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

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 design 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...
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.
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湾区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、以及楼梯与机电水管井的面积。基于此信息，从大楼每一层总面积建筑面积 (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
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 m² 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 serve 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%) 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 (CO₂ 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
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 Figure 7).

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 targets for reducing embodied carbon in future projects.

In this section, we present a series of case studies where the environmental analysis tool has been applied to various projects. The results show the potential for reducing embodied carbon in buildings through the use of base isolation and other structural systems. The carbon targets are based on the assumption that these structures will be designed and constructed to minimize their environmental impact.

Figure 6. Environmental Analysis Tool™ (Source: SOM)

Figure 7. Carbon Assessment of Design Options (Source: SOM)
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

<table>
<thead>
<tr>
<th>Number of Floors</th>
<th>Average NFA (From data analysis)</th>
<th>CO2eq Target (15% Reduction)</th>
<th>Low Seismic (-10% of Target)</th>
<th>High Seismic (+10% of Target)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80+</td>
<td>730</td>
<td>620</td>
<td>560</td>
<td>685</td>
</tr>
<tr>
<td>60-80</td>
<td>630</td>
<td>535</td>
<td>480</td>
<td>590</td>
</tr>
<tr>
<td>40-60</td>
<td>540</td>
<td>460</td>
<td>415</td>
<td>505</td>
</tr>
<tr>
<td>20-40</td>
<td>560</td>
<td>475</td>
<td>430</td>
<td>525</td>
</tr>
<tr>
<td>0-20</td>
<td>490</td>
<td>415</td>
<td>375</td>
<td>460</td>
</tr>
</tbody>
</table>

Table 1. Carbon Benchmarks (kg/m²)

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。
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).

### Future Cities

按作者早先的建议 (Sarkisian and Shook, 2014 年), 已建立了一系列碳基准，并用于理解隐含碳的等级。这些基准是通过研究 SOM 设计的 200 多个结构而制定的，研究时采用了材料用量、结构系统类型和地理位置的记录。这些数据经过处理得出平均值，趋势和相互关系，用于制定一些结构系统的隐含碳限值，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。

### 城市区域

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，并且正在更新一座大型公交中心。在个案研究中，将用参数化城市模型来评估拟建大楼的使用面积，可租面积，及隐含碳量。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施体型从地块边缘统一递15%，而并非使用现有建筑体型。为了重新开发，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，就可以实现初步形态框架了。将此形式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，哪些不大可能达到理想的开发潜力。每个地块都经过经济效率和环境性能评估。经济效益用服务管理 (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，放大限高约 220 米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，如果达到超过都对经济效率和环境性能评估。经济效益用服务管理 (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。

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，正在施工建造一栋高 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，因此无法实现理想的潜力。用参数化城市建模工具可看出更高效的建筑高度。一栋高 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.

References


