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Life Cycle Energy Analysis of Tall Buildings: Design Principles
高层建筑生命周期的能量分析：设计准则

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Dario Trabucco是意大利威尼斯IUAV大学的研究学者。Trabucco先生具有建筑工程博士学位,他的博士论文的论题是从寿命周期的角度来看服务核心对高层建筑能耗的影响。他重点研究高层建筑的可持续性，尤其是在节省建材自含能量方面。他还通过学术和教学方式将其研究成果传授给学生。Dario也是CTBUH在意大利的代表。

Abstract

The goal of the paper is the identification of the most suitable strategies to reduce the energy consumption of a tall building from a life-cycle perspective, thus considering also the energy embodied in the materials it is built of.The paper deals with the case of a 160 meter tall building in Milan, Italy, completed in 2011. Several design options (including the actual building) are assessed, in order to quantify the embodied energy associated with each alternative design asembedded in the required building materials. Energy consumption is also modeled for each design modification, so as to obtain a Life Cycle Energy Assessment (LCEA) of the actual building and a number of design options, in order to select the most energy-efficientone from a life cycle perspective. The conclusions point out a series of useful design recommendations aimed at decreasing the embodied energy content of tall buildings.

Keywords: LCA, Embodied Energy, Design guidelines, Influence of height,

摘要

本文目的是从寿命周期的角度探讨能够降低一栋高层建筑能耗的最佳策略，由此还考虑了建筑用材的自含能量。本文以意大利米兰的一栋160米高，于2011年竣工的建筑为分析案例。文章对一系列设计方案（包括实际建筑）进行了评估，用以量化每个替代设计方案中所需的建筑材料内含能量。能耗也按照每个设计调整来建模，以此得出对实际建筑和一些设计方案的寿命周期能源评估（LCEA），以便从寿命周期的角度，选择最佳节能方案。结论指出了一系列有用的设计建议，旨在降低高层建筑中建材自含能量。

关键词：寿命周期能源评估，自含能量，设计纲要，高度影响

Life Cycle Energy Balance Of Tall Buildings

The increasing energy efficiency of the built environment in the recent years has given some important results that seemed almost unattainable only a decade or so ago. Buildings that consume only one tenth of the energy needed by their predecessors are commonly built in many developed countries and very positive trends can now be seen in the high rise market as well. Tall buildings are a complex building typology and their energy needs are much higher than conventional low-rise buildings. For this reason, it is very difficult to attain the same levels of energy consumption than conventional buildings, and zero energy towers are probably still far in the future.

Also, tall buildings have a lower efficiency than conventional buildings from the point of view of embodied energy, which is the energy required to extract, to transport, to transform and to install the materials they are built of. In fact, tall buildings require per square meter of usable floor a higher quantity of building materials than lower buildings. Most of the additional materials are due to their structural system, which requires exponentially growing quantities of load bearing materials (concrete or steel) as the building total height increases,

高层建筑的寿命周期能源平衡

近年来，由于建筑环境的节能效率的不断提高，带来了一些在仅十几年前看都似乎是不可能做到的重要成果。现在许多发达国家中常见的建筑的能耗只有过去的十分之一，并且这一积极的趋势也可在高层建筑市场中观察到。高层建筑是一个复杂的建筑类型，其能源需求远远高于传统的低层建筑。出于这个原因，要达到与传统建筑同一水平的能耗是非常困难的，要实现零能耗塔楼还可能需要很长的时间。

此外，从建材自含能量的角度来看，高层建筑比传统建筑的效率更低，这是指提取，运输，改造和安装建筑材料中所需要的能量。事实上，高层建筑在每平方米可用面积所需要的建筑材料用量要高于层数较低的建筑。大多数额外材料是出于其结构系统的需要。承重材料（混凝土或钢材）的需要量随着建筑总高度的增加而成倍增长，特别是因为与层高相关的额外风荷载，以及增加的重力荷载。这两种效应结合导致高层建筑的寿命周期能量平衡更高，这对摩天大楼的“反对”者来说，是强而有力的例证。

在过去的20多年中，随着能源管理成本的提高和在市场营销中“绿色”重要性的增加，设计师们成功地设法降低高层建筑的能耗。在另一方面，为降低建筑施工耗能所作的努力却很少，几乎没有。事实上，

especially due to additional wind loading at height, as well as increased gravity loads. The two effects combined cause a higher Life Cycle Energy Balance of tall buildings that makes a for those who are "against" skyscrapers.

In the past 20 years, designers have successfully tried to decrease the energy consumption of tall buildings as a consequence of the increased energy management costs and of the importance of being "green" for marketing purposes. On the other hand, little – if anything at all – has been done to decrease the energy required for their construction. In fact, it can be argued that modern tall buildings have a higher content of embodied energy, as a consequence of the additional materials (increased insulation, duplication of façade layers, etc.) required to meet operating energy saving standards.

A Low Embodied Energy Building Case Study

In order to identify the suitable design solutions to decrease the embodied energy of a tall building, the Life Cycle Energy Analysis for a case study skyscraper is here presented. The case study for this paper is a 161 meter tall building completed in 2011 in Milan, Italy, designed by Henry Cobb. It is a public building, being the offices of the local regional administration. The tower is flanked by lower buildings that form a unique structure completely open to the public (see Figure 1).

The building has a very good insulation system, called "climatic wall": it has a U-value of 1.1 W/m^{2}K being composed by a double skin glazed façade with aluminum louvers between the two layers. Energy required for cooling and heating is obtained through innovative "sustainable systems", such as the 40 deep wells that exchange heat with the underground water (that has an ideal constant temperature of 15° C). Energy is also generated by photovoltaic panels installed on a 2000m^2 surface on the southwest façade, with a peak production of 160kW. Such systems are backed-up by standard high-performance systems fuelled with natural gas and electricity.

For these reasons the building will probably achieve a "Class A" certification (less than 30kWh/m^{2}y of primary energy for heating and cooling) after the tests that are currently being carried out to tune its mechanical systems. Other sources of energy consumption have been calculated for the purposes of this paper (using commercial software and normal floor occupancy data) with a resulting total consumption of 91 kWh/m^{2}y of primary energy. This figure corresponds to a very efficient building, which meets the expected limits in energy efficiency for tall buildings (Raman, 2001).

It should be noted that data regarding this building are not official figures, as the author collected them from various sources (web sites, articles, industries and professionals involved in the project). A specific analysis of the building will be released using official validated figures in the months to come.

Embodied energy calculation and methodology

Embodied energy is calculated using a hybrid methodology (Treloar, 1994): first, the most important nine elements (according to both financial costs and quantities) are highlighted and their contribution is calculated using a ISO-norm complying methodology. The remaining elements are grouped into product classes and their contribution to the embodied energy of the building is assessed using an Input-Output methodology, whose reliability for general products is now widely accepted. The following table (see Table 1) presents a subdivision of the building embodied energy according to its main building materials.

Figure 1. Palazzo Lombardia. (Source: photo by the author)
图1. Palazzo Lombardia （出自：由作者提供的照片）

现代高层建筑之所以含有较高的建材自含能量，这是由于为符合使用节能标准要求而增加额外材料所带来的后果（如增加的保温材料，外墙层的重复等）。

低自含能量建筑案例

为了识别合适的设计解决方案来减低高层建筑的自含能量，本文在此介绍了一个摩天大楼案例的寿命周期能量分析。文中的研究案例位于意大利米兰，是一栋于2011年完成的161米高的高层建筑，由建筑师Henry Cobb设计。它是一栋公共建筑，作为当地区域行政部门的办公楼。塔楼两侧为较低建筑，从而形成一个完全向公众开放的独特结构（见图1）。

该建筑有一个非常良好的隔热保温系统，被称之为“气候墙”：外墙的U值为1.1 W/m^{2}K， 是由其中带有铝百叶的双层玻璃外墙所组成的。通过创新的“可持续性系统”获得采暖和制冷所需的能量，如通过40个深水井与地下水进行热交换，（地下水有15度的理想恒温）。能量也由安装于西南外立面上的，面积达2000平方米的，生产峰值为160KW的光伏电池板所生成。此系统以天然气和电力为燃料的标准高性能系统作为后援。

目前正在为调整其机电系统进行测试，随后，由于这些原因，此建筑将很可能得到“甲级”认证（用于采暖和制冷的主要能量小于30kWh/m^{2}y）。能耗的其它来源也被计算用于本文 （使用商业软件和正常楼层用户数据），由此得出91kWh/m^{2}y主要能源的总能耗。这个数字相当于一个非常高效的建筑，它符合所有高层建筑节能效率的预期界限（拉曼，2001年）。

应当指出，有关这栋楼的数据不是官方的数据，是作者通过各种渠道（网站，文章，行业以及参与此项目的专业人士）收集来的。之后几个月内，将发表使用官方证实的数据对建筑所作的具体分析。

自含能量计算和方法学

自含能量使用一种混合方法学（Treloar，1994年）来计算：首先，强调最重要的9个元素（根据资金成本和数量），并以ISO-标准的方法学来计算其贡献。其余元素被分为产品类别，并以输入-输出的方法学来评估其对建筑自含能量的贡献，这种方法

	Quantities (Kg) 数量	Specific EE (MJ/Kg) 具体内含能量	Total EE (MJ) 总内含能量	Share (%) 比率
Concrete 混凝土	70,870,000	1.4	98,500,000	13.7
Rebars 钢筋	3,320,000	24.6	81,800,000	11.4
Steel 钢	380,000	31.3	11,800,000	1.6
Ligh concrete blocks 轻质混凝土砌块	5,850,000	0.8	4,700,000	0.7
Glass 玻璃	2,460,000	16.8	41,300,000	5.7
Aluminum 铝合金	540,000	157.1	84,800,000	11.8
Plasterboard 纸面石膏板	2,030,000	4.9	9,900,000	1.4
Carpets 地毯	60,000	74.4	4,400,000	0.6
Plaster 抹灰	450,000	2.6	1,200,000	0.2
Total Embodied Energy calculated with ISO methodology 按ISO方法计算总内含能量			338,400,000	47.1
Total remaining EE calculated with I/O methodology 按输入-输出的方法计算总剩余内含能量			379,900,000	52.9
Total Embodied Energy of the Building 建筑总内含能量			718,300,000	

Table 1. Embodied energy of the case study building. (Source: Author)
表1. 建筑自含能量的案例分析。（出自：作者）

As expected, the structural elements (concrete, rebar and structural steel elements) represent the highest share of embodied energy (26.7% of the total) followed by the building envelope (17.6% of the total). However, it should be noted that other elements, that can be largely labeled as "finishes" (thus including MEP systems, internal partitions, etc.) represent more than 50% of the total embodied energy. Anyway, such elements are not specific to tall buildings, unlike the peculiarities of the structural system or the complex curtain wall façades used.

Discussion of results

The examined building has an embodied energy of 15.7 GJ per square meter of gross floor area. This figure is in line with those found in the literature. A study on a 42 floor building in Australia, built with a concrete core and steel columns (Treloaret. Al, 2001) shows an embodied energy of 18 GJ/m^2; the same source reports also a figure of 18.4 GJ/m^2 for a 52 story tower with a similar steel/concrete structure. A study from the author of this paper (Trabucco, 2008) reports an embodied energy of 24 GJ/m^2 for a 40 storey building (though 20 meters taller) with a steel structure. A Lifecycle study in Thailand for a 38 story concrete building (Kofoworola, 2009) shows an embodied energy of only 6.8 GJ/m^2, though the building seems to have a much poorer design than the precedent example. Results show that the embodied energy of the building corresponds to almost 48 years of energy consumption. However, this figure includes also some aspects that are not dependent from the architecture of the building (office equipment, domestic hot water production, etc.) and some that are only marginally affected by its characteristics (lighting, lifts, etc.). If only the energy for environmental control (cooling, heating, ventilation, etc.) is considered, embodied energy corresponds to more than 140 years of its daily consumption (see Table 2).

	Total (MJ) 总计	Per sqm(MJ) 每平方米
Embodied Energy of the Building 建筑内含能量	718,286,178	15,717
Annual Consumption for env. Control 年度环境控制能耗	4,935,600	108
Total energy consumption 总能耗	10,501,277	230
Returning time 回报时间		68
Returning time (env. control only) 回报时间（仅环境控制）		146
30 years life cycle energy (MJ/sqm) 30年寿命周期的能量（兆焦耳/平方米）		22,611
50 years life cycle energy (MJ/sqm) 50年寿命周期的能量（兆焦耳/平方米）		27,207

Table 2. Life cycle energy assessment and returning time of the case study building. (Source: Author)
表2. 建筑寿命周期能量评估和回报案例分析。（出自：作者）

对一般产品的可靠性评估现已被广泛接受。随后的列表（见表1）介绍一个根据主要建筑材料所得的对建筑物建材自含能量的细分。

正如所预计的，结构元素（混凝土，钢筋和结构钢构件）代表最高的自含能量（占总数的26.7%），建筑外墙包覆随后（占总数的17.6%）。然而，应当指出的是，其它在很大程度上可被称为“完成面”的元素（因此包括机电系统，内部隔墙等），代表超过50%的总自含能量。但是，这些元素不是高层建筑所特有的，不同于其所采用的结构体系或复合幕墙外立面的特质。

讨论结果

被研究的建筑在总楼面面积上有每平方米15.7 GJ的自含能量。这个数字与文献相一致。澳大利亚一栋42层高建筑，结构为混凝土核心筒和钢柱（Treloar等，2001年）的研究显示其自含能量为18 GJ/m^2，相同来源的报告中也显示一栋52层高采用类似钢/混凝土结构的塔楼为18.4 GJ/m^2。本文作者的研究报告（Trabucco，2008年）一栋40层高的钢结构建筑的（虽然再高出20米）自含能量为24 GJ/m^2。对泰国的一栋38层高的混凝土结构建筑（Kofoworola，2009年）的寿命周期研究显示只有6.8 GJ/m^{2}的自含能量，尽管此建筑比先前例子有着更劣的设计。结果表明，建筑自含能量相当于其近48年的能耗。不过，这个数字还包括某些不受建筑特点影响的方面（办公设备，生活热水等）和一些只被其特点轻微影响的方面（照明，电梯等）。如果仅考虑供环境控制所需的能量（制冷，采暖，通风等）为日常能耗，自含能量则相当于该建筑140多年的能耗总量（见表2）。

替代方案

本文介绍的替代方案仅是性质上的研究结果，这是因为从来没有通过精确的计算得到所需建筑材料的确切数量。事实上，数据从不同来源的文献中收集，而且本文这一部分的目的是为设计师提供一种“工作方法”，建议他们如何从寿命周期的角度，由最初设计阶段进行到可持续发展的高层建筑的建造。

这项研究的第一部分是关于建筑工程采用钢材来替代混凝土。以下列表（见表3）描述了具有相同建筑高度和楼层面积但结构方案不同的建筑物用钢量（月球，2008年）。此外，它还描述了在每个所介绍的选择对建筑物自含能量的影响。同时假设没有影响被转移到建筑物的日常能耗，因为承重结构对建筑外墙包覆的热传导或其能耗均没有影响。

值得一提的是两种替代方案均可节省近5%的总自含能量，相当于建筑近三年的运行能耗。

Design Alternatives

The design alternatives presented here are the results of qualitative studies only, as no precise calculations have been done to obtain the exact quantity of building materials needed. Instead, data were collected among different sources found in the literature and the aim of this part of the paper is to provide a "working methodology" for designers, suggesting them how to proceed from the very initial design stages toward the creation of a sustainable tall building from a life cycle perspective.

The first part of this study regarded the use of steel instead of concrete for the construction of the building. The following table (see Table 3) describes the steel quantity for buildings of the same height and floor size but different structural schemes (Moon, 2008). Also, it describes the effects of each of the presented choices on the embodied energy of the building. It is assumed that no effects are transferred to the daily energy consumption of the building, as the load bearing structure has no impact on the thermal transmittance of the building envelope or on its energy consumption.

It can be noted that both alternatives lead to a saving of nearly 5% of the total embodied energy, corresponding to almost three years of the building running energy consumption.

The second part of the study is focused on the effects of different façade systems: the first one has a very bad performance, attaining a U-value of 4 W/m^{2}K : it simulates an early generation curtain walling system, commonly found in buildings of the 60's (Oldfield et al., 2009); this envelope would not meet today's energy saving requirements in Italy that ask for a minimum transmittance of 2.2 W/m^{2}K for transparent surfaces (glass and shutters). The second is a norm-complying system that brings the transmittance exactly to 2.2 W/m^{2}K.Such two options have obviously a strong impact on the energy consumption of the building but they have a similar impact on its embodied energy too. In fact, they give a direct contribution with the materials they are built with and an indirect contribution as they occupy floor space that would be free otherwise. The effect of the alternative façade systems on the energy consumption of the building was modeled using commercial software for energy simulation, while their direct embodied energy was calculated referring to ISO-complying databases. In order to assess the consequences caused indirectly on the embodied energy of the building (through a different impact on the occupancy of floor space), the embodied energy of the building is reduced to its mean value for square meter of floor area.

From this point of view it is interesting to note that the actual building design is the most efficient solution from a life cycle perspective over a 30 year period. However, if the façade is renewed once on a 50 year period, the norm-complying solution becomes more sustainable, as its lower embodied energy compensates for the augmented energy consumption (see Table 4).

The Role Of Designers In The Sustainability Of Tall Buildings

The analysis of this case study and of different design alternatives evidences an unjustified lack of attention to the theme of embodied energy and Life Cycle Energy Design. The weight of embodied energy over the life cycle of buildings is now very high, also as a consequence of their improved energy efficiency: the lower their daily consumption, the higher the share of their embodied energy from a life cycle perspective.

Designers are struggling with MEP engineers and a vast range of different expertise in the definition of the most effective solutions for

	Actual design 实际设计	Total (MJ) 总计	Per sqm (MJ) 每平方米
Vertical concrete structures (t) 竖向混凝土结构	23000	-	-
Vertical steel structures (t) 竖向钢结构	-	1,000	800
Embodied Energy whole building (MJ) 整个建筑内含能量（兆焦耳）	718,000,000	688,000,000	683,000,000
Embodied Energy savings (%) 内含能量节能（%）	0	4	5
30 years life cycle energy (MJ/sqm) 30年寿命周期的能量（兆焦耳/平方米）	22,611	21,955	21,845

Table 3. Life cycle energy assessment of the case study building and of alternative structural systems. (Source: Author)
表3. 建筑寿命周期能量评估案例和替代结构系统。（出自：作者）

	Actual design 实际设计	4 W/m^{2}K façade 4 W/m^{2}K外墙	2,2 W/m^{2}K façade 2,2 W/m^{2}K外墙
Env. Control energy consumption (MJ/sqm) 环境控制能耗（兆焦耳/平方米）	108	609	210
Embodied Energy of the facade system (MJ) 外墙系统内含能量（兆焦耳）	126,100,000	21,700,000	28,900,000
Building EE per net squared meter 每净平方米建筑内含能量	15,700	13,500	13,700
30 years life cycle env. Control only (MJ/sqm) 30年寿命周期仅环境控制能耗（兆焦耳/平方米）	19,000	31,800	20,000
50 years life cycle with cladding renovation (MJ/sqm) 50年寿命周期带外墙改建（兆焦耳/平方米）	25,300	44,700	25,100

Table 4. Life cycle energy assessment of the case study building and of alternative façade systems. Only the energy requirement of the environmental control system is considered here. (Source: Author)
表4. 建筑寿命周期能量评估案例和替代幕墙系统。在此仅考虑环境控制系统的能量要求（出自：作者）

此项研究的第二部分是集中在对不同外墙系统的影响：第一种具有非常差的性能，U值达到了4 W/m^{2}K：它模拟早期的幕墙系统，通常可以在60年代的建筑物中找到（Oldfield等，2009年）;此外墙包覆不能满足当今意大利节能要求透明表面（玻璃和百叶窗）的2.2 W/ m^{2}K最低透射率。第二种是符合正规系统所得的精确的2.2 W/m^{2}K透射率。这两种方案对建筑物能耗有强烈影响，而它们对其自含能量也有相似的影响。事实上，它们直接影响建筑材料和间接影响所占用的楼层空间。通过使用模拟能量的商业软件建立模型模拟替代的外墙系统对建筑能耗的影响，同时参考符合ISO-标准的数据库来计算它们对自含能量的直接影响。为了评估建筑自含能量（通过一个对楼面空间使用的不同影响），建筑自含能量被降低至每平方米楼面面积的平均值。

值得注意的是从超过30年的寿命周期角度上看，这个实际的建筑设计是最有效的解决方案。不过，如果每50年对外墙进行重修，符合规范要求的解决方案变得更可持续的，因为它的较低自含能量是对增加能耗的补充（见表4）。

设计师在高层建筑可持续性发展中的责任

对此案例和不同设计选择方案的研究分析证明对自含能量和寿命周期的节能设计缺乏合理的重视。自含能量对整个建筑寿命周期的作用以及它们对提高节能效率的影响重大：日常能耗越低，从寿命周期的角度来看，它们在自含能耗中所占分量就越高。

the energy efficiency of their buildings. Sustainable design principles range from macro to micro scale solutions. The wide principles deal with the building shape and orientation that act at the urban scale. At the building scale the most common features regard the provision of spaces that facilitate cross-wind and natural ventilation using internal voids to promote a controlled stack effect within the building. However, the most effective and diffused solutions can be found at the smaller scale of building details, such as façade design.

It should be acknowledged that those solutions, that transformed the voracious buildings of the '60s into the energy efficient towers of nowadays, rely on other disciplines rather than design and architecture and their correct application requires the use of external expertise. Often, architects that are considered to be on the cutting edge of sustainable design are actually those who are able to make use of these sustainable "tools".

Every design action has a direct impact on the energy balance of the building. It surely impacts the building daily consumption, but it especially affects its embodied energy.

Each "part" of the tall building can be designed keeping its impact on the embodied energy equation in mind. The main components are here analyzed, considering the case study results and the results of previous research experiences and literature analysis.

Load bearing structures

The simplest structural scheme to transfer a load to the ground is a vertical element that brings the forces to the building foundations, as building materials have a good compressive strength. Every alteration from this scheme requires the use of other structural properties of materials, such as bending resistance or traction that are not equally convenient as compression. This idea should influence all the design process of a building from the definition of its shape, to decision on spans, cantilevers, etc. The Miesan towers, though they may be considered "boring" from the general public, made an excellent use of the structural materials (at the standards of that time) as they had a very simple column and beam scheme with limited spans. Unconventional modern shapes, with a global widespread of twisted and tilting buildings, huge spans and cantilevered elements, cause enormous quantities of structural materials (steel and concrete) to be wasted.

Structural materials

Steel structures were predominant until the '80s while concrete is now becoming the prevalent solution, sometime combined with steel columns to form 'composite' structure. Though cost is always a key aspect, the difference between steel and concrete from a sustainability standpoint is remarkable. Even though concrete has a lower embodied energy content if compared to steel,from a building point of view, concrete structures are much heavier than steel structures and they result in a higher embodied energy. Also, concrete cannot be recycled (it can only be crushed and use as a substitute of gravel) while steel is fully recyclable endlessly. For this reason, highly speculative developments or building typologies that have a shorter lifespan (such as hotels), may consider a more extensive use of steel, as its embodied energy can be entirely recovered through recycling at the end of their life cycle.

Floor technologies

Floors, as part of the horizontal structure, transfer to the vertical elements their weight and the loads they carry through bending. Steel is again a better option though its generally more costly. Innovative solutions allow the production of floor plates entirely made of steel, without the need for concrete slabs. Anyway, if concrete is chosen for

设计师与机电工程师以及广泛不同的专业人员共同努力为提高建筑的节能效率确定最有效的解决方案。可持续性设计原则包括从宏观到微观尺度的解决方案。大范围的原则用来处理在城市尺度内的建筑形状和朝向定位。在建筑尺度中最常见的特征是提供可促进对流和自然通风的空间，使用内部空间控制建筑内的烟囱效应，然而，最有效和普遍的解决方案可以在较小规模的建筑细部设计中找到，例如外墙设计。

应当承认这些将60年代铺张浪费的建筑转变成为当今节能建筑的解决方案，需要依赖其它专业而不仅是设计和建筑专业，而其正确的应用也需要采纳外部专业性意见。通常情况下，被认为是站在可持续性设计前沿的建筑师，是实际上那些能够利用这些可持续性“工具”的建筑师。

每个设计动作都直接影响建筑的能量平衡。除了影响到建筑的日常能耗，它尤其影响其自含能量。

设计对自含能量的影响可以在设计高层建筑的每一个“部分”时得到关注。结合案例研究和以往的实验研究和文献分析的结果，分析其中主要的组成部分。

承重结构

最简单的将荷载转递至地面的结构方案是利用竖向构件将荷载传递至建筑基础，这是由于建筑材料具有良好的抗压强度。每一个对此方式的改变则需要使用材料其它的结构特性，如抗弯曲或牵拉，这些都比抗压特性要复杂。这一思维应该影响建筑设计的所有阶段，从确定建筑形状到决定跨度和悬臂梁等。以密斯塔楼为例，尽管一般人可能会认为它们很“单调”，但由于采用非常简单的梁柱结构和有限跨度，它们可视为最佳地使用了结构材料（按当时的标准）。标新立异的现代造型，以及风靡全球的扭曲和倾斜建筑，大跨度和悬臂式构件，导致结构材料（钢材和混凝土）的巨大浪费。

结构材料

一直到八十年代钢结构仍然占主导地位，而当今混凝土正成为流行的解决方案，有时混凝土与钢柱结合起来形成“复合”结构。虽然成本始终是一个重要方面，但从可持续发展的角度来看，钢和混凝土之间的差异显著。从建筑的角度来看，尽管混凝土比钢材的自含能量的单位含量低，但是混凝土结构比钢结构要重很多，因而导致混凝土的自含能量总量比钢材要高。此外，混凝土不能被回收（它只能被压碎和使用作为砾石的替代材料），而钢是完全可回收的。出于这个原因，高度投机性的开发或寿命周期较短的建筑类型（如酒店等），可以考虑更广泛地使用钢材，因为在其寿命周期结束时，自含能量可以通过回收完全恢复。

楼层技术

楼板作为水平结构的一部分，将其自重和弯曲荷载转递至竖向构件。尽管钢材一般来说较为昂贵，但仍然是更好的选择。在具有创新性的解决方案中，整个楼板可完全由钢制成而不需要混凝土板。不管怎样，如果出于成本或结构的考虑而选择混凝土，后压缩构件可能代表一个可行的解决方案，因为它们比标准混凝土楼板需要用较少的材料。此外，创新技术亦可以帮助减少混凝土用量，如轻质填料或轻质空隙元素(如：泡沫板)，(见图片2)。

建筑外墙

从可持续发展的角度来看，围护结构是摩天大楼的最重要组成部分。因为它们代表了内部可控制气候体量和外部环境之间的界面。此外，它们是建筑的外表皮，并且通常在建筑上承担很大的重要性。因此，外墙对降低建筑能耗起很大作用，在另一方面，因为其由自含能量很高的材料（如铝合金，玻璃，密封胶）构成，外墙对整个建筑的自含能量影响重大。从1950年代被初次使用以来，单层玻璃“密封式”窗户已大幅度进化，现在三层玻璃和双重外墙普遍应用于最先进的摩天大楼中。如上所示，运行节能和自含能量之间的适当平衡必须通过详细的寿命周期分析去发现。

cost or structural reasons, post-compressed elements may represent a viable solution, as they require less material than standard concrete slabs. Also, innovative technologies can be adopted to reduce the amount of concrete, such as lightweight fillings or void lightening elements (i.e. bubbledecks, see Figure 2).

Building façades

Enclosures are the most important part of the skyscraper from the point of view of its sustainability as they represent the interface between the internal climate-controlled volume and the external environment. Also, they are the skin of the building, and they are charged of deep architectural significance. Thus, façades contribute significantly to the reduction of the building energy consumption; on the other hand, as they are made with embodied energy rich materials (such as aluminum, glass, and sealants) they have a serious impact on the embodied energy of the building. The single glazed "miesian" window has evolved dramatically since its original use in the 1950's, and triple glazed, double skin enclosures are now common in state-of-the-art skyscrapers. The right balance between running energy savings and embodied energy must be found through a detailed life cycle analysis, as shown above.

Service core

The service core has been used in some innovative tall buildings as a thermal buffer to prevent solar radiation to overheat the occupied floor area, thus transforming it into an active element of the energy behavior of the tall building with a positive impact on energy consumption. However, its role from a life cycle perspective should be carefully addressed. In fact, the service core occupies built space, impacting negatively on the embodied energy of the building. A building with an efficient (read: compact) design of the service core will be smaller than a building with the same usable area but a larger, poorly designed, one: the smaller building will in turn require less building materials and its embodied energy will be smaller than the bigger edifice (Trabucco, 2008).

Design actions should then be aimed at compactness and efficiency, avoiding all those solutions that can lead to long corridors, dead-ends, etc.

Also, among all other considerations, the choice of the lift configuration should take into account the same parameters of compactness: fewer elevators lead to a more compact design of the tower, lowering the use of energy for the production of its building materials.

MEP Systems

Mechanical systems are essential to modern tall buildings. As their efficiency is the key to the operating energy consumption of the building, their design should be aimed at maximum effectiveness. In the choice of mechanical systems, however, the same idea of compactness identified in the design of the service core should be sought, as the floor occupancy of air handling units, ducts, etc. can lead to the construction of additional built area that can be avoided thorough a more careful planning and choice of mechanical components.

Internal layout and finishes

Elements of interior design are the part of the building that are renewed more often than any other building part. This is caused not by the decay of materials but by changes in design styles, working or living habits, etc. Renovations happens every 5–10 years in hotel buildings and every 10–15 years in office buildings, though they may also be more frequent, especially when new tenants move into previously occupied spaces. The choice of the internal layout and

Figure 2. "Bubbledeck" technology. This elements allow a 20% concrete saving if compared to standard solutions. (Source: courtesy of Cobiax)

图2."泡沫板"技术。 此元素可比标准方案节省20% 的混凝土。(来源：由Cobiax提供的照片)

服务核心

服务核心在一些创新型的高层建筑中被用作为热缓冲区，防止太阳辐射造成使用面积过热，因而将其转化为对能耗有正面影响的高层建筑的积极节能因素。然而，从寿命周期的角度看，应对此作慎重处理。事实上，服务核心占用建筑空间，对建筑的自含能量造成了负面影响。建筑具有高效服务核心的（紧凑的）设计将小于具有相同的使用面积而服务核心设计欠佳的较大建筑，其自含能量也必然小于较大建筑物（Trabucco，2008年）。

然后设计应该力图做到紧凑和高效，避免所有可能导致长走道，死角等的解决方案。

此外，在所有其它方面的考虑中，电梯配置的选择应考虑同样的密度参数：使用较少数量的电梯可使塔楼的设计更为紧凑，从而降低生产建筑材料所使用的能源。

机电系统

机电系统是现代化高层建筑必不可少的组成部分。由于它们的效率是建筑运行能耗的关键，其设计应着眼于最大效益。然而，在选择机电系统时，应考虑与服务核心设计中同样的紧凑性设计，精心布置和选择机电设备可避免空气处理机组，管道等占用过多的建筑面积。

内部布局和装修

室内设计元素往往比其他任何建筑的组成部分更新次数更多。这不是由于材料的退化，而是设计风格，工作或生活习惯的改变引起的，酒店建筑每5-10年重新装修，办公建筑每10-15年重新装修，尽管也可能会更加频繁，尤其是当新租户搬进到先前被使用过的空间。内部布局和装修材料的选择应该尽可能的灵活，相同的元素可以用来改变空间功能（如：利用活动隔断将会议室改为办公空间，而不是拆除/重建一个正规的墙）。此外，它们最好应是以回收的/可回收的材料建成，采用机械接头（螺丝，螺栓等）相接，而不是化学接缝（胶，混凝土等），以便解构和材料归类，而不是拆除和丢弃。

finishes should be as flexible as possible, so that the same elements can be used to modify the function of spaces (i.e. a meeting room to be converted into office space by sliding a partition, instead of demolishing/rebuilding a proper wall). Also, they should preferably be built with recycled / recyclable materials, bond with mechanical joints (screws, bolts, etc) rather than chemical joints (glue, concrete, etc.) so as to allow deconstruction and selection of materials rather than demolition and disposal.

Conclusions

Tall buildings are an energy intensive typology as they usually have high operating energy requirements and a high embodied energy. Designers have always tried to focus on the reduction of their energy consumption through the addition of insulating materials, complex façades etc. Such measures positively impact the tall buildings' operating energy needs but have caused the side effect of increasing their embodied energy. It is now time to focus on their embodied energy too, so as to achieve sustainable tall buildings throughout their entire life cycle.

结论

高层建筑是一个能源集中的类型，因为它们通常有较高的运作能量要求和很高的自含能量。设计师们一直试图把重点放在以增加保温材料和外墙复杂化来减少能耗。这些措施对高层建筑运作能量需求产生积极影响，但也造成增加其自含能量的副作用。现在也应关注其自含能量，以使高层建筑在整个寿命周期中达到其可持续性。

References（参考书目）：

KOFOWOROLA, O. F. & GHEEWALA, S. H. (2009).**Life cycle energy assessment of a typical office building in Thailand.** Energy and Buildings, vol. 41, pp. 1076-1083

MOON, K. S. (2008). **Material-Saving Design Strategies for Tall Building Structures.** Proceedings CTBUH 8th World Congress 2008, March.

OLDIFIELD, P. & TRABUCCO, D. & WOOD. A. (2009). **Five energy generations of tall buildings: an historical analysis of energy consumption in high-rise buildings.** The Journal of Architecture, Vol. 5, N° 5, pp. 591-613

RAMAN, M. (2001).**Aspects of Energy Consumption in Tall Office Buildings**. CTBUH Review, vol.1, n°3

TRABUCCO, D. (2008). **An analysis of the relationship between service cores and the embodied/running energy of tall buildings. The structural design of tall and special buildings,** vol. 17, pp.941-952

TRELOAR, G. J. (1998). **A Comprehensive Embodied Energy Analysis Framework.** PhD. Thesis, Deakin University

TRELOAR, G. J. & FAY, R. & ILOZOR, B. & LOVE, P.E.D. (2001). **An analysis of the embodied energy of office buildings by height.** Facilities, vol.19, pp. 204-214