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Curtainwall Lifecycles: Evaluating Durability and Embodied Energy
幕墙生命周期：耐久性与固化能耗的评鉴


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Abstract

Durability is an often-overlooked consideration of materials, components, assemblies, buildings, and cities, and a fundamental attribute of sustainability. The concept of differential service life recognizes that each of the components that comprise a system possesses a unique service life, and that the service life of the various components interact to determine the ultimate service life of the assembly. The service life of an assembly may thereby be reduced to the least robust of its components. This paper investigates the primary components that comprise a typical metal curtainwall assembly to identify service life characteristics, how these characteristics shape the service life of the assembly, and the implications for embodied energy. Evidence is presented that the energy burden of high-performance façade assemblies may be improved through the consideration of durability. Façade system maintenance requirements and renovation cycles are considered as a strategy to extend service life.

Keywords: Durability, Curtain Wall, Service Life, Embodied Energy, Maintenance, Retrofit

摘要

耐久性作为建筑可持续性的基本属性，却往往在材料、构件、组装体、建筑、城市的各项考虑中被忽视。差分使用年限的概念阐释了组成同一系统的各个构件拥有独立的使用寿命，一个组装体的总体耐用年限是由各个不同的组成部件相互影响而决定的。故而一个组装体的使用年限会因使用坚固性差的构件而降低。本文通过探析构成典型性金属幕墙单元板块的基础部件来鉴定使用年限的相关特性，发掘这些特性对单元体使用寿命的影响，以及蕴含的物化能。有证据表明，通过改善耐久性可以明显改善高性能幕墙板块的能量负荷。幕墙系统的维护要求与更新改造周期应作为延续建筑使用年限的战略性考虑。

关键词: 耐久性，幕墙，使用年限，物化能，维护保养，改造

The building skin impacts both the appearance and performance of the vertical urban environment. Yet curtainwall (CW) systems are routinely designed with no target service life or consideration for maintenance and renovation. This paper reports on early stage ongoing research on the durability and energy performance of metal curtainwall systems. A particular focus is the embodied energy represented by curtainwall systems, and the relationship between durability, embodied energy, and the potential for maintenance and renovation as a strategy for extending façade system service life.

Terminology

Durability terminology discussed herein, unless otherwise noted, is derived from the Canadian Standard Association's CSA 478-95 Guideline on Durability in Buildings (Canadian Standards Association 1995), as discussed in Service Live Considerations in Relation to Green Building Rating Systems (Athena Institute 2006, 4-8).

建筑外墙影响城市垂直环境的外观和性能。然而幕墙 (CW) 系统的设计一直以来都是照本宣科般的或从不关注其使用年限抑或考虑其保养与改造。本文旨在论述对金属幕墙系统的耐久性与能量性能的早期阶段的研究。本文着重关注幕墙系统中展现出的物化能量，以及耐久性与物化能和其作为为提高幕墙系统使用年限而维护、改造的潜能之间的关系。

术语

此处讨论的耐久性术语，除非另有注释，皆来自加拿大标准协会CSA478-95条关于建筑物耐久性的指导方针 (加拿大标准协会1995)，而使用寿命的论述源自于绿色建筑的评级 (雅典娜学院2006, 4-8)。

耐久性
建筑或及其组成材料在规定的工作环境中、在预期的使用年限内、在正常维护修理条件下提供所要求性能的能力。

使用年限
建筑结构或其组成材料在进行保养维修前使用的实际时间期限。

Durability
The ability of a building or any of its components to perform its required functions in its service environment over a period of time without unforeseen cost for maintenance or repair.

Service Life
The actual period of time during which the building or any of its components performs without unforeseen costs or disruption for maintenance and repair.

Design Service Life
The service life specified by the designer in accordance with the expectations (or requirements) of the owners of the building.

Differential Service Life
The service life difference between the components of a material or system of a building (Kesik 2002).

Predicted Service Life
The service life forecast from recorded performance, previous experience, tests or modeling.

Service Quality
Functional and aesthetic performance in relation to specified requirements, and the perceptions and expectations of stakeholders (adapted from Kesik 2002a).

Embodied Energy

Building energy efficiency considerations are often constrained to the energy consumed during building operations. While this represents the dominant source of energy consumption over a building's lifespan, it is increasingly important that embodied energy—that consumed during the material cycle from extraction through end-of-life—become an integral building performance consideration. In fact, as improvements are made in operational energy efficiency and buildings progress toward net-zero consumption targets, embodied energy assumes an increasing percentage of building lifecycle energy consumption. The embodied energy of a building is the aggregate of the embodied energy of the constituent systems and subsystems, down to the individual material and product components that make up the building.

Embodied energy analysis brings the issue of durability to the dialogue. Durability is a measure of performance over time in a specific environmental context. The measure of that time is called service life. The Athena Institute (2006, 4-8) defines end of service life as the occurrence of "unforeseen costs or disruption for maintenance or repair." Planned renewal cycles of maintenance and renovation, however, can be factored into the predicted service life of a building component or system as a means to extend service life. The tradeoff is that maintenance and renovation produce recurring embodied energy, which adds to the embodied energy debt over a building's lifespan. Analysis is required in any given situation to determine if extending service life through the provision of maintenance and renovation cycles is truly providing value by reducing the embodied energy debt.

Establishing Service Life Baselines for Buildings and Façade Systems

Durability science is inconsistently applied in the construction arts (Mora, Bitsuamlak and Hovart 2011, 1469), and a design or predicted service life is rarely defined for buildings or façade systems. The Athena Institute (2006, 17) report points out that no current building rating

设计使用年限
设计者根据业主预期 (或要求) 而设计要求的建筑使用年限。

差分使用年限
建筑系统或材料构件中使用年限的不同 (Kesik 2002) 。

使用年限预期
从有记录的性能表现、以往的经验、测试或建模系统的模拟中可以预见的用年限。

功能质量
在股东期望及在特定要求下的功能性与美学性能 (改编自Kesik 2002a) 。

物化能

建筑节能方面的考虑往往局限于建筑施工期间的能耗，当建筑物在整个寿命当中的主要能源消耗作为主要的考量，材料的提取到终结这个生命周期中所消耗的物化能作为建筑性能的一个重要因素显得愈发重要。实际上，施工能效的提高与建筑发展零能耗的目标，物化能占据了建筑使用周期中能耗的绝大比重。一栋建筑的物化能是其各个构成系统与子系统，直至构成此栋建筑的物料与产品部件的固化能耗的总和。

建筑物化能的分析自然延伸出耐久性的议题。耐久性是在特定环境下一定时间内对性能的一种衡量，而这一时间段称之为使用年限。雅典娜学院 (2006,4-8) 将使用年限的终结定义为"维护与保养不可预见的损失或中断"。然而，有计划性的维护改造周期可影响建筑部件或系统的预期使用年限，并成为延伸其使用寿命的一个重要手段。维护与改造产生物化能的循环，这一权衡须增加到建筑使用寿命中物化能量缺失的影响中。特定条件下的分析可以明确在维护和改造来延续建筑物使用寿命中减少物化能量的损耗是非常有价值的。

建筑及幕墙系统使用年限底线的建立

耐久性技术的应用并不与建筑艺术 (Mora, Bitsuamlak and Hovart 2011, 1469) 相一致，设计与预期使用年限也极少在建筑或幕墙系统中进行诠释。雅典娜学院一份报告 (2006,17) 指出，除了加拿大的绿色建筑认证-其根据加拿大标准协会的 S478-95条例对设计使用年限与预期使用年限相一致而授予其奖项之外，现今无建筑评级系统将建筑的整体使用年限作为一个考量因素。考虑到以建筑施工中的物质资源的消耗，耐久性的标准理应进行应用，然而建筑规范并未就此对建筑或幕墙系统地使用年限提出特别规定。

对于设定合适的建筑使用年限并未有统一的意见。西北太平洋国家建筑技术实验室估计商业建筑的使用寿命中间值为70-75年 (D&R International, Ltd 2011) ，而雅典娜学院 (2006.iv) 则较为保守的估计建筑寿命普遍在40-60年。然而，大型商业建筑和居民住宅楼的使用年限似乎较为长久。相对而言，很少的高层建筑会被拆除。世界高层建筑与人居学会CTBUH 收录的高层建筑资料库包含了82座百年高龄的建筑，其中约百分之八十以上依然屹立。位于纽约的伍尔沃斯大厦在2013年经历大范围的办公室翻新与奢华高层公寓的改装后迎来了百岁华诞，为后继数十年的屹立不倒做了必要准备。基于众多先例，柯西克 (2002b) 主张当代建筑的构造系统的设计应支持数百年的使用年限。CSA S478-95(加拿大标准协会1995.7)将建筑物的长寿定义为50-99年并适用于大多数建筑，至少一百年方可称作不朽之作与建筑文化遗产。然而为何不考虑更为长久的时间，为何不考虑建筑生命周期与其构造系统固有能力相一致性? 耐久性规划设计是否可以合理地支持以百年为单位计算建筑的使用年限? 更甚者，对于那些不朽的建筑，千年的使用年限的设计是否合适可行?

system credits the consideration of whole building service life, with the single exception of LEED Canada, which awards the designation of a design service life matched by a predicted service life in accordance with CSA S478-95. Given the consumption of material resources represented by building construction it would seem appropriate that some standard of durability be applied, yet building codes do not specifically address the service life of buildings or façade systems.

There is no general agreement for establishing an appropriate building service life. The Pacific Northwest National Laboratory for the Building Technologies estimates the median lifespan of commercial buildings at 70 – 75 years (D&R International, Ltd 2011) while the Athena Institute (2006, iv) suggests a "conservative" estimate of building lifespan at 40 – 60 years. The lifecycle of large commercial and multi-family buildings, however, seems to be considerably longer. Relatively few tall buildings, for example, have been demolished. The database of tall buildings maintained by the Council for Tall Buildings and Urban Habitat includes 82 buildings over 100 years old, and roughly 80% of them are still standing. The Woolworth Building in New York City turned 100 years old in 2013 amidst a large-scale office renovation and luxury condominium conversion of the upper floors, positioning it for decades to come. Kesik (2002b) contends that the structural systems of modern buildings are engineered to support a lifespan of several hundred years as established by numerous precedents. CSA S478-95 (Canadian Standards Association 1995, 7) categorizes long life at 50 to 99 years and appropriate for most buildings, and a minimum of 100 years for monumental and heritage buildings. Yet what about the consideration of longer timeframes, building lifespans to match the inherent capacity of their structural systems? Can durability planning reasonably support a building service life measured in hundreds of years, and even perhaps, in the case of monumental buildings, a 1000 year service life as both appropriate and achievable?

The Curtainwall Façade System

Curtainwalls, like buildings, are specialized, complex assemblies that deny obvious appropriate service life definitions. Most of the first-generation curtainwall buildings are still in existence, with the earliest among them some sixty years old and older. However, many are badly in need of renovation. So is it fair to say that the service life of these early generation curtainwall systems is in the 40 – 60 year range? The answer depends in part upon what minimum standard of serviceability is considered. The early CW systems were notoriously poor performers. If current code standards for air and water vapor penetration are applied, these older systems may well have been unserviceable from the beginning.

Durability is a function of service life and service quality—of both appearance and performance. One system appearing aesthetically acceptable may be performing well below acceptable standards, yet remain in use for a long time, compromising the comfort and operational energy efficiency of the building. Another system may be functioning to high-performance standards but suffer evident visual deterioration that results in premature maintenance or repair, and an accompanying expenditure of embodied energy. Or a system may become visually dated or otherwise inappropriate and suffer a similar fate. (In fact, it is these aesthetic considerations, not functional performance, that are driving façade renovations.)

幕墙系统

幕墙，同建筑一样，是专业复杂的装配构成，无法给予明显的使用年限划定。第一代幕墙建筑仍存于世，其中最早的建筑已年逾60和更长。然而他们大多亟需翻新改造。是否可以说第一代幕墙系统的使用年限在40-60年之间? 答案从某种程度而言是基于其可用性的最低标准而言的。众所周知，早期的幕墙系统性能很差。若应用当今建筑规范关于空气和水密性渗透方面的标准，此类早期系统从一开始就是不能胜任的。

从外观和性能上而言，耐久性具有使用年限和服务质量的功能。某一符合美学要求的系统很可能会远低于相关通用标准，然而依旧可以在牺牲舒适度与建筑运营能效的情况下被长期使用。另一系统或许可以达到高性能的标准，但因给人明显的视觉缺陷而导致过早的维护与返修，以及随之而来的物化能量消耗而产生的费用。或，某一系统会因外观变得过时或不相适宜而与前例相同命运。(实际上，是此类美学考量而非其工作性能，才使得此类幕墙得以翻新)。

幕墙技术进化的两大特性: 一是继上世纪末70年代初期出现的第一次能源危机而衍生应用的两层密封-或中空玻璃。二是单元体或者是单元体系统的出现，在以增加系统复杂程度为代价的基础上，模块化的工厂预制提高了质量，减少了现场施工的人工。单元式系统出现于19世纪八十年代，并与90年代成长为幕墙应用的首选系统。早期的幕墙系统被称之为构件式系统，指的是现场测量加工铝型材，首先安装层间的竖框，然后是竖框之间的横梁，而后再将玻璃与其它镶嵌板块安装至框架之内。构件式与单元式系统的设计、施工和性能上实质是不同的，这是怀疑其使用年限也会因此不同的理由。

胶条作为空气与水密的阻隔材料，是幕墙系统中一个潜在弱点。图一所示的是一个典型单元式系统的单元相接的节点。下部单元体顶端的胶条扮演着阻挡空气与水汽在与上部单元体之间通道内的作用，即使在单元体互相挤压，抑或嵌槽在腔体内上下移动时，胶条依旧有效。胶条在整个典型单元体中所占重量比重大约是1% (见表一)，而单元体的水密性与气密性要求却完全依靠这些胶条。一旦当单元体系统安装之后，这些胶条因此隐蔽而无法进行检测与保养。

幕墙被有意设计为无维护的系统，而不用后期的维护与改造。试问，在缺失维护的情况下，这些系统将如何在其使用年限内运行? 是什么影响到运行的能耗，居住者的健康与舒适度，结构系统与室内装修的保护，最终到系统本身的使使年限? 更进一步，如果维护和改造是计划和设计好的，哪些纯粹的改进可以做到呢?

另外一个例子，是玻璃，似乎是当代幕墙建筑最为常用的材料。早期的幕墙建筑使用单层玻璃，经常使用有色玻璃或镜面玻璃去控制太阳光。不考虑透明度，有色玻璃与透明玻璃的应用相当成熟，并展现出引人注目的服务质量与无限的使用年限。姑且不论因使用它们产生的太阳能或是热量问题，单层玻璃对于早期幕墙系统的耐久性贡献颇大。

注入惰性气体或镀膜处理的中空玻璃，被用来提升建筑外壳可视玻璃的保温性能。沿周长设置的隔热条将两片玻璃板分隔 (见图二)。保温气体如氩气代替空气被注入腔体之内。隔热条被注满干燥剂以便在装配完成之后去除腔体内残留的水分。周边粘结的密封胶决定着中空玻璃的使用性。如果密封效果差，水汽就能进入腔体并使得整个单元体失效: 如凝结水、涂层氧化、雾化、矿物沉淀导致的永久性晦暗，甚至霉菌的生长 (Ambrose & Karagiozis 2007, 2)。

There are a couple of important distinctions to be made about the evolution of curtainwall technology. First is the adoption of double-glazing—or insulated glass units (IGUs)—following the first energy crisis in the early 1970s. Second is the advent of unit or unitized systems, a strategy of modular prefabrication that enhances quality and minimizes site labor, at the cost of considerable added system complexity. Unit systems first appeared in the 1980s and grew to predominate new façade applications in the 1990s. The early-generation curtainwalls were called stick systems, referencing the practice of processing lengths of aluminum extrusions on site, first installing vertical mullions to slab edges, horizontals between verticals, followed by the setting of glass and other infill panels into the frames. The design, construction, and performance of stick and unit systems are substantially different, and there is reason to suspect that their service life characteristics may differ.

A potential vulnerability of curtainwall systems are the gaskets that provide the air and moisture barrier. Figure 1 is a typical horizontal stack joint detail of a unitized system. The gaskets at the top of the fin of the lower unit act in compression in a channel of the upper unit to provide the air and vapor barrier, even as the units move relative to each other and the fin slides up and down in the channel. While the gaskets represent only approximately 1% of the weight of a typical curtainwall unit (Table 1) the performance of the system relative to the important criteria of air and moisture penetration is entirely dependent upon the functioning of these seals. Yet once the unitized systems are installed, these seals are concealed and impossible to inspect or service.

Curtainwalls are deliberately designed as zero-maintenance systems; they are not designed to be maintained or renovated. In the absence of maintenance, how do these systems perform over their lifetime, and what impacts do they have on such concerns as operational energy consumption, occupant health and comfort, protection of the structural system and interior finishes, and ultimately, the service life of the systems themselves. Furthermore, what net improvements might be attainable if maintenance and renovation cycles were planned and designed for?

Glass – another case in point – is likely the most common material in contemporary façade construction. The early-generation curtainwall buildings were single glazed, frequently using body-tinted and sometimes mirror-coated glass to provide a measure of solar control. The body-tinted and clear glass applications have generally aged without apparent effect, displaying remarkably high service quality and indefinite service life. Despite the solar/thermal problems resulting from their use, single-glazing has contributed to the durability of these early curtainwall systems.

The IGU, with its accompanying gas fill and coatings, was developed to improve the thermal insulation properties of vision glass in the building skin. A perimeter spacer separates two glass panes (Figure 2). Insulative gases like argon are often employed to fill the cavity in place of air. The spacer is filled with a desiccant to eliminate any residual moisture remaining in the cavity after fabrication. The perimeter hermetic seal that bonds space and glass determines the serviceability of the IGU. If this seal is compromised, water vapor can enter the cavity and cause failure of the unit: condensation, oxidation of coatings, fogging, permanent clouding from mineral deposits, and even mold growth (Ambrose & Karagiozis 2007, 2).

The service life of an IGU is a function of design, fabrication, and installation quality, combined with service exposure, and varies widely. Typical commercial warranties range from 5 to 10 years, but a predictable service life for an IGU is more difficult to define. Designers

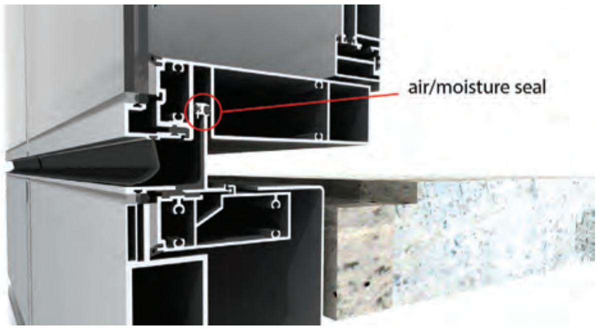

Figure 1. Typical horizontal stack joint between vertical CW units showing location of primary seal (Source: Advanced Technology Studio – Enclos).
图一: 典型单元水平节点显示一道密封的位置 (来源: ATS-Enclos)

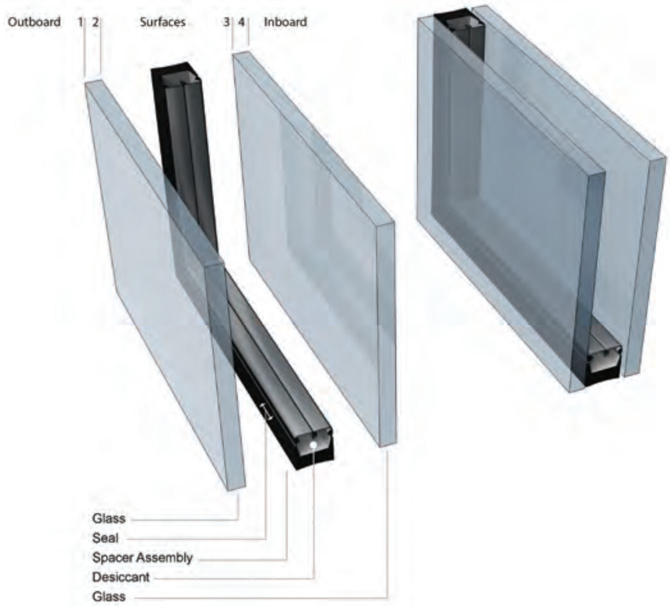

Figure 2. Typical insulated glass unit (IGU) construction. The wet-sealant bonding of the spacer to the glass to provide a hermetic seal, along with the coatings applied to the glass surfaces, reduce the service life and compromise the recyclability of the glass material (Source: Advanced Technology Studio – Enclos).
图二: 典型中空玻璃 (IGU) 组成。 (来源: ATS-Enclos)

中空玻璃的使用年限是由设计、制造、安装质量，和工作条件共同决定的，变化范围较大。典型的商业质保期在5-10年之间，然而中空玻璃的预期使用寿命却很难界定。设计师与业主需要知晓他们的产品能使用多久。一项经常被引用的，长达25年之久的相关研究 (Lingnell & Spetz 2007) 表明在现场条件下中空玻璃单元体分为三级。加速老化试验而进行分级的方法基于美国试验材料协会ASTM E774条关于"密封中空玻璃单元耐久性分级的标准分类法则"，将其分为C级、CB 级以及CBA级，质量要求逐层递增。C级和CB级表明其中14%的玻璃单元无法达到25年的服务年限，而在CBA级中，这一比例下降到3.6%。值得注意的一点是，所有级别中都会有伴随时间发展而提前失效的现象。一栋规模很大的商业建筑或者是居民住宅项目中的幕墙单元体内会嵌入上千块中空玻璃单元。根据上述实验结果，即使是使用最高的产品级别，在25年之内每1000块玻璃单元中至少有36块失效，在一座大型建筑中，这意味着数百块单元体的失效。如果使用的是级别更低的产品，则会有至少百分之二十的失效率，对于一栋建筑而言则是上千单元体的失效。不像幕墙单元的密封，破损失效的玻璃从建筑内外皆可视，并将会直接影响幕墙系统的使用年限。工业领域正继续大力改良中空玻璃单元的耐久性，卡迪纳尔 (2008.4) 工程中使用的最先进产品，其50年的报废率仅为0.74%，然而这仍是探索研究建筑更长使用寿命的一大障碍。

and building owners need to know how long they can expect a product to perform. A frequently referenced 25-year field correlation study (Lingnell & Spetz 2007) examined three certified performance classes of IGUs under field conditions. The classes certified through accelerated testing are established by specification ASTM E774 "Standard Specification for the Classification of the Durability of Sealed Insulating Glass Units," defining classes C, CB, and CBA, with progressively improved quality standards respectively. Classes C and CB exhibited a failure rate of 14% at 25 years of service. With class CBA this failure rate is reduced to 3.6%. Note that with all classes there is some earlier failure rate that accelerates over time. A large commercial or multi-family residential project will typically involve thousands of IGUs embedded within the curtainwall units. With the best product classification, test results indicate that 36 per thousand will fail within 25 years. This could represent hundreds of failed units on a large building. With the lower product classes, 200 per thousand can be expected to fail, representing thousands of potential units. Unlike the curtainwall unit seals, failed IGUs are highly visible from both inside and outside the building, and directly impact the service quality of the curtainwall system. Industry continues to make significant improvements in IGU durability—Cardinal (2008, 4) projects only a 0.74% failure after 50 years for its most advanced product—but this still presents a significant hurdle as longer building lifespans are explored.

Differential Service Life

What are the challenges and limitations to significantly extending the service life of primary building systems? The durability of a system, from building to subassemblies, is ultimately determined by the service life of its least durable component (Kesik 2002a). This is a fundamental yet often ignored aspect of durability and, ultimately, sustainability. The clear or body-tinted single glazing used in the first-generation curtainwall has a service life limited only by damage imposed on the material. In the absence of such damage the material has an unlimited lifespan that can justifiably be measured in hundreds of years and more. In comparison, the IGU has a service life often measured in a few decades. The serviceability of the hermetic seal is the weakest component in the IGU assembly. The rather dramatic effect is to collapse the service life of the glass subcomponent of the IGU assembly from unlimited to well under 100 years (in the very best of circumstances). The result is wasted durability and embodied energy of the glass material, the unintended consequence of improving the thermal and solar performance of glass in the building skin.

However, the service life impact of the hermetic seal does not end with the IGU. As the seal is a subcomponent of the IGU, the IGU is a subcomponent of the curtainwall system, and the IGU seal thus vies with the curtainwall unit seals for the shortest service life, thereby potentially defining the service life of the curtainwall system itself. (The IGU is the more likely culprit in limiting service life because of its visibility, whereas substandard performance resulting from the curtainwall unit seals is often masked, although potentially having far more impact on energy consumption and greenhouse gas emissions.)

Extruded aluminum, another dominant curtainwall material, is typically used to build up the frames for the modular units (Figure 3). It is also a material with a characteristically long lifespan, and is often used for its durability in certain applications, one of these being the building façade. The service life of aluminum is again generally determined by an aesthetic attribute of service quality represented by

差分使用年限

显著延续建筑系统使用寿命的挑战与限制是什么呢?建筑本身到其各个部件系统的耐久性最终决定于其构件的最低使用年限(Kesik 2002a)。这是一个基础的理念，但却往往往往被忽视。早期幕墙所使用的一道密封的有色或者透明玻璃的使用年限只受到材料损坏的影响。不考虑这样的损坏，有理由相信材料的使用寿命是无限的，长达数百年或者更长。相比之下，中空玻璃单元的使用年限往往以数以几十载衡量。中空玻璃单元体最为脆弱的部分实则是其密封的可用时限。其造成的惊人影响，是将中空玻璃单元中玻璃部件的使用年限从无限期至百年之内(最佳的情形下的预测)。结果是，中空玻璃提高了建筑外壳的玻璃的光热性能，却无意中造成了玻璃材料的耐久性与物化能的浪费。

然而，密封对使用年限的影响并不会在中空玻璃单元里终结。因为它是中空玻璃单元的一部分，而中空玻璃单元又是整个幕墙系统的一部分，因此中空玻璃的密封与幕墙单元体的密封的相互影响是决定使用用年限最短的因素，由此才能大概的解释幕墙系统本身的使用年限。(中空玻璃单元却因其可视性而被认为是限制幕墙系统使用年限的罪魁祸首，然而幕墙单元的密封造成不达标的性能情况往往是不明确的，尽管它更多的影响建筑能耗与温室气体排放)。

另一种构成幕墙的主要材料是铝挤压型材，常常被用作典型单元体的框架(见图三)。铝型材因其较长的使用年限的特点，会因其耐久性而被广泛应用，其中之一便是用于建筑幕墙。框架系统中材料的表面处理体现了使用质量的美学属性，而这又决定了铝材的使用年限。当铝材表面被高性能的阳极氧化或氟碳喷涂处理后，它们的性能受暴露环境的影响而退化。跟玻璃一样，铝型材母材若得到最佳的保护和处理，其无限的耐久性即使不以百年为单位，也可以轻松以几十年计。其表面处理，相似于中空玻璃单元，其耐久性在30-50年之间，且受制于设定的幕墙系统最低质量标准的最低的外观要求水平。

与玻璃一样，更低的铝材表面处理或中空玻璃的使用寿命导致的退化非常显著，由此又会产生耐久性的浪费(见图四)。实际上，因为玻璃在一个典型幕墙单元体中所占比重约为铝型材的三倍，铝型材却承担两倍于玻璃的物化能消耗(见表一，表二)。二者一起在典型幕墙系统中占了超过90%的物化能耗(见表二，图四).

Figure 3. CW unit frames are factory assembled from fabricated aluminum extrusions and gaskets fitted to extruded raceways (Source: Mic Patterson).
图三: 工厂组装的幕墙单元体(来源: Mic Patterson)

the material finish as a subcomponent of the framing system. While high-performance anodized or Fluoropolymer coatings are typically employed, they are subject to degradation over time as a function of environmental exposure. Optimally protected and employed, the base aluminum, like glass, has an unlimited durability that is easily measured in decades, if not centuries. The finish, however, is closer to the service life of the IGU, in the 30 to 50 year range, and subject to potentially unacceptable levels of visual deterioration depending upon the minimum quality standards defined for the system.

As with the glass, there is a significant collapse in aluminum service life resulting from the lower component service life of either the aluminum finish or the IGU, again producing durability waste (Figure 4). In fact, while glass in a typical curtainwall unit is approximately three times the weight of the aluminum frame, the aluminum is responsible for well over twice the embodied energy of the glass (Tables 1 and 2). Together, the glass and aluminum represent over 90% of the combined embodied energy of a typical curtainwall system (Table 2 and Figure 4).

Maintenance and Renovation Cycles: Strategies for Renewal

Opportunity, then, lies in a façade system design that fully realizes the durability of its dominant materials: glass and aluminum. One strategy to achieve this is the planned maintenance of the seals, finishes, and other minority materials that have been identified to compromise system façade system service life. This would require a change in CW system design, and in the zero-maintenance design mentality, something that can only be achieved through a clear demonstration of value.

Durability is a design problem. By harmonizing the service life relationships between the various subcomponents that comprise a system, durability can be optimized and embodied energy minimized (Kesik 2002). Glass and aluminum, the primary materials in a CW system, are capable of matching a building structural system in service life. What is needed is a CW system design that fully supports the durability of these materials.

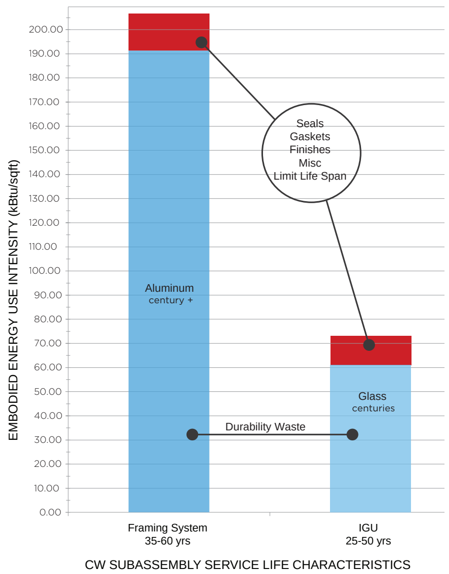

Figure 4: Analysis of embodied energy use intensity of primary CW assemblies
Indicating how minority materials, essentially seals and finishes, compromise the service life of the dominant materials of glass and aluminum, which represent the large majority of embodied energy in the subassemblies (Source: Mic Patterson, Ben Silverman).
图四: 物化能耗的分析
玻璃幕墙系统中主要组件的物化能耗揭示了诸如密封及室内装修这类少数材料如何缩短玻璃和铝材这类主要材料的使用寿命，这些主要材料代表了建筑子系统中绝大部分的物化能。(来源: Mic Patterson, Ben Silverman)

保养与改造周期: 更新策略

幕墙系统的机遇在于充分了解其主材即玻璃与铝材的耐久性的幕墙系统设计。策略之一，便是定期维护保养那些已被认定为会影响幕墙系统使用年限的密封材、表面处理和其它少数材料等。这就需要在幕墙系统设计和零维护设计理念两个方面做出改变，并且这项改变只有通过明确展示幕墙系统的设计价值方能获得。

耐久性是一个设计类难题。通过平衡各个构成幕墙系统的子部件的使用年限的关系，即可取得耐久性的最佳化与物化能耗的最小化 ((Kesik 2002) 。幕墙系统中的基础材料--玻璃与铝材是能够与幕墙结构系统在使用年限上相匹配的，所需的只是幕墙系统的设计中充分考虑此类材料的耐久性。

幕墙更新策略的采用包括保养与改造的合适的周期，故而建筑的千年耐用年限并非空想。然而，保养与改造周期所产生的物化能耗循环，会增加物化能的消耗，至少会部分抵消因增加使用年限产生的物化能 (见图五) 。复杂之处在于决定更新策略对的净价值 (或者说是花费) 、其中包括外界环境与具体运行能耗的双重影响，而这则是下一阶段研究的重点。

CW Unit Component Weight		QTY	UNIT
Dimensions	Unit Width	5	ft
	Unit Height	12	ft
Densities	Glass	156	pcf
	Alum	170	pcf
	Steel	490	pcf
	Silicone	86	pcf
	Insulation - Firespan 90	8	pcf
Aluminum	Vertical Mullion Area (M+F)	5.0	in2
	Horizontals (Stack Joint + Int)	10.8	in2
	Lift Lug	30.6	in3
	Anchor Brackets	65.0	in3
Hardware	#14-14 Weight	0.04	lbf/pc
	#14-14 QTY	24	
	1/2" - 13 Weight	1.00	lbf /pc
	1/2" - 13 QTY	6	
Shadowbox	Height	3	ft
	Aluminum Thickness	0.125	in
	Steel Backpan Thickness	0.036	in
	Insulation Thickness	4	in
Glass	Inboard Lite	0.25	in
	Outboard Lite	0.25	in
	Spacer / Secondary Silicone	0.25	psf
Gaskets	Bed Gasket	0.089	in2
	Air Seal (Vert)	0.055	in2
	Rain Screen (Vert)	0.051	in2
	Air Seal (Horz)	0.043	in2
	Rain Screen (Horz)	0.140	in2
	Structural Silicone (all) 5/8 x 1/4	0.156	in2
Summary	Insulating Glass Units	6.75	psf
	Frame	2.24	psf
	Lift Lug and Anchor	0.16	psf
	Fasteners	0.12	psf
	Shadowbox - Alum Panel	0.44	psf
	Insulation	0.67	psf
	Backpan - Galv Steel	0.37	psf
	Bed Gasket	0.04	psf
	Air Seal (Vert)	0.02	psf
	Rain Screen (Vert)	0.02	psf
	Air Seal (Horz)	0.02	psf
	Rain Screen (Horz)	0.06	psf
	Structural Silicone (all) 5/8 x 1/4	0.07	psf
Total Weight		**10.97**	**psf**
Notes	no thermal breaks shadowbox construction		

Table 1. Preliminary material analysis of baseline CW system (Source: James Casper).
表一: 基准幕墙系统材料初步分析 (来源: James Casper)

CW Unit Makeup	Embodied Energy Coefficient (kBtu/lb)	Weight (lb/sqft)	Embodied Energy Use Intensity (kBtu/sqft)
Insulating Glass Units	10.73	6.75	72.43
Aluminum Framing	66.21	2.24	148.45
Lift Lug and Anchor	66.21	0.16	10.38
Fasteners	24.38	0.12	2.83
Shadowbox - Alum Panel	66.21	0.44	29.31
Insulation	9.18	0.67	6.12
Backpan - Galv Steel	12.25	0.37	4.50
Gaskets & Seals	26.51	0.23	6.10
Totals		10.97	280.11

Table 2. Preliminary embodied energy analysis of baseline CW system using ICE LCI data (Hammond & Jones 2011) (Source: Mic Patterson, Ben Silverman).
表二: 基于ICELCI数据 (Hammond & Jones 2011) 的基准幕墙系统物化性能的初步分析 (来源: Mic Patterson, Ben Silverman)

Employing a strategy of façade renewal that includes harmonized cycles of maintenance and renovation, it is not unreasonable to consider building service life of a millennium. However, maintenance and renovation cycles produce what is termed recurring embodied energy, which adds to the embodied energy debt and at least partially offsets the embodied energy gain resulting from the increased service life (see Figure 5). The complexity is in determining the net value (or cost), including environmental and operational energy impacts, resulting from a renewal strategy. Such is the focus of next stage research.

总结

以上讨论是基于使用碳和能量数据库(Hammond & Jones 2011)对LCI数据的初步分析，以及为建立基准系统而发展起来的幕墙系统理论。对于有效合理的LCI数据的研究正在不断发展。意图通过比较物化能耗而建立和发展一个可以替代当前幕墙系统设计并可以检验其价值和耐久性的研究方法。最终目的是为了发展超耐久、高性能的幕墙系统，以便创造一种寿命持久的低物化能耗的建筑。

Summary

The discussion here is based on preliminary analysis using the Inventory of Carbon and Energy database (Hammond & Jones 2011) for LCI data, and the development of a theoretical curtainwall system in an effort to establish a baseline system. Research on more robust and appropriate LCI data is ongoing. The intent is to develop a methodology by which to compare the embodied energy of alternative curtainwall system designs, and to test strategies for, and the value of, durability planning in extending façade system service life. The goal is the development of ultra-durable high-performance façade systems as a means to low lifecycle operating and embodied energy buildings.

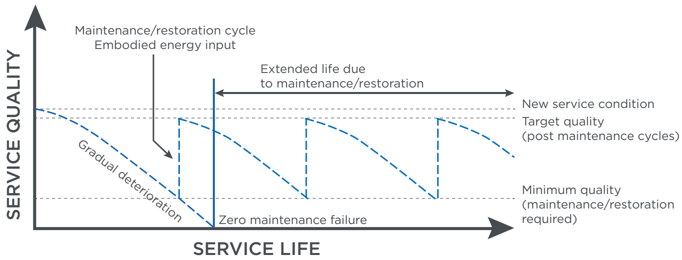

Figure 5. Impact of maintenance and renovation cycles on service life (Source: Kesik 2002).
图五: 维护和改造周期对使用年限的影响 (来源: Kesik 2002)

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