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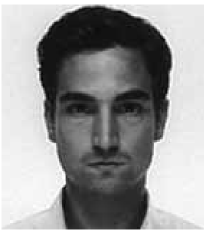
The Design Process of Complex Architectural Façades
复杂的建筑外墙的设计过程

Bert van de Linde



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Abstract

Facades form the identity and functionality of high-rise buildings. The "design process" for complex bespoke architectural high rise facades is an abstract term that in reality is not a single process but a simultaneous cross-disciplinary design processes. These include façade integration with the building environmental systems, holistic system performance, decision making tools and efficiency streamlining for production, procurement and installation. This paper outlines various cross-disciplinary integrated design processes with a particular emphasis on the need for specific customised design systems and tools that enable complex façade forms to be economically and efficiently realised.

Keywords: Design Process, Integrated Design, Holistic Design, Efficiency Streamlining

摘要

幕墙建立了高层建筑物的身份和功能性。对复杂定制建筑的高层建筑幕墙来说“设计过程”是一个抽象名词，但事实上，它不是一个单一的过程，而是同步进行的跨学科设计过程。该过程包括将幕墙与建筑环境系统，整体系统性能，决策工具和高效精简的生产，采购及安装流程相结合进行一体化整合。本文概述了各种跨学科一体化设计的过程，并重点强调对特殊定制设计系统和工具的需求从而能够经济且高效地实现复杂幕墙。

关键词：设计过程、一体化设计、整体综合设计、高效率精简流程

Rethinking The "Design Process"

"Design", particularly as it relates to building facades, is an abstract term often presumed as a linear process. Unlike other systems within the building which have distinct yet relatively independent functions, the façade must be designed to cope with numerous building system requirements including structural (building movements), thermal (solar irradiation, heat transmission), weather tightness (durability, water exclusion), comfort (acoustics, glare), security (blast, intrusion) and safety (fire, impact), whilst maintaining the desired architectural aesthetic.

In reality, "design" is a series of distinct concurrent multi-disciplinary processes that includes:

- Façade whole-building environmental system integration
- Holistic system performance
- Effective & reliable decision making
- Design Streamlining & Efficiency.

“设计过程”的反思

“设计”，尤其是当其与建筑幕墙相关联时，是一个抽象术语，通常被假定为一个单一线性过程。与建筑内部其它系统清晰独特且相对独立的功能不同，幕墙必须设计成能应付众多建筑系统要求包括结构（建筑位移），热工（太阳热辐射，热传递），水密性（耐久性，防水性），舒适度（声学，防眩光），防护措施（防爆，防侵扰）和安全（防火，抗冲击）等，同时还应保持想得到的建筑美感。

事实上，“设计”是一系列独特并行的多学科过程，包括：

- 幕墙与整体建筑环境系统的集成
- 整体系统性能
- 有效及可靠的决策
- 设计精简及高效率

幕墙与整体建筑环境系统集成

减少碳排放量的必要性已在全球各国建筑法规中有多次修订旨在减少能耗。幕墙系统必须被设计为用户提供舒适（眩光，自然采光，表面辐射效应等）之间及节能（太阳热辐射，热量传递，渗漏等）的动态元素。在建筑环境系统的设计中，幕墙性能常常被模拟为静态性能的属性。事实

Façade Whole-Building Environmental System Integration

The need for reductions in carbon emissions has seen many revisions in national building codes worldwide aimed at reducing energy. Façade systems must be designed as dynamic elements providing between comfort (glare, natural daylight transmission and radiant surface effects) and energy (solar heat gains, thermal transmission, leakage). In the design of building environmental systems, facade performance is often modelled using steady state performance properties. In reality, environmental conditions vary and the façade will invariably be dynamically regulated to achieve a balance of occupant comfort and energy efficiency. In order to be able to achieve energy reductions and improved comfort levels in buildings, the dynamic performance advantages of facades need to be accurately modelled as well as controlled and monitored with a high degree of confidence.

From an engineering viewpoint, the dynamic behaviour of the façade can be achieved using an advanced control system that includes blinds, HVAC, occupancy sensors and lighting.

A managerial constraint in achieving façade whole-building environmental system integration is primarily due to the time schedule which the environmental system and façade are procured, with the former usually carried out during the whole building design engineering process whilst the façade is usually procured at the specialist sub-contractor stage when major building design has been "completed". The possibility to use the specialist engineering experience of the façade contractor to integrate the façade and HVAC system is often too late in the main construction programme.

Permasteelisa & SOMFY have developed a BMS system utilizing software algorithms where blind controls have been integrated that interact with HVAC controls that dynamically regulate the façade for cooling demands, using the solar heat gains to condition the building before switching on heating as well as to interact with lighting and glare controls (see Figure 1).

Further optimisation is achieved using occupancy sensors. When the room or office is not occupied, the glare protection or comfort level has no priority setting so blinds can run in the energy mode.

After façade installation, either the façade contractor or blind manufacturer is responsible for all electrical connections from and to the façade. Thus a great deal of site work is required at generally higher costs compared to factory installation. With this technology it is possible to integrate blind controls into the façade. The major advantage being that a majority of electrical connections and programming is completed resulting in considerable time savings and less on-site failures. This integration is undertaken during façade production as well as testing and regulation of the blinds essentially eliminating failures.

Holistic System Performance

The application of advanced materials, particularly composites, in aerospace, automotive and defence industries is well established and gradually being embraced as an architectural material in tall building facades.Design standards relating to the use of innovative materials in building facades are not well established. In order to correctly design innovative materials into facades which have no standards for application or track record, an alternate design process is required that looks at a holistic system performance.

The standard design approach involves specialists in various performance disciplines including design, structural, materials, building

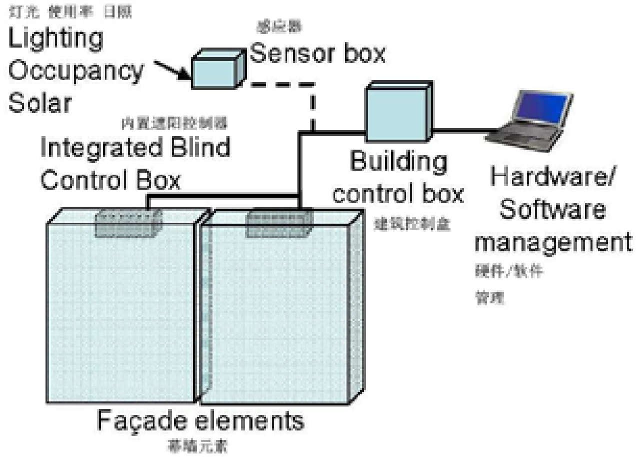


Figure 1. Schematic façade BMS integration (Source: Permasteelisa Group, 2012)
图1. 幕墙BMS集成示意图（来源：帕玛斯迪利沙集团，2012）

上，环境条件是不断变化的，因此幕墙必需动态地调控，以达到用户舒适性和节约能源之间的平衡。为实现建筑物的能耗减少和改善舒适度，需要有充分把握地对幕墙的动态性能优势进行精确模拟，调控及监测。

从工程角度来看，幕墙的动态特性可通过采用涵盖遮阳，HVAC（采暖，通风，制冷），空间占用感应器及照明的先进控制系统来实现。

在实现幕墙与建筑环境系统一体化中有管理上的限制，主要是因为环境系统和幕墙采办的时间安排。前者通常在整体建筑设计工程过程中实施，而幕墙通常则是在大部分建筑设计被“完成”的专业分包阶段采办。由于往往为时太晚，在主要施工程序上利用幕墙承包商的专业工程经验来将幕墙与制热、通风与空调控制（HVAC）系统一体化的可能性几乎微乎其微。

帕玛斯迪利沙与尚飞（SOMFY）联合开发的BMS系统采用与遮阳控制合整的软件算法和HVAC控制互动，从而按制冷负荷动态地调节幕墙，在开启供热前利用太阳辐射热增益来调控预备建筑物，同時与照明及眩光控制互动（图1）。

通过空间占用感应器可实现进一步的优化。当房间或办公室无人时，眩光保护或舒适度不再是首要设定，遮阳可以在节能模式下运行。

在幕墙安装后，则由幕墙承包商或遮阳制造商负责所有与幕墙之间的电子连接。与在工厂安装相比，这样大量的现场工作是通常需要较高成本的。通过这个技术可将遮阳控制合整置幕墙内。该技术的主要优势在于大部分电子连接和编程在幕墙安装之前完成，节省时间并减少工地现场出错。此一体化在幕墙制作及遮阳的测试和调节过程中进行，从而在本质上消除故障。

整体综合系统性能

先进材料，尤其是在航天、汽车和国防工业的复合材料应用已经成熟，并已逐渐被接受为高层建筑幕墙建材。但新材料应用于建筑幕墙的相关设计标准还不完善。在没有应用标准及先例记录的情况下，要正确的设计新材料置于幕墙中，就需要一个统观整体系统性能的交替设计过程。

常规的设计方法牵涉到各性能学科的专业人员，包括设计，结构，材料，建筑物理，声学，防火，表面处理，生产和现场安装，来对系统的需要进行审查并提出建议。

参见图2，此设计过程为会聚法，设计按顺序和不断被审查而产生影响逐步会聚成一个设计方案。此过程的主要限制在于，它不仅耗时，而且扼杀了创新思维， 因为各专业人员的知识往往局限制于其狭窄的领域， 故对设计的贡献有其局限性。

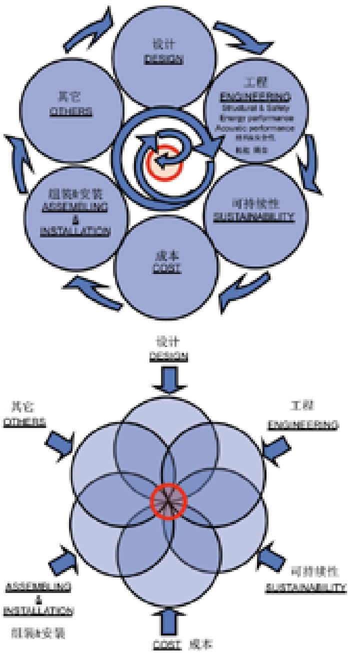


Figure 2. Representation of development flows with a convergent approach (top) and with a holistic approach (bottom); the design solution is represented by the red circle (Source: Permasteelisa Group, 2012)
图2. 会聚法（上）和整体法（下）开发流程示意；红色圆圈表示设计方案（来源：帕玛斯迪利沙集团，2012）

physics, acoustics, fire, finishing, production and site installation to review and advise the needs of the system.

Referring to Figure 2, this design process is a convergent approach with design impacts sequentially and continuously being reviewed, gradually converging to a common solution. The major constraint to this process is that it is not only time consuming but also stifles innovative thinking since specialist knowledge is limited to one narrow field and design contribution limited.

Holistic design involves understanding in a global performance context, how the design decision based on one performance parameter affects other system performances. A holistic design approach requires people involved within the design process to have a basic but broad multi-disciplinary (overlapping) knowledge rather than a narrow in-depth highly specialised view.

The main comparison between the two approaches is that an "outside-in" convergent design process involves the gradual education of specialists to reach a design consensus, whereas an "inside-out" holistic design process focuses on a concurrent design consensus to narrow down design constraints saving considerable time.

A Holistic Design Approach

A comprehensive case study of how a holistic approach can quickly solve complex designs is the TEC façade. The project (Permasteelisa Group, Fiberline Composites and Arup) focused on the developments of an innovative high performance façade system using pultruded glass-fiber reinforced polymer (GFRP) profiles. Due to its low thermal conductivity and high structural strength, the use of GFRP material to replace aluminum profiles presented a good sustainable solution. The use of a relatively transparent resin developed by Fiberline Composites, allows the design of façade panels with translucent framing areas (see Figure 3).

The foremost requirement of the TEC facade is compliance with European market high-rise building requirements. Architectural and market driven design restraints include:

整体综合设计以考虑总体性能为原则，了解针对某一个性能参量的设计决定对其他系统性能的影响。整体综合设计要求参与设计的人员中应有具有基本而广泛的多学科（相互重叠）知识，而非深入狭窄的高度专业化见解。

两种方法的主要区别在于，“由外而内”的会聚设计过程涉及对专家的渐进式教育以达致一个设计共识，而“由内而外”的整体综合设计过程侧重于同步平行地达成设计共识，以缩小设计限制并节省大量时间。

整体综合设计法

TEC幕墙设计即是一个全面的范例，说明整体综合设计如何快速解决复杂的设计。该项目（帕玛斯迪利沙集团，Fiberline Composites和奥雅纳工程顾问）着重于使用拉挤成型玻纤维增强塑料（GFRP）型材的新型高性能幕墙系统的开发。由于其低热传导性及高结构强度，使用GFRP材料替代铝型材视为一个良好的可持续建筑解决方案。使用由Fiberline Composites开发的相对透明的树脂，容许幕墙带半透明框架范围的设计（图3）。

TEC幕墙最主要的要求是要符合欧洲市场高层建筑要求。建筑设计和市场需求导致设计的限制因素包括：

- 减小幕墙厚度（100毫米），增大建筑租用面积和轻身表皮外观。
- 幕墙单元板块高度和宽度的灵活性。
- 具竞争力的成本。

结构和安全特性包括：

- 设计风载荷：2.4Kpa
- 防火性能：等级B-s3-d0 [EN 13501-1，2007]
- 隔音：直接隔音Rw + Ctr ≥ 35dB [EN ISO 717-1，1996]
- 隔热：整体U值 < 1.2W/(m²K) [BS EN 13947，2006]。

整体综合设计方法不仅考虑物理性能要求，还需保持建筑美观：尤其是修长，轻盈的半透明外观。矛盾地是这也会带来问题，尤其是隔音衰减（图4）。

由于GFRP的轻质特性，大型竖框和窗槛板对幕墙的整体隔音性能有较大的影响。为实现较高的隔音性能，幕墙外表面需要有一定重量。可是GFRP密度较低，只有等于1800kg/m³（Fiberline Composites，2002）。

Figure 3. TEC façade design concept (source: Arup, 2007)
图3. TEC幕墙设计理念（来源：Arup，2007）

- Reduced façade thickness (100mm), increasing building lettable area and light skin appearance
- Panel height and width flexibility
- Competitive cost.

Structural and safety properties include:

- Design wind load: 2.4kPa
- Fire reaction properties: Class B-s3-d0 [EN 13501-1, 2007]
- Acoustics: direct sound insulation Rw + Ctr ≥ 35dB [EN ISO 717-1, 1996]
- Thermal insulation: overall U-value < 1.2W/(m^{2}K) [BS EN 13647, 2006].

A holistic design approach was undertaken not only with regards to the physical performance requirements but also maintaining aesthetics: in particular the slender, light translucent appearance. Paradoxically this also posed problems, particularly acoustic attenuation (see Figure 4).

Given the light nature of GFRP, large mullions and spandrel panels have a high influence on the overall curtain wall acoustic performance. To achieve high sound insulation, a heavy external façade surface is required yet GFRP has a low density, equal to 1800kg/m^3 (Fiberline Composites, 2002).

In order to maintain translucency, element thickness were limited. The framing elements, especially the spandrel, could not be extruded as a hollow section which would be optimal from a structural point of view since coupling the inner and outer surfaces enhanced acoustic transmission.

The solution was to develop a float glass/GFRP composite laminate bonded to the GFRP frame with the composite plate placed externally (see Figure 5).

The composite laminate could not be achieved using conventional PVB glass lamination as the autoclave temperature affects GFRP transparency and thus a resin technology was developed. A synergetic solution for both structural performance and acoustic decoupling was achieved by selecting an adhesive system whereby the laminate could be bonded to the GFRP framing element to form a semi-composite, with the adhesive having a sufficient elastic modulus soft enough to acoustically decouple the two elements, yet effectively transfer longitudinal shear due to bending.

To achieve the desired thermal insulation, innovative but also economical translucent insulation materials have been incorporated. Fire reaction performance is achieved by balancing the total heat released and rate of flame spread of the GFRP with the heat conduction characteristics of the glass component of the laminated composite resulting in a reduction of GFRP thickness and consequently an increase of light transmission properties.

Effective & Reliable Decision Making

The major constraint to any design process is time. The design process often requires numerous design permutations and iterations in order to achieve cost efficiency. The adequacy and reliability of a design requires the use of suitable and reliable engineering tools and software. Numerous generic engineering software packages such as FEA and CFD require both specialist modelling and analytical knowledge and depending on model complexity extensive computational time.

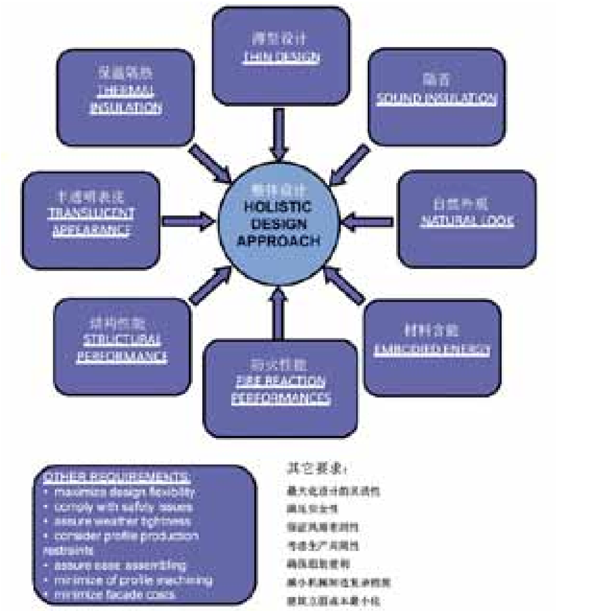


Figure 4. representation of performance requirements set for the TEC façade project. All the requirements have been considered at the same time with a holistic approach (Source: Permasteelisa Group, 2012)
图4. TEC幕墙的性能要求。整体综合设计法同时考虑了所有要求（来源：帕玛斯迪利沙集团，2012）

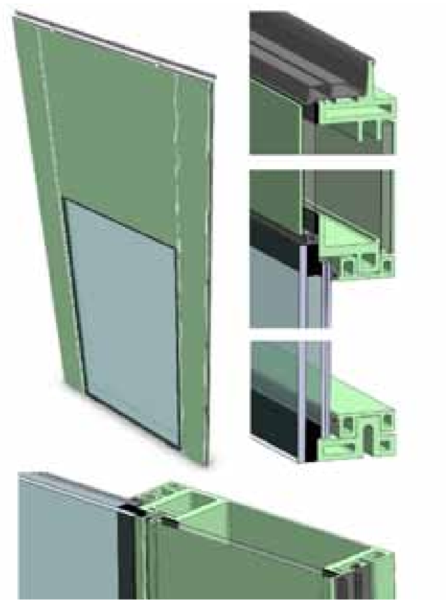
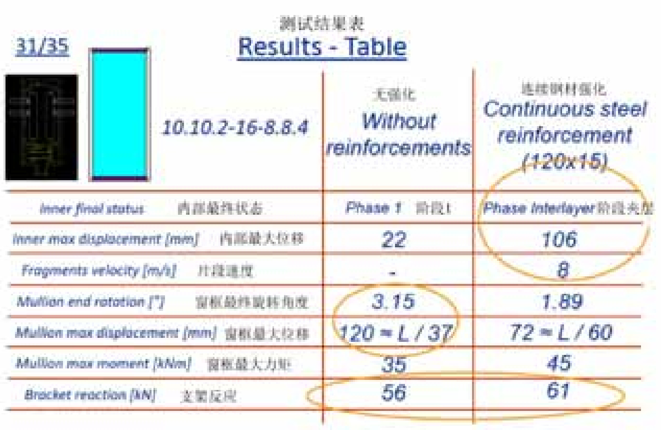


Figure 5. rendering of the developed solution: 3D view of the standard module (top-left); vertical sections at panel top (top-right), at intermediate transom height (middle-right), at panel bottom (bottom-right); and horizontal section at IGU height (bottom) (Source: Permasteelisa Group, 2012)
图5. 解决方案效果图：标准模块的3D视图（左上），垂直剖面，面板顶部（右上），中横梁（中右），面板底部（右下）及在中空玻璃高度的水平剖面（底部）（来源：帕玛斯迪利沙集团，2012）

为保持其半透明性，元素的厚度有一定的限制。同时如果内外表面耦合，会增强噪音传输。框架构件，尤其是窗槛部分，不能从结构优化的角度冲压成空心截面，因于内部和外部的表面耦合增强了声音传递。

解决方法是开发浮法玻璃/GFRP复合板，将复合板设在外表面粘结至GFRP框架（图5）。

由于高压釜温度影响GFRP的透明度，因此无法使用传统的PVB玻璃胶合来实现复合胶合，因此团开发了树脂粘合技术。通过选择粘合系统，实现了结构性能和声学解耦协同的解决方案。凭借夹胶复合板粘结至GFRP框架元件以形成半复合材料，其粘合具有充足的弹性，系数柔软到可以对被粘结的两个构件进行噪音解耦，



测试结果表

Results - Table

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10.10.2-16-8.8.4	无强化 Without reinforcements	连续钢材强化 Continuous steel reinforcement (120x15)
Inner final status 内部最终状态	Phase 1 阶段1	Phase Interlayer 阶段夹层
Inner max displacement [mm] 内部最大位移	22	106
Fragments velocity [m/s] 片段速度	-	8
Mullion end rotation [°] 窗框最终旋转角度	3.15	1.89
Mullion max displacement [mm] 窗框最大位移	120 ≈ L / 37	72 ≈ L / 60
Mullion max moment [kNm] 窗框最大力矩	35	45
Bracket reaction [kN] 支架反应	56	61

Figure 6. Reinforced vs. Unreinforced mullion MDOF Blast Analysis Results (Source: Lori, Zobec et.al. 2009)

图6. 加强和未加强竖框MDOF防爆分析结果（来源：Lori，Zobec et.al. 2009））

As model complexity increases, the influence of design changes on façade system performance becomes less intuitive with "black-box" reliability on software results often leading to incorrect assumptions. Results reliability is also limited to the accuracy and reliability of input data as well as modelling simplifications and limitations.

Many software tools used to assess façade performance are based on analysing individual components rather than analysing the overall façade system, leading to conservative costly designs.

Dedicated software tools that analyse the overall system and interaction of all façade components are required. Three examples of software tools (amongst numerous others) used in the areas of security (blast enhancement), energy efficiency (EPBD) and comfort (acoustics) are described as follows:

Security - Blast Enhancement: TESTUDO

The common approach in the design of blast enhanced facades is to model the façade as a series of individual components applying the reactions of supported element. Structurally this would appear to be valid but for impulsive blast loads results in oversized and expensive elements and lower levels of security since the flexibility of the element supporting the component is not effectively considered in dissipating blast energy.

Figure 6 describes the advantages of such an approach comparing two façade systems. Using an elemental approach, the façade mullion required costly steel reinforcement and the glazing was predicted to crack with ensuing fragmentation. Undertaking an integrate façade system analysis using TESTUDO, shows that mullion reinforcement is unnecessary with greater glazing support flexibility and glazing remaining intact. The resulting advantages are a lighter economical façade, thinner glazing with a higher level of protection.

TESTUDO is based on a coupled MDOF model that analyses the interaction of the façade system including glazing, framing and fixings (see Figure 7).

Whilst the software utilizes an "approximate" method of analysis, the results are sufficiently accurate to within +/-5% of FEA models for typical façade modulations (Lori, 2009). Model run times are less than a minute, allowing rapid design iterations.

Comfort – Acoustics: SEHMA

In order to reduce traffic congestion and lower carbon emissions, sustainable design in cities favours developments to be within close proximity of efficient public transport networks. This requirement has seen greater attention to acoustic issues in buildings.

但是又能有效地传输为由弯曲引起的纵向剪力。

为实现所需的隔热性能，一个创新且经济的半透明隔热材料合并其中。防火反应性能则通过平衡总热量释放和带有夹胶复合玻璃部件热传导特性的GFRP的火焰蔓延率来实现，结果减小GFRP厚度，从而增强透光特性。

有效及可靠的决策

任何设计过程的主要限制均为时间。设计过程通常需要大量的置换与迭代从而达到成本效益。设计的充分性和可靠性需要使用适当可靠的工程工具和软件。许多通用工程软件包，例如FEA和CFD，需要具有专业建模及善于解析的知识，同时取决于模型复杂性，需要大量的计算机运行时间。

的复杂性随着模型复杂性的增加，对幕墙系统性能的设计影响力变得不太直观，以软件中“黑匣子”的可靠性结果往往会导致不正确的假设。结果的可靠性也受限于输入数据的精确性和可靠性，以及模型的简化和限制。

许多用于评估幕墙性能的软件工具都是基于分析每个单一部件，而非分析整个幕墙系统，从而造成保守而昂贵的设计。

分析整体系统及所有幕墙部件之间的相互作用的专用软件工具是有必要的。下文描述了三个软件（在众多其它软件中），分别应用于：防护措施（增防爆性能），节能效率（EPBD）和舒适性评估（隔音）领域。

防护措施 – 增强防爆性能：TESTUDO

设计具有防爆幕墙的通用方法为，将幕墙作为一系列独立的部件进行建模並施加支撑元件的反应。在结构上这似乎是有根据的，但因在耗散爆炸能量中没有有效地考虑部件支撑件的柔韧性，脉冲爆炸荷载会导致构件尺寸过大及造价昂贵，并且降低防护措施的水平。

图6通过对两个幕墙系统的比较，阐述该方法的优点。若采用独立构件分析方法，幕墙竖框需要昂贵的钢补强，分析预计玻璃会破裂继而碎片飞溅。利用TESTUDO软件进行整合幕墙系统分析，显示带有更大的玻璃支撑柔韧性，竖框无需强化，同时玻璃可保持完好无缺。相应结果的好处是更轻巧经济的幕墙，更薄的玻璃和更高水平的保护。

TESTUDO基于耦合的MDOF模型，分析幕墙系统的相互作用包括玻璃，框架和紧固件之间的相互作用（图7）。

尽管软件采用“近似”的分析方法，结果是充分精确的，均在有限元模型中典型幕墙分格的 + /-5%范围内（Lori，2009）。模型运行时间少于1分钟，允许快速的设计迭代。

舒适度 – 隔音：SEHMA

为减少交通拥堵和降低碳排放量，城市的可持续设计规划倾向于与高效公共交通网络距离相近的有利发展。这项规定已使建筑物的隔音问题更受关注。

M. Blasco开发出了一个半实验性的分析工具（SEHMA）对幕墙（尤其是多层组成）的隔音性能进行预估（Blasco，2011）。该计算工具采用统计能量分析，使用调整的正常吸收系数，对有限空间尺寸的修正，临界频率的变化和临界频率的阻尼，进行了进一步的改善。利用统计能量分析可高效迭代地将幕墙系统模拟为一个包括通风间隙的附加子系统和竖框相连，而无需再建一个全新的声学模型。此方法的主要优点在于计算几乎是瞬时完成的，平均模型预估误差小于3 dB，可以很容易的与其它计算工具合整，使其成为项目招标和预设计阶段的卓越工具。

节能效率 – EPBD

建筑的舒适度和能耗预测极大程度上取决于众多的幕墙参数，包括玻璃，遮阳，幕墙（单，双层）类型，BMS设置，自然通风布局及与建筑相关的属性，例如，地理位置，气候条件，朝向，建

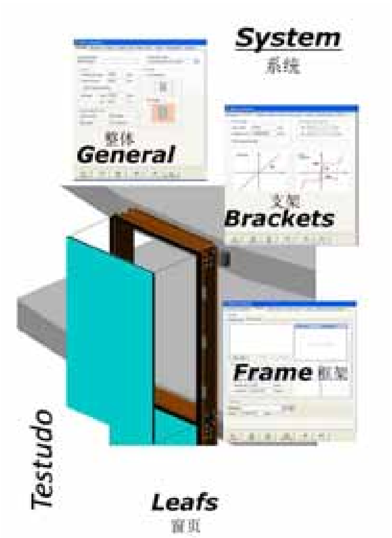

Figure 7. blast enhanced façade software Testudo (Source: Lori, Zobec et.al. 2009)
图7. 具有防爆幕墙的幕墙分析软件Testudo（来源：Lori，Zobec et.al. 2009）

For the acoustic prediction of facades (particularly multi-layers) a semi-empiric analytical tool (SEHMA) was developed by M. Blasco (Blasco, 2011). This calculation tool is based on Statistical Energy Analysis and further refined using an adapted normal absorption coefficient, a correction for finite sizes, and shift in the critical frequency and damping at the critical frequency. The use of statistical energy analysis allows the façade system to be effectively and iteratively modeled as an additional subsystem including ventilation gaps and connecting mullions without the need to create a completely new acoustic model. The main benefit of this approach is that the calculation is almost instantaneous, average model prediction errors below 3 dB and is easily integrated with other calculation tools, making it an excellent tool during the tender and pre-design stage of a project.

Energy Efficiency – EPBD

Comfort and energy consumption predictions of buildings is greatly dependent on numerous facade parameters including glazing, shading, façade (single, double skin) typologies, BMS settings, natural ventilation strategies as well as building related properties such as geographic location, climate conditions, orientation, intended building use, thermal mass and occupant behaviour.

Current energy modelling software used to size environmental systems often utilize simplistic façade models and properties particularly incident glazing properties and U values. Advanced façade systems with multiple layers, dynamically varying ventilation and shading controls are often modelled incorrectly and inaccurately. Stringent national energy codes are also incorrectly focused on component properties such reducing U-values in the belief that minimising heat transfer rather than balancing in buildings will provide energy savings. This strategy has seen numerous buildings especially in cold climates require cooling even in winter months.

The EPBD software developed by Permasteelisa undertakes dynamic whole-building energy simulation that considers the dynamically variable façade properties as well as the impact of ventilation, shading response and day-lighting. The multi-compartmental model also allows multiple façade types to be modelled in order to assess the most economical façade typology per elevation that will maximise both energy and comfort.

Figure 8 describes such an example, whereby comparing a triple glazed unit (TGU) with a closed cavity façade. Simply comparing glazing U values would indicate the TGU to be a more viable energy

筑用途，热质量和用户的行为等。

目前用于确定环境系统大小的能耗模拟软件通常采用简单的幕墙模型和属性，尤其是玻璃属性和U值。而先进的幕墙由多层组成，动态变化的通风和遮阳控制通常会被错误和不准确地模拟。各国严格的节能标准错误地集中在部件属性上如减小U值，相信可以通过尽量减少热传递而非对建筑物内部的平衡来达到节能的目的。此策略已导致许多建筑，尤其是位于寒冷气候带的，有时甚至在冬季也需制冷。

帕玛斯迪利沙开发的EPBD软件采用动态整体建筑能耗模拟，考虑到动态可变的幕墙属性，还有通风，遮阳反应和自然采光的影响。多间隔的模型还允许模拟多样的幕墙类型，以容许评估在每个立面上采用最经济的幕墙类型组合来最大限度地降低能耗，提高舒适度。

图8给出了一个类似案例，将双中空玻璃单元（TGU）与闭式腔体幕墙(CCF)进行比较。仅考虑玻璃U值，TGU为更加可行的节能选项，但当考虑全年总能耗时，CCF在节能和舒适性方面均远远超过TGU。

设计精简与效率

市场因素推动的复杂性

众多市场因素影响幕墙的复杂性。标志性建筑物要求独一无二的解决方案，会影响生产系统的设置。对于设计模拟，独特的软件包尽管需要，但不切实际，因互用性是最常见的幕墙设计问题之一。

施工技术的进化导致对复杂性的期盼不断增加。新的技术解决方案要求采用适当的技术应用程序（CAD，数据库等）。项目时间表计划被大幅压缩，因此需要一个多用户，多“切入点”的设计系统。项目设计的设计修改直到完工时才结束，替代解决方案和选项需要灵活的项目信息管理工具。不精确和误差也会增加及扩大项目成本。能识别和防止问题，以及进行不产生影响后果的变更的能力是必要的基础。幕墙业务全球化的结果意味着项目涉及多个，地理上分隔的实体，需要一个精心设计的，有雄厚技术支持的，无处不在的全球系统。

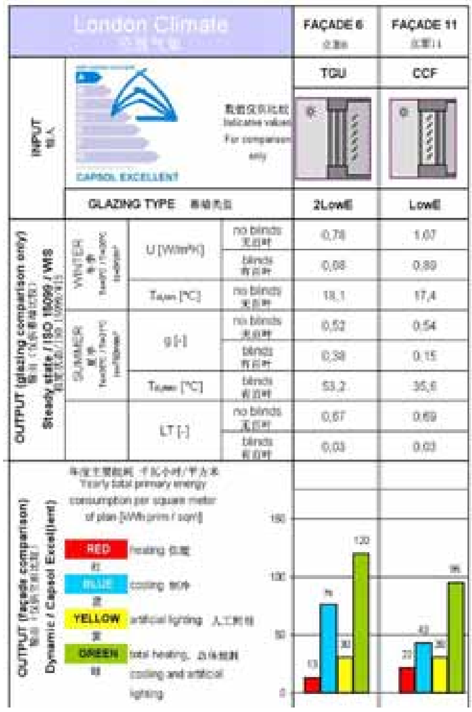

Figure 8. EPBD (Source: Permasteelisa Group, 2012)
图8. EPBD（来源：帕玛斯迪利沙集团，2012）

efficient option compared to the CCF but when considering the overall annual energy consumption, the CCF far exceeds the TGU for both energy and comfort.

Design Streamlining & Efficiency

Market Factors Driving Complexity

Numerous market factors impact facade complexity. Monumental buildings demand bespoke solutions that impact the production system setup. With regards to design modelling, unique software packages, though desirable, are impractical as interoperability is one of the most frequent façade design issues.

Construction technology evolution is resulting in ever increasing complex expectations. New technological solutions require the adoption of suitable technical applications (CAD, database etc.). Project schedules are becoming greatly compressed, thus requiring for a multi-user, multiple "entry point" design system. Project design is perpetual up to completion with design changes, alternative solutions and options requiring flexible project information management tools. Inaccuracies and errors also increase and amplify project costs. The ability to identify and prevent problems and make changes without consequences is a fundamental necessity. The consequences of curtain wall business globalization are projects that involve multiple, geographically separated entities, requiring a well-designed, supported and ubiquitous global system.

Effective Design Complexity Management

Monumental projects require multiple solutions often not applicable to other projects. The most evident complexity factor of a building is its geometry. Projects have a high number of similar but not repetitive components that must be tracked separately.

One of the greatest challenges of Beekman Tower in New York (see Figure 9) was the eight thousand unique panel subassemblies, fixed to the curtain wall units. The engineering of the ten thousand potentially unique curtain wall units required tracking of thousands of various parts and system types with permutations and combinations necessitating a strong set of organizational capabilities and the ability to compare resulting parts in order to maximize the re-use across the project. On the first fifteen floors, six hundred and fifty configurations are applied to more than two thousand units. Each unit configuration comprises nearly one hundred components; each reusable in more than one configuration. Construction of projects such as Beekman Tower in congested city centres poses challenging logistical issues particularly when multiple entities are involved in the design, fabrication, sub-contracting, assembly and installation of the same project or when projects comprise multiple buildings and challenging site conditions (e.g. the KAFD project in Riyadh, see Figure 10).

Complex information flow must be addressed with the correct use of appropriate tools. Generic commercial software packages are unsuited to the specific complexity of a curtain wall project through all its phases, from tender to post completion maintenance. These constraints have driven the development of proprietary software, Permasteelisa Moving Forward (PMF), conceived to improve complex process efficiency (see Figure 11).

PMF is a comprehensive, custom SAP integrated solution, providing tailored functionality for tendering, design, technical development, and production of Permasteelisa Group exteriors projects and supports an extensive range of business processes, from tendering to on-site status reporting.

Figure 9. The Beekman Tower in New York (Source: Permasteelisa Group / ©Lester Ali Photography)
图9. 纽约的比克曼大厦（来源：帕玛斯迪利沙集团 / ©Lester Ali Photography）

Figure 10. The King Abdullah Financial District in Riyadh, Saudi Arabia (Source: King Abdullah Financial District).
图10. 沙特阿拉伯利雅得的阿卜杜拉国王金融区（来源：阿卜杜拉国王金融区）

有效的设计复杂性管理

地标性的项目需要多种解决方案而往往不适用于其它项目。一个建筑物最明显的复杂因数是其几何形状。项目有许多类似但不重复的部件，必须单独追踪。

纽约比克曼大厦（图9）最大的挑战为固定在幕墙单元上的八千块独特的面板子组件。一万个潜在独特的幕墙单元工程设计，需要追踪数千种不同带有置换和组合的部件和系统类型，迫使有强大的组织能力和比较成果部件的能力，以容许在整个项目中的再利用最大化。在最下面的十五层，将六百五十个组合应用于两千多个单元中。每个单元组合包含近一百个组件；每个重用均多过一个组合。诸如位于拥挤城市中心的比克曼大厦之类的建设项目，尤其是当多个单位从事设计、制作、分包、装配，安装涉及在同一项目或当项目包含多个建筑物，工地条件具挑战性时，就对物流问题构成了挑战（例如，利雅得的KAFD项目，图10）。

为此必须正确使用适当的工具处理复杂的信息流动。通用的商业软件包不适用于幕墙项目从招标至完工后维修整个阶段的特定复杂情况。这些限制促使了专用软件的开发，Permasteelisa Moving Forward（PMF），用于提高处理复杂过程的效率（图11）。

PMF为综合定制的SAP一体化解决方案，为帕玛斯迪利沙集团幕墙项目的投标、设计、技术开发和生产安装提供定制的功能，并支持从投标至现场状态报告等广泛的业务过程。

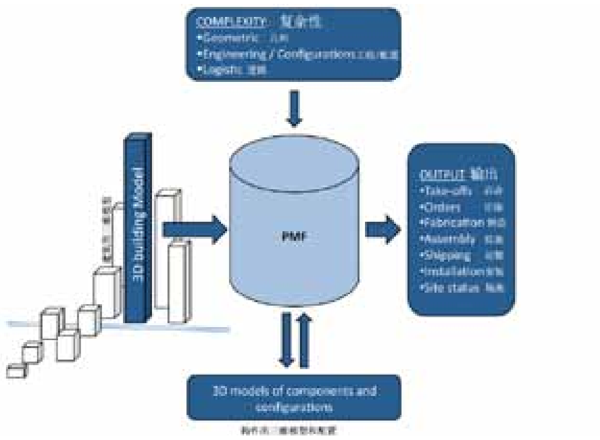

Figure 11. PMF conceptual flow of information (Source: Permasteelisa Group, 2012)
图11. PMF概念信息流（来源：帕玛斯迪利沙集团，2012）

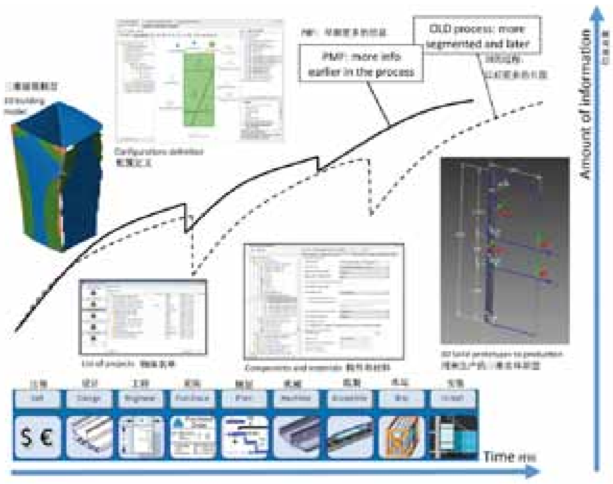

Figure 12. PMF: more info earlier in the process (Source: Permasteelisa Group, 2012)
图12. PMF：过程早期的更多信息（来源：帕玛斯迪利沙集团，2012）

In early project stages, reliable information is available through the use of a 3D building database stored model that allows the geometrical complexity of the building to be controlled. Geometrical properties of curtain wall units are identified using 3D closed polylines (the outline frames) and lines (intermediate elements). The 3D building model is the exact repository of geometric information, allowing in the tender stage to associate the curtain wall types to each façade unit, hence running precise evaluations of geometrical properties and project costs.

Upon project award, the design and engineering of the curtain wall systems are incorporated into the database allowing precise material take-offs subsequently resulting in correct purchase and planning tasks. Geometrical elements extracted from the 3D building model act as driving constraints commencing 3D solid modelling of components prototypes and to assemble them into curtain wall configurations. Solid 3D models are checked, properly coded and delivered to production also organizing and outlining the packing of assemblies. PMF logistically manages SAP integrated design lots and tracks the projects status with a globally networked system built on a single project database.

As shown in Figure 12, reliable information is provided earlier in the design process not only shortening the time schedule but information flow is more streamlined and not lost through the necessity to re-input information into subsequent process non compatible software. PMF is used both by tender and technical teams to solve and identify façade project elements and allows teams to effectively exchange more complete information throughout the entire process originating from the design. In particular the impact of design changes can also be effectively managed.

Prior to the development of PMF, various CAD and facade configuration management systems were used during the awarded phase of a project. Collaboration with Autodesk to develop PMF allowed consolidation and standardization of CAD programs and versions. The resulting single system avoids the tedious choice of the 'right' CAD system based on the project's complexity factors, resulting in increased process efficiency. PMF has incorporated and improved the basic concepts of all systems. Flexibility and adaptability to any project type allows an integrated, global, specialized, well-supported system, extended to a 3D modelling working environment.

在项目早期阶段，可靠的信息可通过使用3D建筑数据库的存储模型获得，允许对建筑的几何复杂性进行控制。幕墙单元的几何特性通过3D封闭多段线（轮廓框架）和线条（中间元件）确定。3D建筑模型为精确的几何信息库，允许在招标阶段，将幕墙类型关联至每个幕墙单元，从而对几何属性和项目成本进行精确的评估。

项目中标后，幕墙系统的设计和工程即被纳入数据库中，以允许精确的材料存取，导致随后的正确采购和规划任务。提取自3D建筑模型的几何元件作为驱驶限制，着手组件原型的3D实体分类建模，进而将其装配到幕墙组合中。对实体3D模型进行检查，正确编码并交付生产，同时也组织和概括了组件的包装。PMF 在后勤方面管理 SAP 一体化的设计划分，并根据单个项目的数据库所建立的全球网络化系统跟踪项目状态。

如图12所示，在设计过程早期提供可靠的信息，不仅可以缩短时间进度，并且使信息流动更为精简，不会在重新将信息输入随后过程的不兼容软件中时，将信息丢失。PMF被投标和技术团队用于解决和确认幕墙项目组件，并容许团队在从设计起的整个过程中有效地交换完整的信息。尤其是，可对设计变更的影响进行有效的管理。

在开发PMF前，各种CAD和幕墙组合管理系统用于项目中标阶段。与Autodesk 合作开发 PMF 可将CAD程序和版本联合并标准化。所产生的单一系统避免了基于项目的复杂因数，繁琐的选择“正确的”CAD系统，从而提高了过程的效率。PMF融合并改进了所有系统的基本理念。其对任何项目类型的灵活性和适应性容许一体化、全球性、专业化且良好支援的系统，扩展至3D建模工作环境。

结论

总之，设计过程多种形式。当执行复杂的项目时，有必要对建筑物采用一般方法。使用整体综合设计方法，可以最佳地实现技术问题的有效解决方案。软件包不仅是重要的建筑工具，还可辅助驱动决策过程。决策工具应是直观的，允许快速的设计迭代并有模拟整个幕墙系统相互作用的能力，而非对孤立的单个组件进行建模分析。

Conclusions

In conclusion, the design process takes many forms. When undertaking complex projects it is necessary to adopt a general approach to the building. Effective resolution of technical issues is optimally achieved using a holistic design approach. Software packages are not only important architectural tools but can assist to drive the decision making process. Decision making tools should be intuitive, allow rapid design iterations and capable of modeling interaction of the overall façade system rather than individual components in isolation.

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