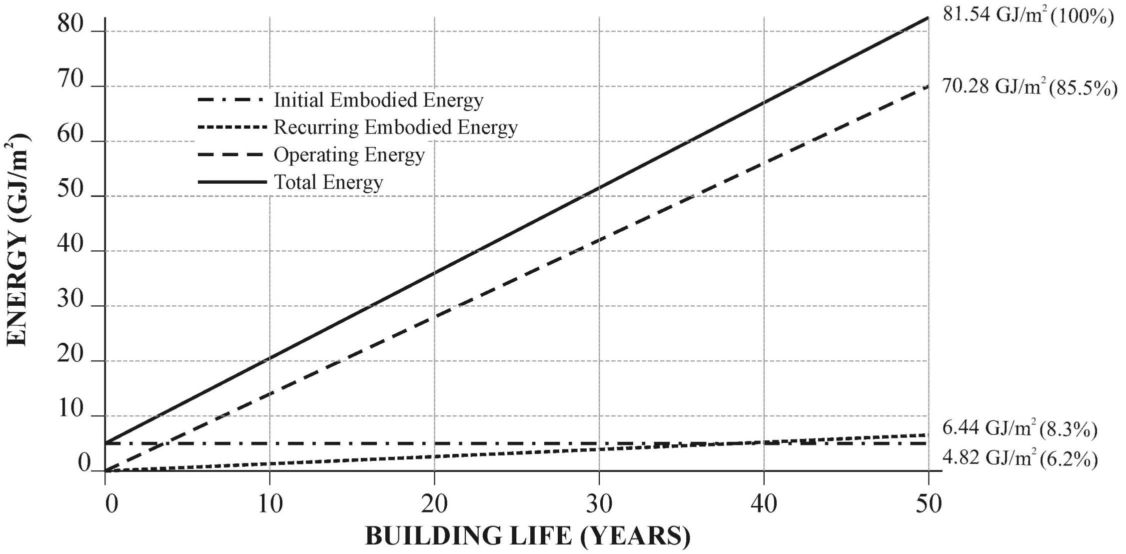

Figure 8 - Components of Energy Use During 50-Year Life Cycle of Typical Office Building with Underground Parking, Averaged Over Wood, Steel and Concrete Structures in Vancouver and Toronto. [Cole and Kernan, 1996]

Further, as modern building technology improves upon the energy efficiency of buildings, and passive environmental control systems, and/or benign sources of renewable energy, increasingly displace non-renewable energy sources for the operation of buildings, the initial and recurring embodied energy content becomes more significant in the life cycle of buildings. Typically, recurring embodied energy surpasses the initial embodied energy of buildings, and as we approach "zero non-renewable energy" buildings, it is reasonable to expect that careful consideration of differential durability will grow in future importance.

Durability and Total Building Performance

Durability, traditionally referred to as *firmness*, remains a cornerstone of sustainable architecture. It must now be reinterpreted within the context of the "total building performance" concept, which recognizes the environmental, economic, technical and social dimensions of buildings as cultural resources rather than real estate commodities.

In order to effectively apply this holistic concept, means of reconciling qualitative and quantitative data with incommensurable parameters must be incorporated into the architectural design process. Recent research has suggested that tools with this sort of sophistication are yet to be developed [13]. It is also unclear how training on the use of these tools could be delivered to design professionals within current disciplinary structures. However, with respect to durability issues, the challenges associated with implementing the total building performance concept have been identified as:

1. Preparation of comprehensive guides on the performances of various building details;
2. Development of tools for durability analysis and life expectancy prediction of building elements and major building parts; and
3. Follow-up and monitoring of projects built under the performance concept for more practical and reliable feedback into the process. [14]

The importance of addressing the durability challenge can be appreciated by considering the four key parameters governing total building performance: 1) user satisfaction; 2) organizational flexibility; 3) technological adaptability; and 4) environmental and energy effectiveness [15].

Differential durability, when it is understood to include the service life of materials and assemblies, and the obsolescence of whole building systems, plays a significant role in the total building performance concept. It directly impacts three of the four key performance parameters, and may in some cases influence user satisfaction when differential durability affects aesthetics or ergonomics.

Conclusions

Differential durability affords a different perspective on the sustainability of buildings because it takes into account both physical deterioration and obsolescence. These two aspects of differential durability are not yet fully appreciated or understood in conventional approaches to durability design and assessment.

When environmental criteria are applied to physical deterioration, the minimum performance requirements for materials and components, or assemblies, differ from current normative standards. They become based on the time it takes for the environmental impacts associated with extraction, processing, transportation and installation (initial embodied energy), as well as the recurring embodied energy between replacement cycles of building elements, to be absorbed by the ecosystem. This implies more durable building elements with better harmonized durability incorporated into flexible and adaptive architectural design.

In order to advance differential durability research and practice, numerous barriers and opportunities have been identified in the recent literature. It must be recognized that a concerted research effort undertaken across a number of disciplines will be required to effectively address the differential durability issues raised in this paper.

For the next phase of research associated with the work presented in this paper, the following areas will be investigated:

1. Estimates of the amount of underutilized (wasted) and prematurely expended durability for typical building envelope components;
2. Estimates of the economic and environmental impacts associated with these forms of recurring embodied energy demand in existing build stock; and
3. Forecasts of the required levels of durability corresponding to sustainability thresholds for commonly employed building materials.

It is acknowledged this represents a modest contribution to the entire issue of differential durability, and it is hoped related efforts by others will reinforce the view that research in this area is vital. Much gratitude is owed to those who have initiated fundamental durability research underpinning the ideas presented in this paper. But above and beyond these contributions, the task of integrating differential durability in daily design practice remains most daunting.

The acceptance of sustainability criteria to derive durability parameters will require careful consideration on the part of the architect. The building must be viewed at varying levels of resolution, from the detail through to the whole artifact, and beyond to its community interactions. Failure of a minor detail, such as the attachment of stone cladding to the structure, could undermine the durability of the façade. Similarly, an inflexible building which is not adaptive to evolving use could face demolition even though all of its components are durable and performing adequately. To achieve a level of durability which fully utilizes natural resources within sustainable thresholds, idiosyncratic notions of design must be reconciled with proven precedents and typologies. The timeless desire by humans for shelter, health and well being must be balanced with material chemistry, statistical models of environmental loads, and ecological carrying capacities. Innovation so constrained represents the challenge of differential durability research applied to sustainable architecture.

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