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Embodied Carbon in Our Future Cities
未来城市的碳自含量

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Abstract

Innovative planning for cities of the future is essential. Cities are the solution to responsible habitation as issues of the environment gain increasing importance. Even early at planning stages, cities, districts, parcels, and buildings can be evaluated for efficiency and environmental impacts. Design parameters such as site conditions, building height and form, structural system and materials, and anticipated construction time can be considered when evaluating design opportunities. Net usable space, specifically relating commercial value can be interactively considered based on anticipated service areas, structural systems and building shape. Considering only height limits and parcel sizes, the Parametric City Modeling™ can parametrically consider the impacts of building systems on net usable area, therefore efficiency / marketability of space. In addition, and perhaps most importantly, the algorithm can evaluate the environmental impact of these systems as well as the cost-benefits of enhanced system components over the development's service life.

Keywords: Embodied Carbon, Urban Planning, Parametric Modeling, Seismic Risk, Enhanced Structural Systems

摘要

摘要文本: 创新规划对于未来城市是必不可少的。鉴于环境问题日益重要，城市是负责任地解决居住环境的方法。即使在规划阶段的初期，已可评估城市、市区、地块、及建筑物的效率和对环境的影响。在评估设计需求时，具体地块条件、建筑高度和形体、结构体系和材料、以及预计施工时间等设计参数都需要加以考虑。净使用面积直接关系到商业价值，可基于预期配套面积、结构体系、及建筑形体探讨它们的相互作用。"参数化城市建模™"只需知高度限制和地块面积，即可参数化考虑建筑系统对净使用面积的影响，从而估计空间的使用效率/可销售性。此外，也许最重要的是，该算法还可以评估这些系统对环境的影响以及增强系统部件在开发项目使用寿命期间的成本效益。

关键词: 碳隐含量、城市规划、参数化建模、地震危险性、增强结构系统

Introduction

Designs for cities of the future need to be conceived by performance-based design. With decreasing material supplies and increasing demands, the cities of the future must use fewer natural resources while providing greater urban density and ultimately even the regeneration of resources. Decisions cognizant of the broader impacts on the environment and urban landscape need to be made early in the planning process through the conceptual design of districts, parcels, and buildings. Design must consider optimal net floor area efficiency, material use and resiliency to environmental disaster risks. Although efforts have been made at a broad level, little effort has been made to quantify performance at an individual parcel level. For example, municipalities can quantify fiscal and logistical impacts of increased height limits by allowing higher occupancy floor area ratios, but they do not account for potential limitations such as net usable area efficiency or embodied carbon. To quantify these and other metrics

序言

未来城市的设计需要由性能化设计作为出发点。鉴于材料供应减少而需求不断增长的情况下，未来城市必须减少使用自然资源，同时提高城市密度，最终甚至具有再生资源的功能。在规划过程的初期直到市区、地块、及建筑的概念设计阶段，需根据对环境和城市景观产生广泛影响进行决策。设计必须考虑最佳使用面积效率、使用材料、以及能不受环境灾害危险影响的适应性。虽然这些努力已在广泛的设计层面有所体现，但是基本未对个别地块的性能进行量化计算。例如，市政府可以量化提高建筑限高后因提高了楼层人数密度而对财政和物流产生的影响，但未免可以计算净使用面积效率或隐含碳等潜在的局限性。为了量化未来城市的这些及其它度量，已经提出了先进算法并已用于参数化城市建模™ (PCM) 内。可以变化各种参数，如地块面积、建筑形体、建筑高度、以及主要结构材料和地震等异常荷载的需求，来了解这些参数单独和一起所产生的影响。只需已知地块面积和建筑限高，即可评估净使用面积/商业价值以及对环境的影响 (隐含碳量) 。主要的算法包括:

Figure 1. Rendering of the Redeveloped Transbay District of San Francisco. Highlighted buildings indicate current and planned construction (Source: SOM)
图1. 旧金山跨湾交通中心区重新开发效果图。加亮的大楼目前正在施工和计划施工 (SOM提供)

of future cities, advanced algorithms have been assembled and are used within Parametric City Modeling™ (PCM). Parameters including parcel size, building shape, building height as well as primary structural material and abnormal loading demands such as seismicity can be varied to understand their individual and collective impacts. With only the parcel size and height limit known, net usable floor area / commercial value and impacts on the environment (embodied carbon) can be evaluated. Key algorithms include:

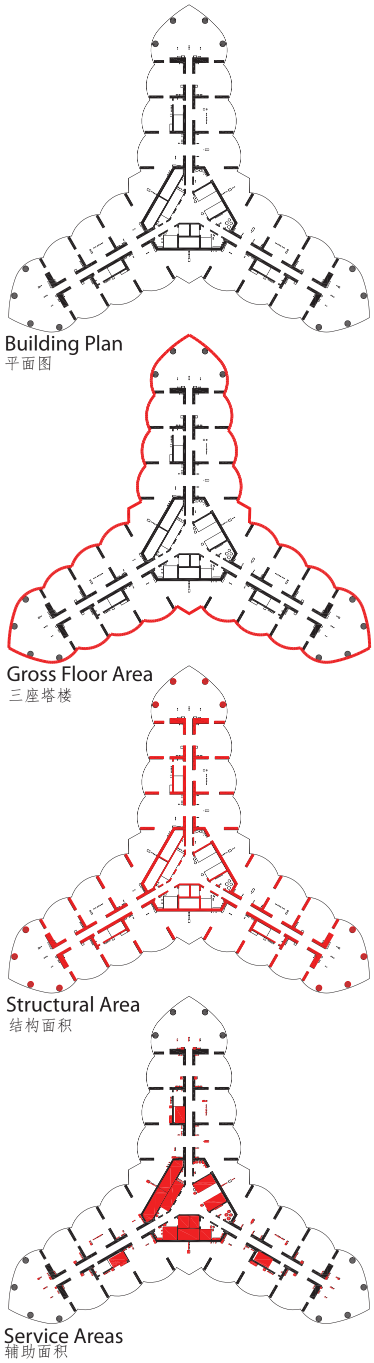
1. Building Systems Modeling (BSM): This algorithm calculates building systems floor area, anticipated lease spans, and net floor area given only a parcel's plan extent and height. Building systems modeled include core program, structural system, elevators, stairs, and MEP shafts.
2. Environmental Analysis Tool™ (EA Tool): This algorithm computes embodied carbon associated with structural systems.

In the future other parameters such as shadow casting, day lighting, utility use such as water and electricity can be added with a weighting function to determine other optimal collective solutions.

With knowing only parcel sizes and height limits, PCM has been applied to the Transbay District of San Francisco, California, to evaluate net usable floor area and embodied carbon of structures. With a significant number of parcels being developed (see Figure 1) the goal is to review impacts of the district as-planned as well as consider the impacts of taller height limits and variations of structural materials used for construction.

Parametric City Modeling™

Parametric City Modeling™ is used to evaluate the city, the district, the parcel, and the building. The two key components of the model are Building Systems Modeling and the Environmental Analysis tool. In the following section these algorithms are described in detail and have been based on hundreds of buildings designed previously by Skidmore, Owings & Merrill LLP over the last 40 years.



Average Percent GFA of Building Systems
建筑系统中各功能区占建筑面积百分比

Lease Area (75%) 可租面积（75%）	Core Program Area (12%) 核心筒内功能面积（12%）
Structural Area (7%) 结构面积（7%）	Elevator Area (4%) 电梯井面积（4%）
Stair Area (1%) 楼梯面积（1%）	Shaft Area (1%) 机电水管井面积（1%）

Figure 2. Components of Building Systems Modeling (Source: SOM)
图2. 建筑系统模型组成部分 (SOM提供)

Building Systems Modeling (BSM)
The BSM algorithm facilitates an accurate and rapid estimation of building systems floor area requirements. With only the building form, seismic and wind conditions for the site, and structural material type, the floor area requirements of structural systems, elevator systems, corridor area, and area for stairs, mechanical, electrical, and plumbing systems are calculated. With this information a Net Floor Area (NFA) is determined by subtracting the area required for these items from the Gross Floor Area (GFA) at each floor of the building (see Figure 2).

Researchers and economists have concluded that a minimum NFA of 75% is typically required to make a tall building profitable (Yeang 1995). Lower NFA values are common, many between 70-75% as documented for tall buildings constructed through the 1990's. Recently, developers have demanded NFA ratios of 80%, up to even 90%. These targets are increasingly challenging since the average height of newly constructed tall buildings continues to increase with proportional demand on building systems and consequently sizes of these systems (Sev & Ozgen 2009). When building heights become significant (height > 200m), NFA efficiencies greater than 75% are even more difficult to achieve (Sev & Ozgen 2009).

Conditions which greatly influence the profitability, livability, and NFA are often set during planning stages with parcel sizes, height limitations, and other occupancy restrictions. Later, during detailed design phases decisions which also affect space efficiency are often made in the conceptualization of a building, before any detailed programmatic studies can be conducted, leading designers to 'best guesses' of an efficient building. Using the PCM methodology, a holistic and robust evaluation can be conducted in a parametric environment to estimate metrics and inform design decisions.

Building Systems. Using final design drawings, a floor area survey of several constructed buildings has revealed averages and trends among floor area usage of building system. Results from three example buildings in this survey are reported in Figure 3 including building system floor area usage, NFA, and lease span. Furthermore, BSM is used to estimate the same metrics. As can be observed, the NFA and lease span calculations by BSM are reasonable estimations based solely on plan extents, height and primary structural material.

The floor area survey of building systems has provided average values of key NFA components. Figure 4 is a graphical representation of these components. On average, core area is 23% of GFA. Building systems floor areas are, on average: 12% core program, 5% structural area, 4% elevator shaft area, 1% MEP shaft area, and 1% stair area. Core program consists of corridors, vestibules, lobbies, electrical and plumbing closets, janitorial, etc. The structural area is the plan extent of structural systems including enclosing finishes.

Structural Systems. Floor area required for structural elements such as columns, walls, and braces are estimated considering a self weight of the structure based on material quantity estimation methods employed by the EA Tool, assumed superimposed dead load of 0.7 kPa, and live load of 3.8 kPa. These are applied uniformly over the gross floor area and the total gravity weight is summed from top of building to base. This total load at the base is divided by the selected material yield strength. To account for additional material corresponding to the lateral force resisting system a factor is applied to the yield strength. For high seismic a factor of 0.25 is utilized whereas a factor of 0.4 is used for high wind. When wind or seismic is considered moderate, a factor of 0.5 is utilized. A minimum structural floor area of 3% is utilized.

1. 建筑系统建模 (BSM) : 该算法在已知地块平面范围和建筑高度的情况下计算建筑系统建筑面积、预期可租面积跨度、及使用面积。模型中的建筑系统包括核心筒功能、结构系统、电梯、楼梯、及机电水管井。
2. 环境分析工具™ (EA工具) : 该算法计算与结构系统相关的隐含碳量。

将来可结合日照阴影、采光、以及水电等市政管线设施等其它参数，以此设计出其它最优的集合解决方案。

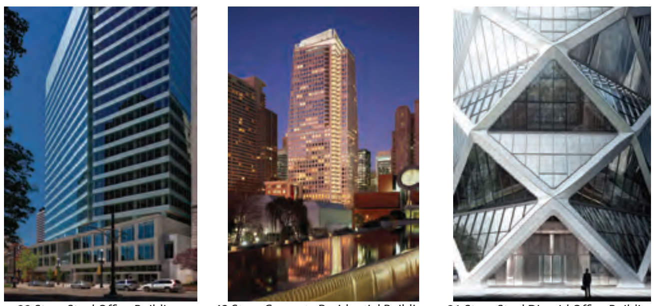
参数化城市建模在仅知地块面积和高度限制的情况下，就已用来评估加州旧金山跨湾交通中心内区的净使用面积和结构中的隐含碳。鉴于大量地块正在开发 (图1) ，评估目标是审核所规划城区的影响，并考虑提高限高以及施工所用各种不同结构材料的影响。

参数化城市建模™

参数化城市建模™的作用是评估城市、城区、地块、及建筑。该模型的两个关键组成部分是建筑系统建模和环境分析工具。这两个算法的详细说明如下，依据的是SOM公司40年来设计的数百栋建筑物。

建筑系统建模 (BSM)
建筑系统建模算法用于准确快速地估计建筑系统的建筑面积要求。只需已知大楼形体、地块地震与风力条件、及结构材料类型，即可计算结构系统的建筑面积要求、电梯系统、走廊面积、以及楼梯与机电水系统的面积。基于此信息，从大楼每层总建筑面积 (GFA) 减去上述所需面积，得使用面积 (NFA) (图2)

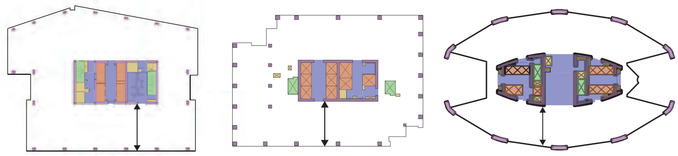
研究人员和经济学家得出结论，高层建筑的使用面积率一般需至少75%才有经济效益 (Yeang 1995年) 。较低的使用面积率很常见，按记录1990年代所建高层建筑许多在70～75%之间。最近开发商



22 Story Steel Office Building
Salt Lake City, Utah, USA
22层钢结构写字楼
美国犹他州盐湖城

42 Story Concrete Residential Building
San Francisco, California, USA
42层混凝土结构公寓楼
美国加利福尼亚州旧金山

31 Story Steel Diagrid Office Building
Bejing, China
31层斜交网格结构写字楼
中国北京



Metric	Actual 实际数据	BSM 模型数据	Actual 实际数据	BSM 模型数据	Actual 实际数据	BSM 模型数据
Net Floor Area 净楼面面积（使用面积）	82%	82%	81.5%	80%	80%	83%
Core Program Area 核心筒内面积	8%	10%	8%	10%	10%	10%
Structural Area 结构面积	4%	3%	4%	3%	4%	4%
Elevator Area 电梯井面积	3%	3%	5%	5%	4%	1%
Stair Area 楼梯面积	1%	1%	1%	1%	1%	1%
Shaft Area 机电水管井面积	2%	1%	0.5%	1%	1%	1%
Lease Span (m) 可租面积跨度（米）	13.7	14.3	10.5	12	13.1	12.7

Figure 3. Floor Area Survey Examples (Source: SOM)
图3. 建筑面积调查样例 (SOM提供)

Through this process a required plan area of structural material is determined considering the buildings form, height, material and subjected lateral loads. For steel, the plan extent of material is relatively small, but often steel shapes must be fireproofed and enclosed in finishes. As such, calculated structural steel floor area is multiplied by 10 to account for fireproofing and rectangular enclosure finishes.

Elevator Systems. Typically, a single cab elevator requires 9 m^2 floor area. A tower under 45 stories will often have six to eight passenger elevators depending on the use, above 45 stories more extensive groups of elevators, up to 18, can occur at a single floor. In this scenario, the elevator groups will stack and sky lobbies introduced every 45 floors. Groups of six elevators can serve approximately 15 floors each. If a group of 18 elevators occurred in a 45 story module of a tall tower, three groups of six passenger elevators would service 15 floors each. The elevators which service the lower 15-floor sections would stop at the top of their respective zones and that floor area would be utilized for increased NFA. Allowances for one service elevator and one sky lobby elevator per sky lobby are included.

Building Service Systems. Allowances are utilized for the core program (12%), shafts (1%) and stairs (1%) base on the building systems floor area survey.

Environmental Analysis Tool™ (EA Tool)
Most of the efforts to date made in calculating the carbon footprint of a building are associated with the operations of buildings with little or no focus on the structure at the time of construction and over its service life. The Environmental Analysis Tool™ calculates the expected carbon footprint of a structure at the time of construction considering its location and site conditions (Sarkisian et al 2012). Based on the structural system considered, a damage assessment is performed based on the expected seismic conditions. Equivalent carbon dioxide emissions (CO_2 eq) associated with the structural system of a building may be categorized as those resulting from the following three major components: materials, construction, and seismic damage (see Figure 5).

It is important that the carbon footprint accounting is accurate even when limited information is available. The Environmental Analysis Tool™ is capable of calculating a structure's carbon footprint with knowing only:

1. The number of stories (superstructure and basement).
2. The total framed area in the structure or average area per floor.
3. The structural system type.
4. The expected design life.
5. Site conditions related to expected wind and seismic forces.

With this small amount of information, the program refers to an algorithm developed from data mining of hundreds of built structures. This algorithm assists the designer when project-specific information, such as material quantities, is limited. Assumptions, such as crane operation and formwork durations, are based on practitioner experience and varied for different structural material systems. The goal of the algorithm, and corresponding software, is to be a design aid for the accounting of embodied carbon in structural systems.

The EA Tool™ has been used on multiple projects for critical design decisions, often resulting into either significant consideration or adoption of carbon mitigating measures such as enhanced seismic performance. A residential development of two towers in San

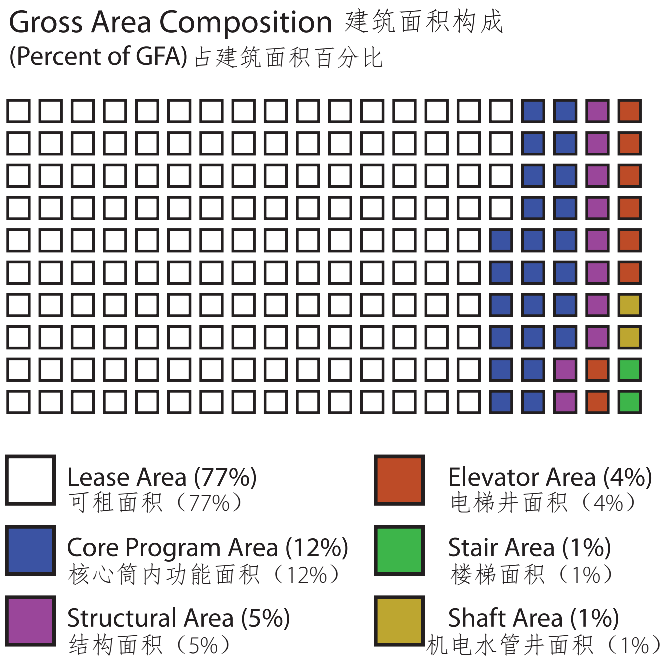


Figure 4. Average Composition of GFA (Source: SOM)
图4. 总建筑面积平均构成 (SOM提供)

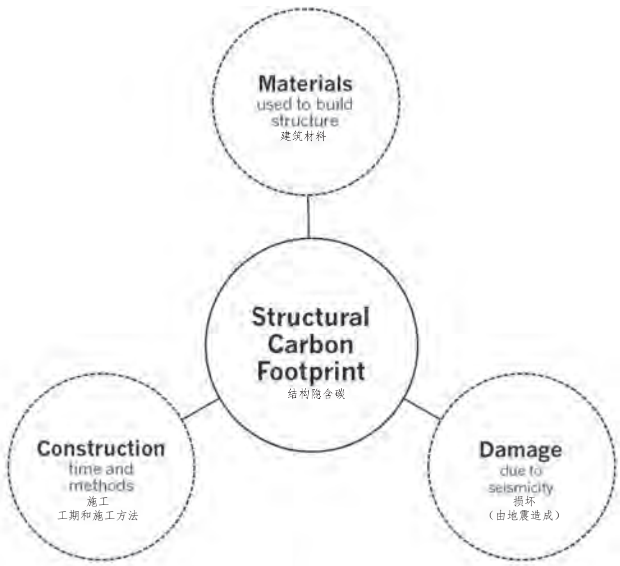


Figure 5. Components of Structural Embodied Carbon (Source: SOM)
图5. 结构隐含碳的组成部分 (SOM提供)

要求使用面积率达80%，甚而90%。由于新建高层建筑的平均高度一直不断增高，建筑系统的需求及其尺寸也相应地成倍增长，使这些指标更难以达到 (Sev和Ozgen 2009年)。当建筑高度达到某种程度 (> 200米)，使用面积率就更难超过75%了 (Sev和Ozgen 2009年)。

对收益性、宜居性、及使用面积产生重大影响的条件经常在规划阶段随着地块面积、限高、及其它占用限制而设定。然后，在详细设计阶段，经常会在大楼概念设计期间、在进行任何详细功能空间配置研究之前作出影响空间使用效率的决策，使设计师不得不对高效建筑做尽量准确的猜测。用PCM方法可在参数化环境内进行整体、保持有效的评估，来估计度量并为设计决定提供信息。

建筑系统: 用最终设计图纸，几个已建成建筑的调查揭示了建筑系统楼面使用面积的平均值和趋势。本次三个示例楼宇调查结果

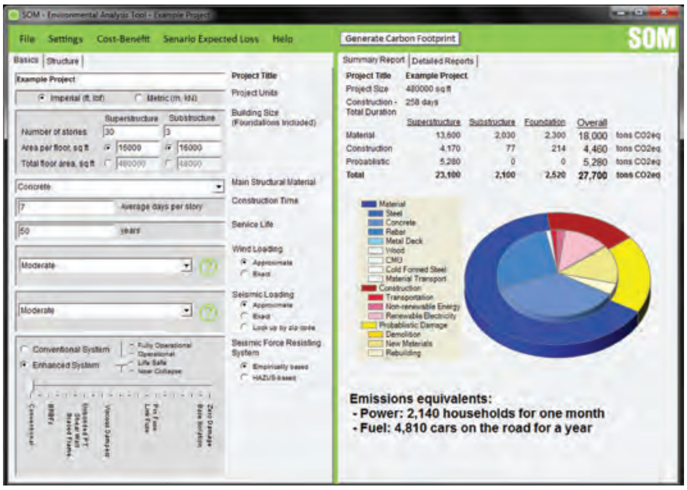


Figure 6. Environmental Analysis Tool™ (Source: SOM)
图6. 环境分析工具 (SOM提供)

Francisco, California, is considerate where carbon impacts and financial performance of a base isolated scheme were evaluated and conveyed to the client for an informed decision that lead to the inclusion of base isolation into the design of the buildings (see Figure7).

The EA Tool™ has been made available for free to the public to provide engineers, architects, owners, and contractors the means to evaluate embodied carbon (www.som.com). The ultimate goal is to enable the quantification of embodied carbon in structures which ultimately leads to a discourse across the profession and adds to a conversation already happening world-wide regarding the sustainability of the built environment.

Embodied Carbon Targets for our Future Cities

As proposed previously by the authors (Sarkisian and Shook 2014), a series of carbon benchmarks have been developed and used for understanding embodied carbon levels. These targets have been formulated through the investigation of over 200 SOM-designed structures using records of material quantities, structural system type, and geographic location. This data has been processed for averages, trends and correlations which were used in formulating a set of

的报告在图3中，其中包括建筑系统使用面积，使用面积和可租面积跨度。此外，建筑系统建模用于估计同样的数据。可见用建筑系统建模可以仅依据平面范围、高度、及主要结构材料即合理地估计出使用面积率和可租面积跨度。

建筑系统的建筑面积调查提供了重要使用面积部分的平均值。图4用图形表现了这些组成部分。核心筒面积平均占总建筑面积的23%。建筑系统的建筑面积平均为: 核心筒功能占12%，结构面积5%，电梯井面积4%，机电水管井面积1%，楼梯面积1%。核心筒功能包括走廊、门厅、大堂、配电间、水管设施间、清洁工具间等。结构面积是结构系统及其围护饰面的平面范围。

结构系统: 估计柱、墙、斜撑等结构元素所要求的建筑面积时，考虑了用环境分析工具的材料量估计法所计算的结构自重，假设附加恒载为0.7 kPa，活载为3.8 kPa。这些都均匀施加于总建筑面积，并计算了建筑从顶到底的总重力荷载之和。基底的总荷载除以所选的材料屈服强度。为考虑抗侧力体系另外所需的材料，将屈服强度乘以一个折减系数。强震区的系数为0.25，强风区的系数为0.4。对于中等风区或震区，系数为0.5。最少使用结构建筑面积3%。

在这个步骤中通过考虑建筑形体、高度、材料、及所承受的侧向荷载，得出了要求的结构材料平面面积。钢材的平面范围相对较小，但型钢经常必须经防火处理并用饰面围护。如此，所得结构钢建筑面积需乘以10来计入防火材料与矩形围护饰面。

电梯系统: 通常单轿厢电梯需要9 m2建筑面积。低于45层的塔楼按使用情况经常有6～8部载客电梯，高于45层的塔楼会有更多电梯组，最多一层18部。在此情况下，电梯组将分区叠加，每45层设一间空中大堂。一组6部的电梯，每组可供15层使用。假定一幢45层的高层塔楼使用18部电梯，则每15层将使用6部一组的客梯，共使用3组。每15层所用的电梯将止于其服务区的顶部，其上部建筑面积将成为增加的使用面积。计算模型另外包括一部服务电梯以及每间空中大堂配置一部空中大堂电梯。

大楼服务系统: 按大楼系统建筑面积调查结果，容许核心筒功能面积12%，管井1%，楼梯1%。

环境分析工具

至今大部分建筑碳足迹计算都是考虑大楼运作，基本都忽视了结构的施工以及使用。环境分析工具按结构位置与地块条件计算了结构预计在施工期间的碳足迹 (Sarkisian等，2012年)。根据所考虑的结构系统，按预计地震情况进行了损坏情况估计。与大楼结

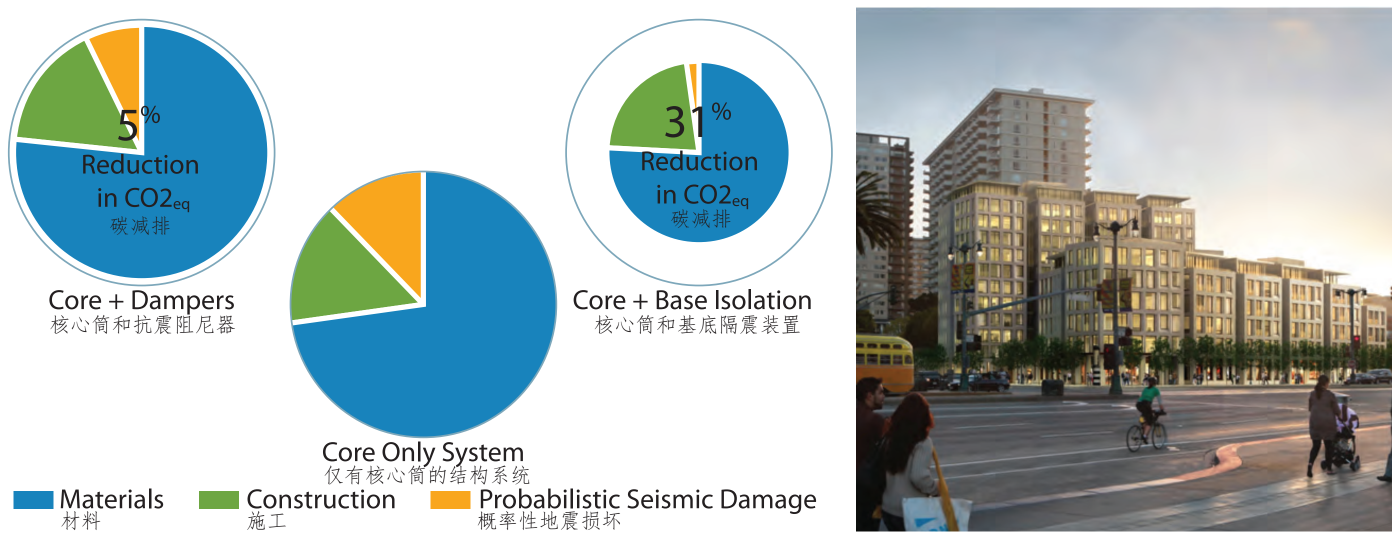


Figure 7. Carbon Assessment of Design Options (Source: SOM)
图7. 设计方案的碳评估 (SOM提供)

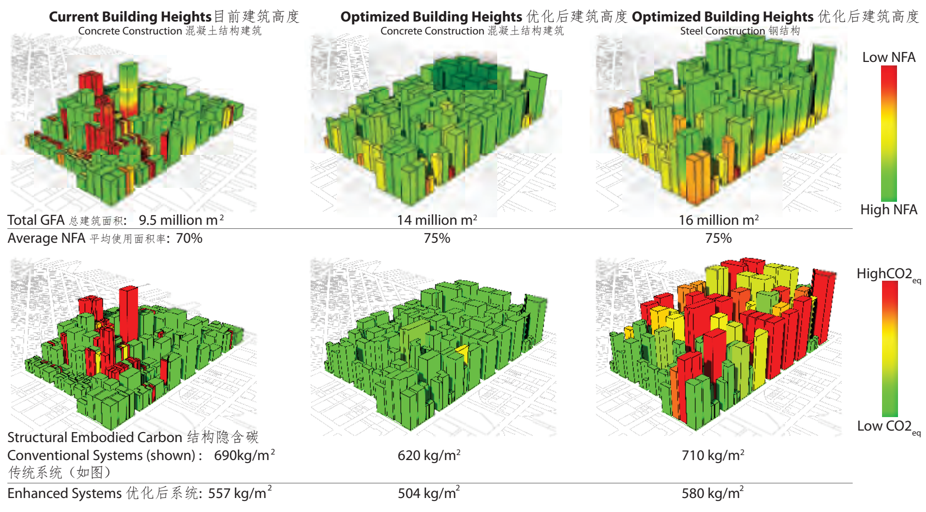


Figure 8. Results of PCM analysis (Source: SOM)
图8. 参数化城市建模分析结果 (SOM提供)

embodied carbon targets for structural systems shown in Table 1. These goals are envisioned to help form the basis for incentive-based system and future codification.

The incorporation of embodied carbon limits would not only reduce environmental impacts, it would impact broader goals of society and economic performance. Limiting embodied carbon would bring environmental performance into design and construction more directly and could fundamentally alter building composition. The quantification and management of embodied carbon also brings the opportunities to identify correlations and synergies among building systems not previously considered.

The District in the City

The Transbay District of San Francisco is a district currently under redevelopment. Several height limitations have been increased to encourage replacement of older, less efficient buildings and a large mass transit center is being replaced. As a case study investigation, PCM will be employed to evaluate NFA, lease spans, and embodied carbon of potential building forms. As opposed to evaluating current building forms, the investigation will focus on the potential of each given parcel extents and height limitations. A uniform offset of 15% from parcel edge to building form is assumed.

To encourage redevelopment, the height limits of several parcels have been increased, some limits have been increased to over 220 meters, even 300 meter for a single parcel which would make it the tallest building in San Francisco. By knowing the parcel limits and height

构系统相关的二氧化碳等量 (CO2eq) 可归于由以下三种主要原因而造成的一类: 材料、施工、地震损坏 (图5) 。

尽管在所知信息有限时，碳足迹计算的准确度仍同样重要。环境分析工具能在仅知以下条件时便可计算结构的碳排放:

1. (地上地下) 楼层数
2. 结构内楼盖总面积或每层平均面积
3. 结构系统类型
4. 预计设计年限
5. 与预计风力和震力相关的地块条件

综合知上述有限信息后，软件会使用参考几百个已建结构数据的算法，在材料用量或其他具体项目资料缺乏的情况下为设计师提供帮助。吊车操作、支模时间等条件是依据从业者的经验而假设的，按不同结构材料系统而变化。该算法以及相应软件的目的是作为设计工具来计算结构系统内的碳隐含量。

环境分析工具已用于数个项目的重要设计决定，结果经常是能使诸如加强抗震性能等碳减排措施得到认真考虑或实际采用。加州旧金山两幢住宅楼的开发项目评估了基底隔震方案的环境影响和经济性能，并向客户作了汇报，客户从而在掌握充分的资料的情况下决定在大楼设计中采用基底隔震 (图7) 。

环境分析工具已免费向大众提供，工程师、建筑师、业主、及承包商可用之评估结构隐含碳 (www.som.com) 。其最终目标是建立结构中隐含碳的量化计算，最终将在各行业中引起专业讨论，对目前全球的建筑环境可持续发展性话题作补充。

Number of Floors 楼层数	Average 平均值 (From data analysis) （根据数据分析）	CO_{2eq} Target 预估含碳量 (15% Reduction) 减排15%	Low Seismic 地震低发地区 (-10% of Target) （较预估值低10%）	High Seismic 地震高发地区 (+10% of Target) （较预估值高10%）
80+	730	620	560	685
60-80	630	535	480	590
40-60	540	460	415	505
20-40	560	475	430	525
0-20	490	415	375	460

Table 1. Carbon Benchmarks (kg/m²)
表1. 碳基准 (kg/m²)

limitations an initial form extent can be realized. Viewing this form as a GFA limit of the parcel, a study of the potential performance of the parcel can be conducted with PCM. The methodology can identify parcels which are well suited for their designated height limits as well as parcels not likely to develop their desired potential. Each parcel is evaluated for fiscal and environmental performance. Fiscal performance is quantified through the BSM algorithm by computing NFA and maximum lease spans as these are reasonable indicators of how well a building could perform fiscally and what occupancy might best suited for it. Environmental performance is evaluated using the EA Tool.

To investigate the potential impact planning and design decisions have at a district scale using PCM, a series of analysis are conducted where building height, material, and resiliency are considered. First, the current Transbay District is evaluated using PCM as can be seen in Figure 8. Red indicates buildings with low or poor NFA values and green indicates parcels with NFA values exceeding 75%. As can be observed, a large number of small parcels which have been zoned with tall height limits cannot reach their desired potential due to poor NFA values and corresponding financial performance. Next, each parcel's height limit is adjusted to produce a NFA value of 75%. The resulting urban form is relatively uniform, but can potentially facilitate nearly 50% more GFA. This is an important consideration with the increasing densities of our future cities. The effect of structural material selection is also considered and even taller buildings can be facilitated with steel construction and yield a nearly 70% increase in GFA.

Structural embodied carbon considerations are quantified for the three above mentioned cases. It is determined that while some buildings achieve the previously mentioned carbon benchmark targets, many do not. For the optimization height limits with concrete as the structural material the overall environmental performance is very good, while the opposite is true for the steel scenario. This could be due to the material and taller height limits. This environmental issue can be mitigated through enhanced seismic performance. For low-rise buildings this could be achieved with technologies now in use such as base isolation and in taller building with novel energy dissipating elements such as the Pin-Fuse seismic systems (Sarkisian et al 2012).

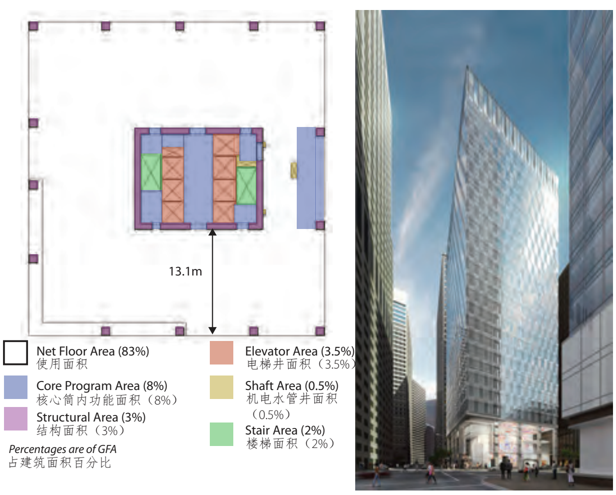


Figure 9. Example Parcel (Source: SOM)
图9. 实例地块 (SOM提供)

未来城市的碳隐含量指标

按作者早先的建议 (Sarkisian和Shook，2014年)，已建立了一系列碳基准，并用于理解隐含碳的等级。这些指标是通过研究SOM设计的200多个结构而制定的，研究时采用了材料用量、结构系统类型、及地理位置的记录。这些数据经处理得出平均数、趋势、及相互关系，用于制定一组结构系统的隐含碳量指标，如表1所列。这些指标将用于为鼓励减排系统和将来制定规范奠定基础。

隐含碳限额的推出不仅能减少对环境的影响，并且会影响到更广泛的社会和经济表现的目标。限制隐含碳会更直接地为设计和施工带来环保性能，并且可能从根本上改变建筑的组成。隐含碳的量化和管理也带来了先前没有考虑过建筑系统之间关联和协同作用的机会。

城市市区

旧金山的跨湾交通中心区是目前正在重新开发的城区。此区放宽了几项高度限制来鼓励更新效率较低的旧楼，而且正在更建一座大型公交中心。在个案研究中，将用参数化城市建模来评估拟建大楼形体的使用面积、可租面积、及碳隐含量。此项研究着重于每个地块的潜力，根据已知范围和限高假设建筑形体从地块边缘统一退15%，而并非使用现有建筑形体。了鼓励重新开发，几个地块的限高都提高了，有些限高提高到了220多米，甚至有一个地块到300米，这将成为旧金山最高的建筑。知道地块的限制和限高后，就可以实现初步形体范围了。将此形体作为地块的总建筑面积限度来看，即可用参数化城市建模来研究地块的潜在性能。此方法可指出哪些地块适合既定限高，哪些不太可能达到理想的开发潜力。每个地块都经过经济效益和环境性能评估。经济效益用业务服务管理 (BSM) 算法进行量化计算，步骤是计算出使用面积和最大可租面积，这两者能合理地指示大楼的经济效益如何、人数多少合适。环境性能则用环境分析工具来评估。

为了用参数化城市建模来研究规划和设计决策对城区范围的潜在影响，在一系列分析中考虑了建筑高度、材料、及适应性。首先，目前跨湾交通中心区用参数化城市建模评估的结果可见图8。红色表示使用面积率低的地块，绿色表示使用面积率超过75%的地块。如图8所示，划入限高较高区的大量小面积地块由于使用面积率低，相应的经济性能也低，而无法达到理想的潜力。其次，每个地块的限高都经过调整，达到75%的使用面积率。结果造成城市形态相对统一，但有潜力可增加近50%的总建筑面积。在未来城市提高密度时，这是个重要的考虑因素。另外也考虑了结构选材的效果，就是更高的建筑也可用钢材建造，使总建筑面积增加近70%.

上述三种情况的结构隐含碳都作了量化计算。虽然有些建筑达到前文所述的碳基准指标，许多其它建筑无法达标。对于优化的限高，如用混凝土作结构材料，总体环境性能非常好; 而用钢则非常差。环境问题可通过加强抗震性能来改善。对于低层建筑，可用目前采用的基底隔震等技术来解决; 对于高层建筑，可用销式活节抗震系统等新的耗量体系 (Sarkisian等，2012年)。

城市建筑

作为跨湾交通中心重新开发规划的一部分，有一处地块被指定限高220米。该地块已完成设计，正在施工建造一幢高115米的大楼 (图9)。地块由于面积相对较小，而且无法扩展到相邻地块，所以无法实现理想的潜力。用参数化城市建模工具可算出更高效的建筑高度。一幢高220米的大楼的使用面积率估计为58%，这也就

The Building in the City

As part of the Transbay redevelopment plan, a parcel has been identified to have a height limit of 220 meters. The parcel has been fully designed and is under construction as a 115 meter tall building (see Figure 9). The parcel cannot reach its desired potential due to its relatively small parcel size, and cannot expand into neighboring parcels. Using PCM tools, a more efficient building height can be identified. The NFA for a 220 meter tall building is estimated to be 58% which is why designers lowered the building height to 115 meters to achieve a more economical NFA of 83%. Had the PCM methodology been used to inform this parcel's height limit, perhaps a more favorable height limit would have been assigned and another, more well suited parcel, been given the 220m height limit.

Planning for Cities of the Future

Master planning efforts have greatly improved the flow of modern cities and facilitated guidelines for urban growth when compared to previous decades, but only consider factors immediately relevant to developers and municipalities. Yet, the impacts of these decisions have far-reaching effects that are generally not considered until later stages of design development. Harvesting existing built environment information for the generation of predictive tools facilitates the consideration of these factors at early design stages. Influences such as city-wide effects of carbon, relative building locations and orientations, building materials and their sources, wind-mitigating measures, probabilistic seismic damage, and life-cycle assessments could guide design towards intelligent design.

Beyond the efficiency of space and energy, the regeneration of resources is needed, especially in our urban centers. Where energy and materials are most consumed, they must also be replenished. Building systems must serve multiple roles in their service life. Some roles could be regular while others are only needed in rare events. All of these efforts, evaluations, and components are part of the future of embodied carbon in our cities. Each decision, especially the ones with the broadest impact, must be considered through the lens of future implications. Cities should seek both fiscal and environmental performance with specific measures that are sensitive to actual conditions. With holistic approaches quantified through accurate assessments and executed through regenerated resources the cities of our future will thrive.

是为什么设计师把楼高降低到115米来达到更经济的83%使用面积率。如果当时采用了参数化城市建模方法来决定地块的限高，那么也许会制定更有利的限高，而220米的限高则会用于其他更合适的地块。

未来城市规划

相比起前几十年，总体规划工作既大量改善了现代城市的流线，又促进了城市成长的导则规定，但是仅考虑了与开发商和市政直接相关的因素。然而，这些决策的深远影响，一般要到扩初设计的最后阶段才会考虑。收集现有已建环境资料来运用预测未来的工具将促使在设计早期就考虑这些因素。全市碳影响、相对建筑位置和朝向、建筑材料与来源、减风措施、可能的震害、及使用周期评估等影响可指导设计向更具智慧的设计发展。

除了有效使用空间和能源以外，还需再生资源，尤其是我们的城市中心。能源和材料在消耗最多的地方都必须重新补充。大楼系统必须在使用寿命期间起到多个职能，有些平时使用，而有些则偶然需要。所有这些工作、评估、成分都是未来城市隐含碳的一部分。每个决策，尤其是影响范围最广的，都必须以长远的眼光来考虑影响。城市应希求经济和环境两种性能，因地制宜采取具体措施。以综合整体的方式，通过准确评估做量化计算，用再生资源实施建造，未来的城市将蓬勃发展，繁荣昌盛。

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