绿色建筑设计——内涵碳优化的新方法

Climate-conscious Building Design : New Approaches to Embodied-carbon Optimization

撰文 DONALD DAVIES, P.E., S.E. (Principal)
Magnusson Klemencic Associates Inc.
资料提供 Magnusson Klemencic Associates Inc.

全寿命周期碳模型是衡量建成环境影响的一个重要工具，并为相关决策提供依据。美国绿色建筑委员会、居住建筑挑战者2.0以及其他一些机构已经开始把全寿命周期模型作为评价一个项目的要求之一。

虽然这是很有意义的尝试，但是第一阶段内涵碳涉及设计和施工阶段，而这一阶段关于内涵碳的计算常常过于简化，不足以得到具有实用意义的结果，或者牵涉太多的参数，有些人会质疑是否值得推行，但建立一个有实用意义、相对简单的内涵碳模型是可能的。计算过程必须集中在相关的范围，结果也需要有足够的精度。另外，将实时的信息应用到实时的设计中也是非常重要的。本文介绍了结构内涵碳的测量和优化方法以及一些非常重要的经验。通过碳的优化，可以同时实现可持续设计和降低成本。

1 背景

建筑业已成为最大的温室气体排放来源，这些碳排放来自于第一阶段建筑物建造产生的碳排放、第二阶段建筑物运转使用的碳排放和第三阶段建筑物拆除的碳排放的总和。包括可持续建筑联盟（SB Alliance）、联合国环境规划署可持续建筑和气候倡议（UNEP-SBCI）在内的许多组织将建筑物视为温室气体减排的一个潜力最大的因素。他们认为建筑行业最大的碳排放来源是第二阶段即建筑物运转阶段使用的化石燃料，因此大部分工作都是围绕着测量和减少该阶段的碳消耗方面开展的。

第二阶段建筑物使用期的碳减排来自于能效更高的建筑设计，包括目前经常采用的美国绿色建筑委员会（USGBC）的LEED体系和其他体系的目标标准。一些政府机构也已经开始为建筑环境制定更高的能效指标，而且它们可能是第二阶段碳减排的最有效的平台。更为雄心勃勃的是，建筑行业的减排目标计划（比如“建筑物2030”和“生态建筑挑战计划2.0”）与其他可持续性发展目标一同旨在实现零能耗的建筑物。

随着建筑物能效的提高及第二阶段碳排放的减少，第一阶段内涵碳在建筑物寿命周期碳足迹中占的比例越来越大。然而目前对第一阶段内涵碳的减排几乎没有得到任何重视，这是建筑行业碳减排领域的下一个关键的前沿课题。

Life cycle carbon modeling can be an important tool for measuring our built environment’s impacts, and to aid in decision-making processes. USGBC, the Living Building Challenge 2.0 and others are starting to include this modeling as part of a project’s accreditation process.

While this is definitely a worthy effort, The “Phase 1” embodied carbon involved in the design and construction stage is frequently either oversimplified to the point of meaningless results, or the variables are considered to be over whelming and others say “why bother?”

The challenge of meaningful but not over-burdensome embodied-carbon modeling is possible. The process has to be focused on the areas of relevance, and it needs to be accurate enough to deliver credible and useful results. It is also important that the information be timely and embedded into current design efforts. This article describes an approach for measuring and then optimizing the embodied carbon in a structure and several of the very important lessons that have been learned along the way. Through carbon optimization, sustainability and cost savings can go hand in hand.

1 Background

Most experts agree that over the next few decades, the world will undergo significant changes in climate, which will impact almost every aspect of the world’s environment, economies and societies. It has been reported that the building sector is responsible for 40% of the world’s energy consumption and more than one-third of global greenhouse gas emissions. In many countries, both developed and emerging, it is the largest emissions source. These emissions come from a combination of “Phase 1” embodied emissions to construct the building, “Phase 2” emissions of building operations and “Phase 3” emissions of deconstruction.

Multiple organizations, including the Sustainable Building Alliance (SB Alliance) and the United Nations Environment Program’s Sustainable Buildings and Climate Initiative (UNEP-SBCI), identify buildings as the single greatest area for potential reductions in greenhouse gas emissions. They identify the largest emissions in the building sector as coming through the use of fossil fuels during the Phase 2 operational phase. As such, most efforts to date have been in measuring and reducing building operational carbon consumption.

Phase 2 operating carbon reductions are resulting from more energy-

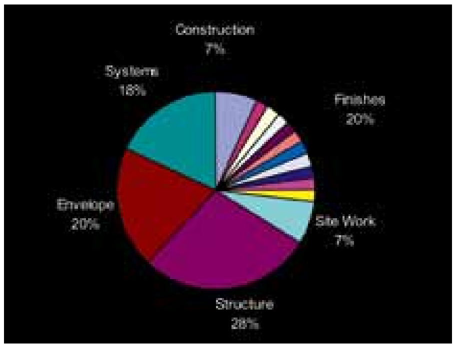

图1 第一阶段内涵碳–MKA酒店案例研究结果

2 结构相关性

第一阶段内涵碳的数量取决于许多因素。可以说目前和将来都很难直接度量第一阶段的所有内涵碳，在大多数情况下甚至是不可能度量的。但是，我们可以通过现有的一些方法来确定最大的碳阱，并以统计学的精度测定碳足迹。更重要的是，通过确定最大的碳阱，我们就可以采取有效的方法显著地降低建筑物的内涵碳足迹。

MKA多年的碳足迹研究结果表明，建筑结构是新建项目内涵碳足迹最大的来源（图1）。鉴于建筑结构材料的种类和行业数量有限，所以优化这些材料是非常值得投入时间和精力的一个领域。

3 设计优化

结构的内涵碳量依据材料选用、建筑物功能和设计效率的不同而存在显著的差异。安全方面的要求也会影响进行碳优化过程中可以选择的结构替代方案。典型的例子是：5层以上的建筑物一般需要采用不可燃的材料作为其结构主体的材料（即非木材）。

在当前“标准”的建筑设计中，内涵碳优化减排的时机在很大程度上没有得到重视。一个最重要的时机就是在确定结构体系的概念阶段，必须确定正确的“大方向”。结构体系需要与建筑功能和建筑表达和谐一致。最佳设计是结构与建筑形式的一体化设计，结构起到多重作用，比如支承建筑物、作为外饰面或成为保温隔热层以削减高峰的制冷和供热需求。结构体系到地面的传力途径应该最短。选用材料应根据其性能扬长避短，比如混凝土用于所有受压情况，钢材用于所有受拉情况。

例如大都会建筑事务所设计的西雅图中央图书馆外立面系统方案是个“三合一”的体系（图2），MKA设计了该图书馆的外部斜交网格钢构架。这个外表面钢构架既是结构侧向力系统，同

efficient building designs, including target standards now frequently adopted from the United States Green Building Council’s (USGBC) LEED process and others. Government bodies have also begun to set higher energy performance targets for the built environment and are probably the most effective forum for immediate Phase 2 carbon reductions. Most aggressively, building challenges such as Architecture 2030 and the Living Building Challenge 2.0 are, among other sustainability goals, aiming to achieve net-zero-energy buildings. There is still considerable work to do in the energy efficiency of buildings and it is by no means a “solved” issue, but progress is definitely occurring.

As buildings become more energy efficient and Phase 2 operational carbon is reduced, the Phase 1 embodied carbon becomes a much larger percentage of the life cycle carbon footprint of a building. With little current attention being focused on the Phase 1 embodied carbon, this as a critical and next frontier in the quest for carbon-footprint reduction in the building industry.

2 Structural Relevance

Phase 1 embodied carbon is affected by a very large number of variables. It is a difficult, and in most cases impractical, goal to say that all Phase 1 embodied carbon can and will be directly measured. However, by identifying and then focusing on the largest carbon sinks in a building, it is possible to estimate a carbon footprint with statistically relevant accuracy. By tracking this information, it becomes possible to both influence industry production processes holistically and to make project-specific carbon reduction decisions in a meaningful way.

Prior carbon footprint studies have shown that the structure has the single largest embodied-carbon footprint for new construction projects. Given the limited number of materials and industries that produce the structural frame for a building, focusing on optimizing those materials becomes a very high-value area to invest time and energy.

3 Optimization in Design

The embodied carbon of a structure varies widely depending upon material selection, building function and efficiency of design. Realities in life-safety requirements can also influence the structural alternatives available for carbon optimization. The classic example is buildings over five stories typically require noncombustible materials for their primary structural frame (i.e., no wood).

Opportunities for embodied-carbon optimization are largely unrealized in today’s “typical” building designs. One of the biggest opportunities is to determine the right “big idea” within the structural concept. Structural systems need to work in harmony with the architectural function and building expression. The best examples are when the structure

图2 西雅图中央图书馆斜交网格和外墙模型（资料来源： MKA）

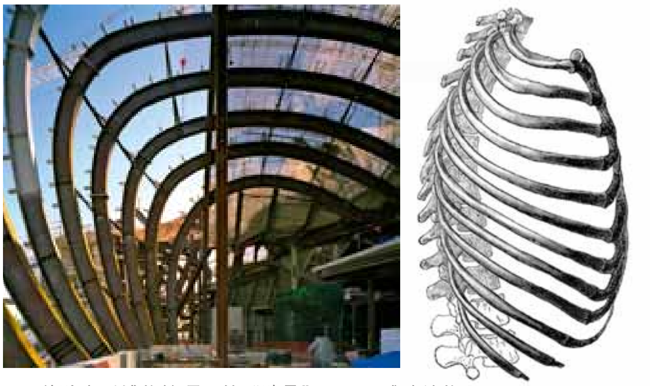

图3 体验音乐博物馆项目的“肋骨”——灵感建筑物

图4 钢管混凝土柱模拟大自然（资料来源：Paul Vlaar, 聚焦照片; MKA）

时也是建筑学意义上的外饰面和窗框，由此避免了使用传统的铝制窗框，而铝正是当今建筑行业大量使用的一种能耗最大（通常也是具有最大碳足迹）的材料之一。

利用大自然中的创意（仿生学）优化建筑构件是一个合适的切入点。万物的进化有其合理性，从大自然中得到灵感的解决方案是材料优化和碳优化的基础。Gehry Partner设计的体验音乐博物馆项目就包含了MKA根据人体肋骨架原理设计的钢构架，钢构架由混凝土薄壳连接在一起（图3）。西雅图市双联广场（Two Union Square）写字楼的结构设计也是一个优秀的例证。这座56层大厦位于美国西海岸的高地震带，MKA通过创新地采用钢管混凝土柱和非对称焊接钢梁，最终其结构总用钢量仅为12.5psf（61kg/m^2），比同期建造的类似规模项目减少了50%。此外，MKA在中国广州设计的60层利通广场项目也是类似的情况（图4），用钢量比同时施工建设的相邻类似写字楼的用钢量低40%。上述几个例子的共同点是结构和建筑的共生性能。材料和体系起到双重作用，碳优化和材料优化互补，以实现项目的最佳价值。

4 内涵碳统计

目前大多数内涵碳建模方法都是基于一次性建筑评估，因此缺乏真正准确了解项目中的内涵碳所必需的详细信息。目前为止，我们发现的最好的方法是“混合建模法”，而这种方法也正在获得越来越多的关注（图5）。

“混合”碳建模的第一步是从经济角度上对碳足迹进行估算，估算的依据是承包商的工程预算。第一步模型虽然总体上描绘了所有的建筑组成部分，但是缺乏详细性和准确性。即便这样，它也为更小的、更难跟踪的内容提供了足够的信息，同时也

and expressed architecture are one and the same, with the structure performing multiple duties, such as supporting the building, serving as an exposed finish and contributing thermal mass to cut peak cooling and heating demands. Systems should include minimal load transitions, as forces are brought to the ground. Materials should be used for their most efficient purposes, such as concrete for all conditions of compression and steel for all conditions of tension.

An example is the Office for Metropolitan Architecture’s (OMA’s) design for the exterior skin system of the Seattle Central Library that achieved what they call a sustainability “three for one.” MKA’s design of the exterior diagrid steel frame was engineered to serve as the lateral load-resisting system. This frame was also the architecturally exposed finish and the window mullion system. The last of these allowed for the elimination of almost all aluminum that would otherwise typically be included in the exterior window framing system. Aluminum is the single most energy-intensive (and frequently the highest-carbon-footprint) material typically used in mass in the building industry today.

Using ideas in nature (bio-mimicry) to help inform optimal building elements is a great starting point. Nature-inspired solutions, by virtue of evolution, are the essence of material and carbon optimization. Gehry Partner’s design for the Experience Music Project included MKA designing stiffening ribs based on the analogy of the human rib cage. Interconnecting these ribs was a thin-shell concrete skin.

Another example of MKA’s optimization pursuits is incorporated into the structural design for the Two Union Square office building in Seattle, Washington. This 56-story tower, located in the high seismic zone of the U.S. West Coast, achieved a total structural steel building weight of 12.5 psf (61 kg/m2). Such efficiencies were possible through the use of composite steel pipe column design innovations and asymmetrical built-up steel beams. The design reduced structural steel tonnage by 50% compared to similar-sized projects constructed at the same time. A very similar story is found in MKA’s design of 60-story Leatop Plaza in Guangzhou, China, where the measured material quantities were 40% less than those for adjacent office towers under construction at the same time.

Common to each of the above examples is the symbiotic performance of structure and architecture. Materials and systems serve double-duty, with carbon and material optimization complimenting each other for best-value project solutions.

4 Embodied-Carbon Accounting

Most embodied-carbon modeling approaches currently available are based on a one-time building review, lacking the detail for a truly accurate picture of the carbon embodied within a project. The best exception we have found to date is a hybrid modeling approach, which is now gaining more attention.

“Hybrid” carbon modeling starts with an economically derived carbon estimate, based upon a contractor’s cost estimate. That first model provides a “fuzzy first picture” of all building components but lacks detailed accuracy. It does, however, provide sufficient detail for the smaller and harder-to-track items, as well as guidance on where to focus a more detailed investigation for the biggest embodied-carbon sources.

It is an iterative process of increasing accuracy. As the project cost model is refined and project materials are sourced and measured during the normal evolution of design, the embodied-carbon modeling can also be refined. With less than 15% of the materials initially evaluated typically

经济模型–模糊的全面形象　材料组成模型–清楚但是遗漏的部分　混合模型–两者的结合

图5 混合成本建模（资料来源：Climate Earth）

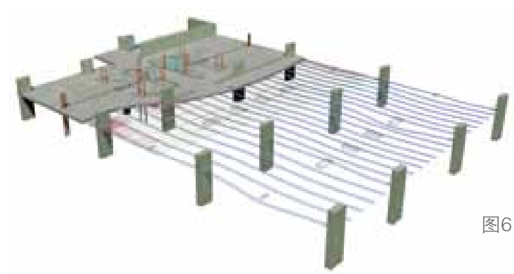

图6 BIM模型

指明了何处寻求对最大内涵碳来源的更加详细的研究。

这是一个提高准确度的迭代过程。随着正常的设计进展过程中项目成本模型的完善、更直接的项目材料来源的确定及测量，内涵碳模型也可以得到深化。最初评估不足15%的材料通常产生项目内涵碳的85%以上。这个经济模型表明我们需要在哪一步进行深化研究。

之后重要的是不要在最初的经济碳估算阶段停下来。碳排放量大的材料的碳足迹（比如水泥）根据其采购地点和生产方式的不同可能有100%以上的差异，因此需要对这些最大的统计学上最相关的碳来源进行更加详细的调查研究，从而获得一个相关的碳足迹模型。

多家机构正在推广“混合建模法”，但是他们在内涵碳足迹的建模方式方面却提供了不同的详细程度。MKA认为这种方法可以作为内涵碳统计的一种可实行的框架。

为了在材料组成的基础上对建筑结构的内涵碳进行更加详细的研究，MKA开发了一种碳计算工具MKA C-Tool，C-Tool工具与上述方法结合使用。从过去的案例研究中，我们发现商业建筑项目的结构一般占到项目的总内涵碳的28%~33%。因此，建筑结构肯定是值得进一步研究的方面之一。

MKA的 C-Tool工具包括以下6个步骤：

（1）利用结构框架的建筑信息模型（BIM）建模和估算材料数量——当把一体化BIM建模与建筑和机电专业结合使用时，可以产生非常准确的材料数量，这也为完全一体化的项目的碳建模建立了平台（图6）。

（2）确定材料来源。为了确定材料的来源，必须要明确将来所使用材料的重复利用的成分，然后确定运输距离和材料运送到生产厂和项目现场的运输方式（CO_2/吨/英里）。

（3）确定生产材料所需的能量。MKA开发了一个建筑业最常用材料的详细数据库，包括可能用于结构框架设计的材料。这一数据库收集了美国具体的钢筋、钢材和混凝土供应商生产材料所需的能源。随后对巴斯大学2008年和雅典娜大学2009年编制的欧洲碳和能源详细目录（ICE）进行了比照和补充。

（4）确定材料生产所使用的能源的碳足迹。这需要了解材料制造生产中的设备能源需求（燃气、电力和其他能源）以及生产和制造过程中直接发生的热电联产过程。借助能源生产领域的其他研究者进行的广泛研究，可以合理地确定任何一个地点的电能供应的碳足迹。MKA从这一信息开始，结合具体制造商工厂所

producing over 85% of a project’s embodied carbon, this economic model shows where to invest further effort.

It is important not to stop at the initial economic carbon estimate. The footprint of large carbon items, such as cement, can vary by over 100% depending upon where it is sourced and how it is produced. These largest and most statistically relevant carbon sources require a more detailed investigation in order achieve a relevant carbon footprint model.

The hybrid modeling process is being promoted by several organizations, with varying degrees of detail in how they model for the embodied-carbon footprint. MKA supports the approach as a viable broader framework for effective embodied-carbon accounting.

In an attempt to provide a more detailed examination, on a material-component basis, of carbon embodied within a building’s structure, MKA has developed a carbon calculation tool (MKA-C Tool). The C-Tool works in conjunction with the approach described above. From earlier case studies, we have found the structure of commercial construction projects to typically represent from 28% to 33% of the overall embodied carbon of the project. Thus, the structure definitely qualifies as one of these areas worthy of a more detailed investigation.

MKA’s C-Tool involves a six-step process:

Utilize BIM modeling and material quantity definition for the structural frame - When utilizing integrated BIM modeling in conjunction with the

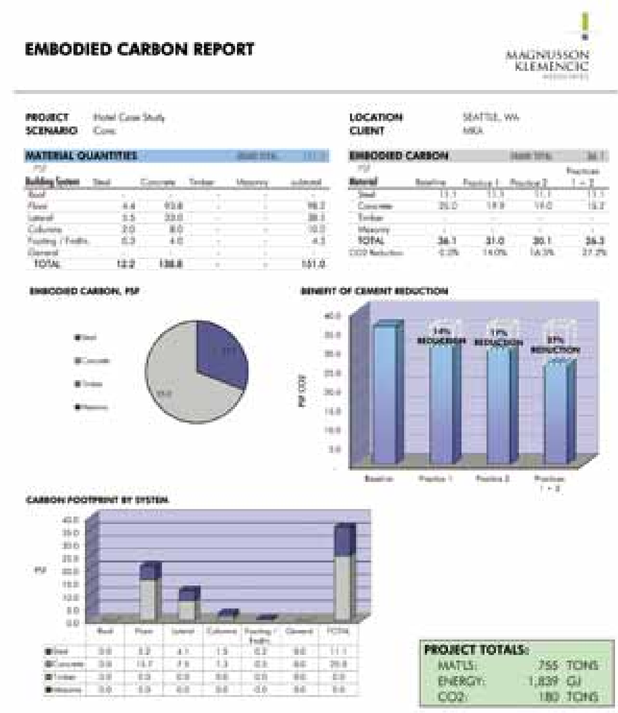

图7 MKA的C– Tool工具的输出.

采用的任何已知的热电联产过程或其他能源生产过程。

（5）数学计算。MKA的C–Tool工具将项目和材料采购输入信息结合起来，参照上述的数据库，然后计算结构估算内涵碳足迹。

（6） 跟踪和报告结果。通过将结构总内涵碳进行量化，可以清楚地看出从何处进行优化（图7）。它同时还有助于建立一个基准条件，根据这个条件可以跟踪检查项目设计进展中的落实情况。

5 案例研究

MKA最近完成了并且正在进行一些详细的案例研究来检验上述方法和评估更大规模的碳足迹研究中的结构的影响。这一工作包括评估最近建造的建筑物，从而为未来的项目比较建立一个基准。至今为止，案例研究包括了高层酒店、高层住宅楼、停车场和写字楼。这些研究揭示了重要的经验并且找到了碳优化的机会，具体如下。

5.1 材料系谱的相关性

比较西雅图市两家大的混凝土供应商，其中一家供应商通过市区内一家水泥厂的直接气动传输管道接收水泥。该水泥厂对现场的热电联产设备生产所需的大部分能源、原材料通过驳船运入。第二家混凝土供应商采用燃煤的能源发生工艺，从亚洲获得其50%的水泥熟料。

再来比较西雅图市两家最大的钢筋供应商，一家供应商从位于市区的一家工厂接收棒料，在钢筋生产过程中使用80%~90%的回收钢材，并利用西雅图电力部提供的水力发电。工厂在电力需求非高峰期运行，以减少西雅图电力网负荷。 第二家供应商的钢筋从美国中西部运入，用于生产钢筋的大部分能源来自于燃煤的火力发电厂。即使当材料数量和成本几乎相同时，这些建筑结构材料的碳足迹也会有显著差异，诸如混凝土、轧制钢材、轻型

architectural and MEP disciplines, it is possible to produce very accurate material take-offs. This also creates the platform for carbon modeling of the fully integrated project.

Track the material pedigree – To track the material pedigree, it is necessary to define the recycled content of the material being used, then the travel distances and shipping mechanisms used to get the material to the fabrication plant and the site (CO2/ton/mile).

Determine the energy required to produce the material – MKA has developed a detailed database of the materials most commonly used in the building industry, and likely to be used within the structural frame design. This database started with an internal investigation of energy requirements for material production by specific U.S.-based rebar, steel and concrete suppliers. It has subsequently been checked against and supplemented by references to Europe's Inventory of Carbon and Energy, or "ICE," as produced by the University of BATH, 2008, and Athena, 2009.

Identify the carbon footprint of the energy used to produce the material – This requires both an understanding of the plant energy requirements (gas fired, electric or other) in the production of material fabrication and any co-generation processes that happen directly in the production and fabrication processes. By relying on extensive research done by others in the energy production field, it is possible to reasonably assign a carbon footprint of the electrical energy supplied to any one location. MKA starts with this information, augmented by any identified co-generation or other energy production process utilized at a particular manufacturer's plant.

Do the math – MKA's C-Tool assembles the project and material sourcing input information, references the database look-up tables noted above, and calculates the structural estimated embodied-carbon footprint.

Track and report the findings – By quantifying the total embodied carbon within the structure, it becomes much clearer where to go for optimization potential. It also helps to establish a baseline condition from which to track a project's ongoing design progress.

5 Case Study Lessons Learned

MKA has recently completed and is conducting several detailed case studies to both test out the above process and assess the impact of structure within the larger carbon footprint discussion. Part of this effort has been to assess buildings recently built but not focused on carbon optimization efforts, in order to develop a baseline for future project comparisons.

Case studies to date have included high-rise hotels, high-rise residential towers, parking garages and office buildings. These investigations have revealed important lessons learned and identified carbon optimization opportunities. Some of these lessons include the following

Relevance of the Material Pedigree

When comparing two concrete suppliers active in the Seattle downtown market, one of the suppliers receives their cement via a direct pneumatic pipe from a cement production plant within the city limits. That plant produces the majority of its energy needs from on-site co-generation, with raw materials shipped in by barge. The second concrete supplier receives 50% of its cement clinker from Asia, using a coal-fired energy-generation process.

When comparing two rebar suppliers active in the Seattle downtown market, one receives their bar stock from a mill located within the city limits, utilizes 80 to 90% recycled steel in the production of their bar and uses electrical hydropower purchased from Seattle City Light. The plant

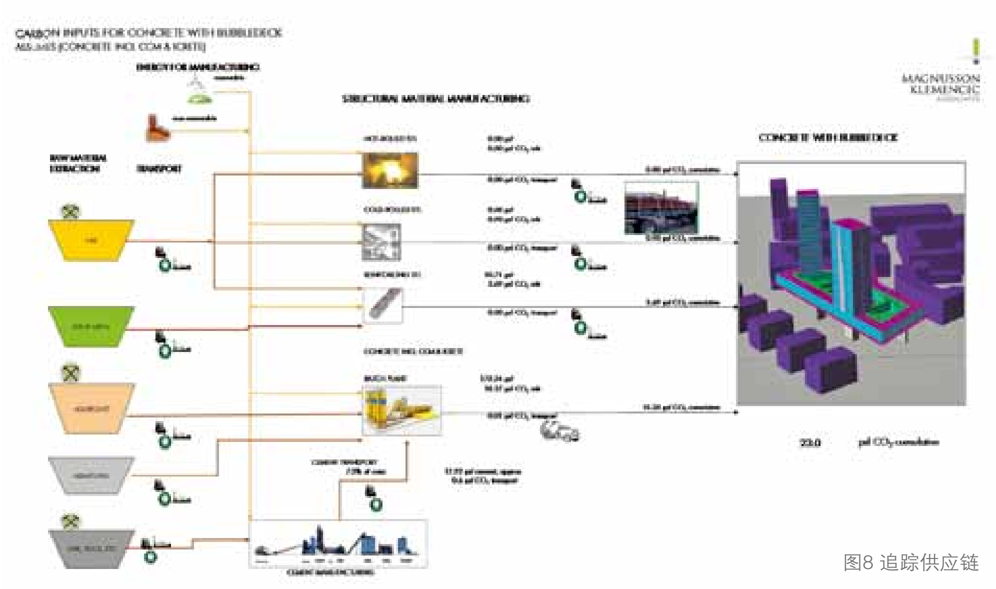

图8 追踪供应链

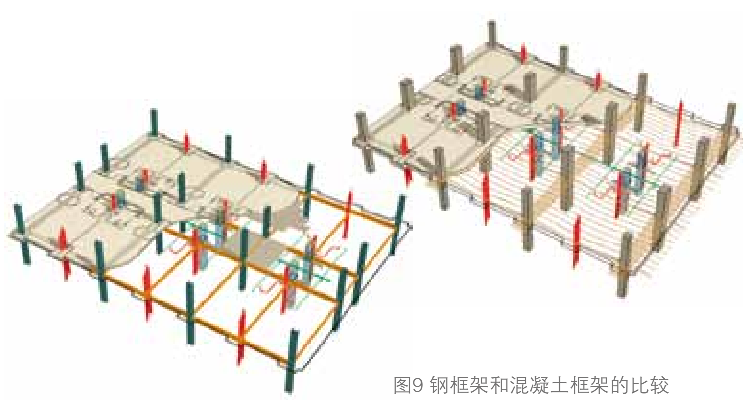

图9 钢框架和混凝土框架的比较

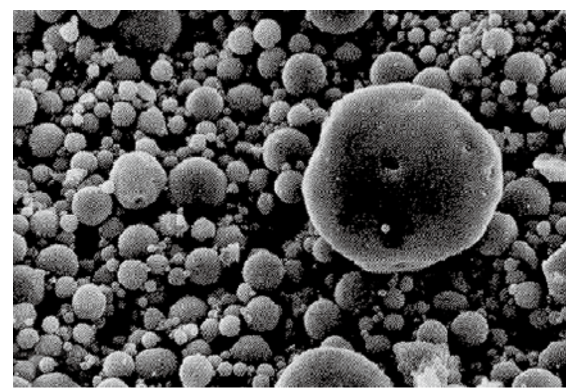

图10 混凝土添加剂（CCM’s）

钢材，特别是铝都具有高度可变的碳足迹。

如果对一个项目进行内涵碳统计，必须要建立一个系谱图，通过这个系谱图来追踪到这些基本建筑材料的制造和采购点（图8）。

5.2 钢框架和混凝土框架的对比分析

钢框架建筑和混凝土框架建筑哪一个碳排放较少？这个看似简单的问题其实答案非常复杂，见图9。比选择混凝土框架还是钢框架影响更大的是项目的钢材或混凝土如何采购，以及二者被优化的程度。MKA能够对于每一种材料结构类型实现高达50%的碳足迹削减，同时不会显著改变建筑物的外观或功能。碳足迹最优化的设计实际上使用两种材料，根据材料的特点利用每一种材料。

5.3 从水泥开始

在一座建筑物内，很少有材料能够实现与混凝土相同的功能。而且因为混凝土往往可以用于多种用途，比如建筑框架、隔热保温、隔音和隔振、建筑外饰面等，所以它与其他方案相比往往减少了项目潜在的碳足迹。但是，它在一般情况下也是一个项目最大量使用的材料，具有最大的碳足迹。因此，它是优化和减少内涵碳足迹的最佳目标。

通过实施新技术来改进混凝土生产厂的质量控制后的结果表明，对于相同强度的混凝土配比，可以节省水泥用量20%~50%。对于建筑业来说，这个领域需要进一步研究和改进。

“混凝土添加剂”（CCM）可以进一步降低水泥含量要求，

operates during non-peak electrical demand periods to reduce overload on the Seattle City Light grid. The second supplier’s rebar supply is shipped in from the U.S. Midwest, with the majority of the energy used to produce the bar coming from coal-fired generation.

Even when material quantities and costs appear to be the same, there can be a significant difference in the carbon footprint for these structural building materials, which historically have very high energy-production requirements. Materials such as concrete, rolled steel shapes, light-gage galvanized metal and especially aluminum can all have highly variable carbon footprints.

If embodied-carbon accounting is pursued on a project, it is important to require a pedigree that can be tracked back to the fabrication and points-of-resource extraction for these base building materials.

Analysis of Steel versus Concrete Frames

Which is less carbon intensive, a steel- or concrete-framed building? What seemed like a simple question turned out to have a very complex but short answer: it depends. More impactful than the choice of a concrete or steel frame is how the steel and/or concrete is sourced for the project and the degree to which both are optimized. MKA was able to show carbon footprint reductions of up to 50% for either building type without significantly changing the look or function of the buildings. The most carbon-optimized design actually includes a blend of both materials, utilizing each for their best-performing characteristics.

Start with the Cement

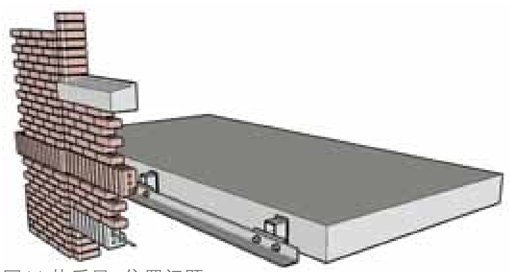

图11 热质量-位置问题

但是其对混凝土性能的影响需要进行评估（图10）。通过使用CCM可以最高实现100%的水泥替换混凝土，但是这并不总是可行的，而且并不是在建筑物内的所有位置都可以采用。CCM是讨论的一个重要内容，但是它们的使用需要慎重考虑。

5.4 热质量——神话和现实

在选择材料种类和使用位置时，需要记住热质量只是在温度变化的位置有助于减少使用能耗要求（图11）。对于没有开启窗扇而由人工控制温度环境的建筑物，楼板体系的能源需求的影响不大。如果采用开启窗扇，特别是在外立面朝向温度变化很大的方向，比如南向的外立面，热质量的作用就很明显。

6 结论

如今的建筑团队投入了更多的可持续设计人员来考虑无水便池甚至何处设置自行车架，而没有考虑内涵碳优化的问题。这些方面固然重要，但是内涵碳分析在解决绿色建筑设计和建筑行业的温室气体减排问题上是一个被忽视的重大的领域。

内涵碳优化并不意味着给可持续性目标带来额外的成本。事实上正好相反。碳优化和材料优化是同一件事。 随着第二阶段运行期碳排放通过更高能效的建筑物和更低碳的能源供应而降低，第一阶段的内涵碳成为需要解决的下一个最重要的碳来源。

内涵碳统计方法最初是因为没有能够准确说明结构构件内涵碳模型而开展起来的。这项工作已经在第一阶段内涵碳统计的信息探索方面迈出了一步，但是它仍然只是全寿命周期碳分析大目标的一部分。（王建业/译，朱晓琳/校）

Within a building, few materials can achieve the same function as concrete. Further, because concrete can often serve multi-function purposes, such as building frame, thermal mass heat reservoir, acoustic and vibration isolation and exposed architectural finish, it can often reduce a potential project’s carbon footprint over other alternatives. However, it is also typically the single-point source of the largest volume of materials and the largest carbon footprint of any single building element. As such, it presents the best opportunity for optimization and reduction in the embodied-carbon footprint.

Implementing new techniques that improve a batch plant’s quality control for the production of concrete have shown cement savings of 20% to 50%—or more—for same-strength mixes. This is an area in need of further study and improvement within the building industry.

“Complementary cementing materials” (or CCMs) can further reduce cement content requirements but can impact the performance of the concrete in ways that need to be evaluated. Up to 100% cement-replacement concrete is possible with CCMs, but it is not always practical and not at all locations in a building. CCM’s are an important part of the discussion, but their use needs to be carefully considered.

Thermal Mass – Myth and Reality

In choosing material types and where to put them, remember that thermal mass only helps reduce operational energy demands at locations where the temperature actually changes. For buildings without operable windows and thermally controlled environments that do not change daily, the floor system building mass does not affect the energy requirements much. However, with operable windows, and especially with surfaces exposed to high temperature changes such as the exterior cladding on southern exposures, thermal mass plays a much larger role.

6 Conclusions

Today’s building teams invest more sustainable-design brainpower considering waterless urinals or where to put bike racks than embodied-carbon optimization. These other items are important, but embodied-carbon analysis can represent a significant missed opportunity when tackling the issues of climate-conscious building design and greenhouse gas reduction.

Embodied-carbon optimization does not mean adding costs to meet a sustainability goal. In fact, it likely means just the opposite. Carbon optimization and material optimization are one and the same. As Phase 2 operating carbon reduces through more energy-efficient buildings and lower-carbon energy supplies, Phase 1 embodied carbon becomes the next and most significant source of carbon to address.

The mentioned embodied-carbon accounting efforts were initially developed out of a frustration of not being able to accurately account for the structural components of embodied-carbon modeling. It has become a step forward in the evolution of information for Phase 1 embodied-carbon accounting, but it remains only one part of a larger goal of full cradle-to-grave life cycle carbon analysis.

DONALD DAVIES

MKA简介

Magnusson Klemencic Associates Inc.（MKA）是一家结构和土木工程设计公司，迄今已有88年的历史。公司总部位于美国西雅图市，在美国芝加哥、沙特阿拉伯利雅得和阿联酋阿布扎比设有分部，其设计工程分布于48个国家和美国47个州。这些项目涉及多种类型和规模，最高项目造价逾20亿美元。MKA近期参加设计的中国项目包括49层的上海21世纪大厦，60层的广州利通广场和12.1万m^2的广州国际体育演艺中心（2010年广州亚运会比赛场馆）。MKA的设计人员按15种建筑类型和22个技术领域分组，以便为客户提供更先进更专业的服务。土木工程部提供项目场地和基础设施设计。MKA在LEED标准建立之前就开始推行绿色设计，是该领域的先行者，始终强调降低材料用量和采用本地建材。MKA在1999年即设计了美国最早5个获得LEED金质认证的项目之一。