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Life Cycle Analysis: Are We There Yet?

生命周期分析：我们达到目标了吗？


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Abstract

To help advance Life Cycle Analysis (LCA) for building systems, this paper reviews the history and state of LCA practice in the U.S. from a structural engineering perspective. The recently released Revit LCA module "Tally" is utilized for case studies of the structural frame of two High-Rise buildings on the West Coast. The implications of LCA use, including its value and limitations, will be discussed.

Keywords: Life Cycle Analysis, EPD, PCR, Tally, Embodied Carbon

摘要

为了推动建筑体系生命周期分析 (LCA) 的发展，本文从结构工程的角度回顾了美国生命周期分析实践的历史和现状。最近发布的Revit生命周期分析模块"Tally"被用于对美国西海岸两幢高层建筑结构主体的案例研究。 文章讨论了使用生命周期分析所带来的影响，包括其价值和限制。

关键词：生命周期分析，环境产品证明，产品类别规则，Tally，内涵碳

Throughout the A/E/C industry, as elsewhere, what is measured gets attention and often becomes targeted for improvement. This is the real significance of Life Cycle Analysis (LCA) and the force behind its emergence as an enhanced sustainable building practice. When at its potential, LCA tracks the consumption and emissions throughout a material or product's life cycle and reports its environmental impact, such as greenhouse gas emissions or global-warming potential. LCA has been used to evaluate buildings for some time. The use of LCA integrated within design decision making, though, has been limited primarily due to a disconnection between the time and effort to produce a detailed LCA and the pace of the building design process. The development of meaningful, but not overly burdensome, LCA is growing, with attention focused on workable tools for the building industry. The concrete, steel, and timber industries have all embraced the concept, with each launching LCA-related initiatives to document the sustainability benefits of their materials, as partially outlined within this paper. BIM modeling and the recent release of Revit's LCA module "Tally™"[1] facilitate real-time evaluation of industry-average LCA data for a range of materials and building products as well as overall building assessment during design. This advancement means LCA is now nearing the point where it can be credibly used during the decision-making process of building design.

纵观建筑/工程/施工行业，与其他行业一样，度量的结果得到关注并且经常成为改进的目标。这是生命周期分析 (LCA) 的真正意义和促使它发展为可持续建筑实践的推动力。生命周期分析具有潜力跟踪材料或产品生命周期中的消耗和排放，并报告其对环境的影响，如温室气体排放和全球变暖潜能。 生命周期分析被用于评估建筑物已经有一段时间。但是在设计决策中的应用是有限的，这主要是因为制定一个详细的生命周期分析需要时间和努力，使其和建筑设计进度脱节。具有实用意义但不繁琐的生命周期分析正在发展，重点应用在建筑行业中。混凝土、钢和木材等行业都已经接受了这个概念，分别起草了与生命周期分析相关的文件，列举本行业材料的可持续性优点。本文对此进行了部分叙述。 BIM建模和近期发布的的Revit的生命周期分析模块"Tally™"[1]使设计过程中根据行业的平均生命周期分析数据对很多材料和建筑产品，以及整体建筑评估的实时生命周期分析变得方便。这个进步意味着目前生命周期分析已接近在建筑设计的决策过程中可以令人信服地使用的程度。

生命周期分析正式始于20世纪90年代，当时国际标准化组织 (ISO) 定义了它的ISO 14044系列，提供了一个通用的生命周期分析方法。 ISO 14044定义生命周期分析为"汇总和评估一个产品系统在整个生命周期的输入，输出和对环境的潜在影响。"生命周期评价方法也已经正式编入英国标准协会的PAS 2050，世界资源研究所协议，及ISO 14067[2]。

在美国，美国检验与材料协会 (ASTM)，国际建筑规范 (IBC) 和LEED最近都深入探讨了

LCA began formalization in the 1990s, when the International Organization for Standardization (ISO) defined its ISO 14044 series, providing a general LCA approach. ISO 14044 defines LCA as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." LCA methods have also been formalized by British Standards Institute's PAS 2050, the World Resources Institute Protocols, and ISO 14067[2].

In the United States, the American Society of Testing and Materials (ASTM), the International Building Code (IBC), and LEED have all recently delved into various facets of LCA in an attempt to provide structure and define relevance of their organization within the field. Architecture 2030's Challenge for Products and the Carbon Leadership Forum are both leading advocates in the application of LCA to the U.S. building industry[3].

LCA is an evolving field, and it would be misleading to imply that all participants have the same objectives. Yet there are more common themes and activities than differences. Within the United States, we are seeing the following structural material supplier initiatives:

- Arcelor Mittal is conducting LCA research for the steel industry through CTBUH, comparing the life-cycle implications of steel, concrete, and composite structural systems in tall buildings to establish a baseline embodied LCA footprint for multiple structural frame alternatives[4].
- The National Ready Mix Concrete Association (NRMCA) is studying the life cycle assessment of concrete buildings[5] and supported the development of the standards for reporting the environmental footprint of concrete, Product Category Rules (CLF, 2013). Central Concrete and Cemex of San Francisco and Cadman of Seattle have all taken industry first-steps to use this standard to create third-party-validated Environmental Product Declarations (EPD's) for their mix designs.
- The masonry industry is in the process of creating EPDs, with the first domestic concrete masonry unit (CMU) EPD published by Angelus Block in January 2014[6]. Several block manufacturers are working on EPDs for a range of CMU unit sizes, colors, and configurations. ASTM has also just issued a draft PCR for Masonry.
- The timber industry is pushing EPDs on several fronts, advocating wood as the lowest-environmental-impact building material available[7].

Several of these groups, though, promote a different set of boundary conditions for LCA. Timber minimizes land-use considerations, such as road building, and the potentially sequestered carbon from letting trees grow beyond 30 years[8]. The World Steel Association assigns what is likely too high of a carbon credit for recycling steel[9]. While the challenges are not yet settled, progress is being made through conversations, refinement, and publication of production impacts by material type.

[1] http://choosetally.com/now, Kieran Timberlake, 2013
[2] http://lcacenter.org/lcaxiii/final-presentations/964.pdf (www.lcacenter.org)
[3] http://architecture2030.org/2030_challenge/products (architecture2030.org)
[4] http://www.ctbuh.org/TallBuildings/ResearchDivision/ArcelorMittalResearchProject/tabid/3976/language/en-US/Default.aspx (ctbuh.org/ … /ArcelorMittalResearchProject)
[5] LEMAY, L. (2011) Life Cycle Assessment of Concrete Buildings; Lionel LeMay, P.E., S.E., LEED AP, Sr. VP, Sustainable Development, NRMCA, October, 2011.
[6] http://www.angelusblock.com/news.cfm
[7] http://www.awc.org/greenbuilding/epd.php

生命周期分析的各个方面，试图提供结构和界定与该领域的相关性。2030建筑产品的挑战组织和碳领袖论坛是把生命周期分析在美国建筑行业应用的两个主要倡导者[3]。

生命周期分析是一个不断发展的领域，认为所有参与者都有相同的目标会是一个误解。然而，共同的主题和活动远大于分歧。在美国，我们知道的有如下的结构材料供应商的倡导:

- 阿塞洛-米塔尔通过CTBUH正在开展钢铁行业生命周期分析研究，比较钢材，水泥和复合结构体系在高层建筑的生命周期影响，以建立多种结构方案的生命周期分析足迹基准[4]。
- 全国商品混凝土协会 (NRMCA) 正在研究混凝土建筑物的生命周期评估[5]，并支持制定混凝土对环境的影响足迹标准，产品类别规则 (CLF，2013年)。圣弗朗西斯科的Central Concrete和Cemex公司以及西雅图的Cadman公司已经在业界率先使用这个标准，由独立的第三方据此为其混凝土配合比设计进行认证并颁发环境产品证明 (EPD's)。
- 砌体业正在制订环境产品证明，2014年1月Angelus Block公司发布了美国第一个混凝土砌块 (CMU) 环境产品证明[6]。有些混凝土砌块制造商正在根据砌块尺寸、颜色和形状制订环境产品证明。美国检验与材料协会也刚刚颁布了砌块产品类别规则草案。
- 木材行业正在在几个方面推动环境产品证明，倡导木材是对环境影响最小的建设材料[7]。

但是，这些团体推荐不同的生命周期分析边界条件。木材行业尽量减少对土地使用的考虑，如道路建设，和让树木生长超过30年潜在的封存碳[8]。国际钢铁协会给予钢材回收可能过高的碳信用分值[9]。尽管面临的挑战仍未解决，目前正在根据材料种类通过对话，细化，和制定出版等措施在解决的道路上取得进展。

如何衡量影响?

对于首次接触生命周期分析者，有几个术语有助于理解产品类别规则 (PCRs)。这些术语是为了制定环境产品证明 (EPD) 而定义特定行业的测量的指南。产品类别规则提供环境产品证明结果报告所要求的结构[10]。

类似于食品的营养标签，一份环境产品证明说明该产品在其预期寿命中对环境的影响。环境产品证明宜由第三方认证，并在完成后公开发布。环境产品证明和相应的产品类别规则至少宜符合ISO 14025和21930，并全文公布[11]。

大多数的生命周期分析建模方法至今专注于一次性建筑核查。多数设计相关的生命周期分析只选取设计过程中一个时间点的建筑信息，缺乏完成状态的实际细节。其他建模方法在项目完成时采集数据，但是对建筑设计过程中的决策没有实际影响。

我们发现最好的方案是多阶段生命周期分析模型，类似项目的成本估算工作。这个模型始于设计阶段的生命周期分析估算。估算是根据该项目的BIM模型和/或承包商的项目概预算，使用行业平均生命周期分析数据，例如PE International的GaBi数据库[12].这种设计阶段的分析提供了一个含有所有建筑组成部分的"模糊的第一张照片"，但缺乏详细的精度。因为它只是基于行业平均的数据信息。在设计的早期阶段，具体的材料供应商和承包商通常尚未确定。然而，这张"照片"对于较小的和难以追踪的事项提供了足够的细节，也可以作为在特定设计中的指南，以确定进一步深入研究对环境影响的对象。生命周期分析建模的最佳应用应是不断提高精度的迭代过程。

How Should Impacts be Measured?

For those first stepping into the LCA field, there are several terminologies that are useful to understand Product Category Rules (PCRs) are guidelines that define industry-specific measurements agreed to for the purpose of producing an Environmental Product Declaration (EPD). PCRs provide the structure needed to report the results of EPDs[10].

An EPD declares the environmental impacts of a product over its expected life, similar to a nutrition label on food. An EPD should be third-party verified and publicly published upon completion. An EPD and the respective PCR should, at a minimum, be compliant with ISO 14025 and 21930 and be posted in their entirety[11].

Most LCA modeling approaches to date focus on a one-time building review. Most design-related LCAs to date capture a snapshot during design but lack the detail of what actually gets built. Other modeling approaches look back when a project is done and capture final built data, but do not actually impact decisions made during building design.

The best option we found to date is multi-phase LCA modeling, similar to a project's cost estimating effort. This modeling starts with a design LCA estimate, based upon the project BIM model and/or the contractor's early cost estimate, and utilizes industry-average LCA data, such as the GaBi databases by PE International[12]. This design-phase analysis provides a "fuzzy first picture" of all building components but lacks detailed accuracy as it can only be based upon industry-averaged information. The specific material suppliers and contractors are generally not known during early stages of design. It does, however, provide sufficient detail for smaller and harder-to-track items, as well as guidance on where to focus a more detailed investigation for the environmental impacts within a specific design. LCA modeling at its best can then become an iterative process of increasing accuracy.

It is important to not stop with the initial design LCA model. The LCA footprint of large volume and energy-intensive items, such as steel or concrete, can vary widely depending upon source and production, influencing final LCA results by 30% or more. These largest and most statistically relevant carbon sources require a more detailed investigation to achieve a relevant structural LCA.

Tally

Tally is a just-released LCA module for Revit® software to quantify the environmental impact of building materials for whole-building analysis as well as comparative analyses of design options. While working on a Revit model, the user can define relationships between BIM elements and construction materials from the Tally database, which relies on GaBi databases from PE International. The result is a design-level LCA that helps with decision making as the building design moves forward[13].This new LCA tool is a major advancement, greatly simplifying initial LCA project modeling.

[8] PUETTMANN, M. (2013) Cradle to Gate Life Cycle Assessment of Glue-Laminated Timbers Production from the Southeast, Maureen Puettmann, WoodLife Environmental Consultants, LLC, January 2013.
[9] https://www.worldsteel.org/publications/position-papers/lca.html
[10] http://www.carbonleadershipforum.org/epds-and-pcrs.html
[11] http://architecture2030.org/about/products_faq#EPD
[12] http://www.gabi-software.com/america/databases/

切不可止步于最初的设计生命周期分析模型。体积大和耗能高材料-如钢或混凝土，的生命周期分析足迹根据其来源和生产情况会大幅度波动，影响最终的生命周期分析结果30%甚至更多。这些用量最大并与统计最相关的碳源需要更详细的研究，以实现相关的结构生命周期分析。

Tally

Tally是Revit®软件刚发行的一个生命周期分析模块，用于数量化分析建筑材料的环境影响，可以用于整个建筑的分析，也可以用于设计方案的比较分析。使用Revit模型时，用户可以定义BIM构件和Tally数据库中建筑材料之间的关系。后者是基于PE International的GaBi数据库。其结果是一个设计阶段的生命周期分析，在设计推进过程中提供决策帮助[13]。这个新的生命周期分析工具是一个重大的进步，大大简化了初期的生命周期分析项目的建模工作。

Tally只能采用模块自身数据库中的产品信息进行生命周期分析建模和分析。目的是保证输出的生命周期分析结果的质量和可靠性。面对海量并在不断增长的数据，模块在处理项目指定和独特材料，如项目的具体混凝土配合比设计时，就受到限制。对于这种情况，Tally输出一个电子表格格式的材料用量表，以便用户在模块之外自行进行数据处理。

由于本文案例研究的项目设计时Tally模块还没有发行，其设计决策过程中没有使用这种生命周期分析模型。但是，案例中的数据已经被用来研究Tally的功能和精度，并将结果用来建立用于未来项目的基准。

案例研究中生命周期分析的第二阶段工作包括对结构主体最主要的部分，即混凝土配合比设计和钢筋，用项目的具体环境产品证明和其他项目特定的数据替代Tally模块中的行业平均数据。然后对结果进行评估，以检查Tally初始模型的有效性，建立美国西海岸两个城市高层混凝土结构生命周期分析的基准，并确定需要进一步研究的问题。

生命周期分析案例研究

第1阶段 – 设计阶段生命周期分析

本文采用了两阶段的生命周期分析方法。第一阶段使用Tally和项目的BIM模型产生设计过程中项目对环境影响的初步评估。我们采用了初步设计阶段成果进行第1阶段代表性的生命周期分析。

第2阶段 – 施工阶段生命周期分析

第2阶段的生命周期分析包括从案例研究项目的结构材料供应商处获取项目具体的环境产品证明和最新的结构材料用量。当没有环境产品证明 (如钢筋) 时，我们则关注材料的内含碳并要求制造地点信息进行从产地到出厂的研究。

两个案例研究中均进行了2个阶段的分析。案例研究的项目由Magnusson Klemencic Associates设计，其生命周期分析的研究范围仅限于主体结构。

案例研究项目A，加里福利亚州圣弗朗西斯科市

案例A项目位于加州圣弗朗西斯科市，由四幢住宅楼和五层地下停车场组成 (见图1) 。两幢住宅塔楼分别为42和37层，高度122和107米。该项目包括新建14万平方米。团队包括铁狮门 (

Tally does not provide the ability to directly model LCA data for anything other than products specified within its database. This is done to control the quality and reliability of the LCA data being reported by Tally. While the database is quite extensive and growing, this creates a limitation when attempting to identify project-specific and unique material traits, such as project-specific concrete mix designs. Tally does, however, provide a bill of quantities output within an Excel spreadsheet, allowing for data manipulation outside of Tally.

Since Tally was not available until after the case study projects of this paper were already designed, LCA modeling was not used to inform decisions during design. The data from these case studies have been used to investigate Tally's abilities and accuracies and establish a benchmark baseline for future projects.

The second-phase LCA of the case studies involved replacing Tally's industry-average inputs with project-specific EDPs and other project-specific data for the most significant parts of the structural frames, namely the concrete mix designs and rebar. The results were then evaluated to check the validity of Tally's initial modeling, create baseline LCA data for High-Rise concrete structures in two U.S. West Coast cities, and identify areas for further research.

LCA Case Studies

Phase 1 – Design-Phase LCA

This paper used a two-phase LCA process. Phase 1 involved using Tally and the project's BIM model for a preliminary view of the project's environmental impact during design. We utilized Design Development information for the Phase 1 representative LCA.

Phase II – Construction-Phase LCA

The Phase II LCA included reaching out to the structural material supply subcontractors for the case study projects and requesting project-specific EPDs and up-to-date quantities for what actually was going into the buildings. When EPD's were not available (i.e., rebar), we focused on the embodied carbon of the materials and solicited information on points of manufacturing for a cradle-to-gate study.

Both phases were implemented for the two case-study buildings, which were designed by Magnusson Klemencic Associates. The scope of the LCA studies focused solely on the structure.

Case Study Project A, San Francisco, California

Case Study Project A in San Francisco, California, is comprised of four residential buildings with five levels of below-grade parking (see Figure 1). There are two residential towers, 42 and 37 stories and 122 and 107 meters (400 and 350 feet), respectively. The project includes 140,000 square meters (1.5 million square feet) of new development. The team includes Tishman (owner), Arquitectonica (architect), Lend Lease (general contractor), and Webcor Concrete (structural frame supplier). The project broke ground in June 2013 with completion expected in June 2015.

The project features reinforced mat foundations of variable thickness. The lateral-force-resisting system for the tower and plaza structures include coupled concrete shear walls placed around central elevator and stair cores. The columns and basement walls are reinforced concrete, as are the below-grade, at-grade, amenity-level, and podium-level slabs.

[13] http://choosetally.com/

业主)，Arquitectonica公司(建筑师)，Lend Lease (总承包)，以及Webcor Concrete (结构主体供应商)。项目于2013年6月破土动工，预计2015年6月建成。

项目采用不同厚度的筏板基础。塔楼和广场结构的侧向力体统为布置在中央的电梯井筒和楼梯间的钢筋混凝土剪力墙。地下室墙、柱，以及地下室、首层、设备层和裙房层楼板为钢筋混凝土。标准住宅楼板为8英寸后张预应力无梁楼盖。

案例研究项目A – 材料

设计要求的混凝土圆柱体强度从杂项混凝土f'c=20 MPa(3,000 psi)，到筏板基础56天强度f'c=40 MPa(6,000 psi)，柱和剪力墙28天强度40-55 MPa(6,000-8,000 psi)不等。后张预应力楼板混合了72小时强度f'c=29 MPa(3,000 psi)，28天强度38 MPs(5,500 psi) (见图2和3)。

在要求项目的混凝土配合比设计的环境产品证明时，CEMEX公司以湾区另一家供应商为例，同意成为美国第一个根据批次提供独立认证的环境产品证明的混凝土供应商。圣弗朗西斯科的Climate Earth公司为CEMEX编制了环境产品证明 (见图4)。

表1示该项目标准混凝土配合比设计。表2示环境产品证明涵盖的环境影响准则

同样也要求钢筋供应商提供环境产品证明，但他们推脱在美国钢筋产品类别规则更好地建立和为业界所接受前，采用行业平均值。然而，了解了钢筋生产厂商所在地，考虑工厂供电，产品运输过程和距离的碳足迹，项目具体的核算也是可能的。模板材料也做了估算。假设模板为1/2英寸夹合板，可以重复使用10次。其对环境的影响根据美国木材委员会制定的北美软木夹合板环境产品证明估算。

案例研究项目A – 第1阶段生命周期分析

Tally是第1阶段生命周期分析工具。Tally研究使用Revit模型的混凝土数量，和PE International Gabi数据库中的用户选择的混凝土配合比 (见图5)。

Figure 1. Case Study A – San Francisco, CA (Source: Arquitectonica)
图1. 案例研究A – 加州圣弗朗西斯科市 (Arquitectonica提供

Figure 2. Revit Model for Case Study A (Source: Magnusson Klemencic Associates)
图2. 案例研究A的Revit模型 (Magnusson Klemencic Associates提供)

A typical residential level consists of 8-inch post-tensioned flat slabs.

Case Study Project A – Materials

The design-required concrete cylinder strengths vary from f'c = 20 MPa (3,000 psi) for miscellaneous concrete to f'c = 40 MPa (6,000 psi) at 56 days in the mat foundation and 40-55 MPa (6,000-8,000 psi) at 28 days for the columns and shear walls. The PT slab mixes are f'c = 29 MPa (3,000 psi) at 72 hours and 38 MPs (5,500 psi) at 28 days. (See Figures 2 and 3.)

In requesting EPDs for the project's mix designs, CEMEX followed the lead of another bay area supplier and agreed to become one of the first concrete suppliers in the U.S. to prepare independently verified, batch-plant-specific EPDs for their mixes. Climate Earth in San Francisco developed the EPDs for CEMEX (see Figure 4).

Table 1 presents the typical mix designs provided for the project. Table 2 shows environmental impact criteria covered within the EPD.

EPD information was requested from the rebar suppliers, but they deferred to industry average values until the PCR for rebar in U.S. is better established and industry accepted. However, knowing the mill location for the rebar produced, project-specific accounting was possible by considering the electrical-supply carbon footprint to the mill and transportation processes and distances. Variation in formwork materials was also estimated. Formwork assumed 1/2-inch plywood forming with 10 cycles of re-use before replacement. The environmental impacts were based on the EPD for North American Softwood Plywood as created by the American Wood Council.

Case Study Project A – Phase I LCA

Tally was the tool of choice for the initial Phase I LCA. The Tally study included the modeled concrete quantities in Revit, using a user-selected concrete mix from the PE International Gabi database (see Figure 5).

For the purposes of this study, the global warming potential (in units of kilograms of CO_2 equivalent) was used for a more detailed focus (see Figure 6).

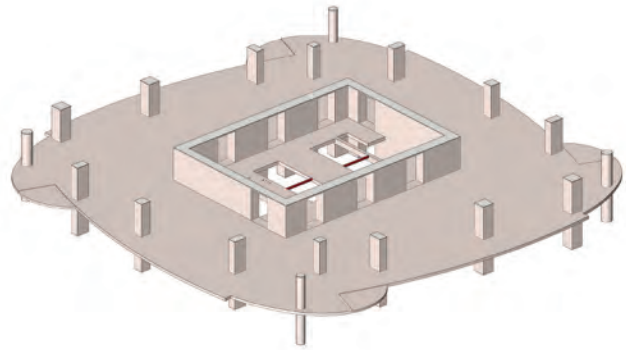

Figure 3. Typical Tower Floor (Source: Magnusson Klemencic Associates)
图3. 塔楼标准层平面 (Magnusson Klemencic Associates提供)

Environmental Product Declaration

This Environmental Product Declaration (EPD) covers twelve concrete mixes produced by CEMEX at the Pier 92 plant in San Francisco, California.

Company

CEMEX is a global building materials company that provides high quality products and reliable service to customers and communities throughout the Americas, Europe, Africa, the Middle East, and Asia. We produce, distribute, and sell cement, ready-mix concrete, aggregates, and related building materials in more than 50 countries, and we maintain trade relationships in close to 100 nations.

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LCA and EPD Developer:
Visrin Vichit-Vadakan and Rick Betita • Climate Earth, Inc. • 415-391-2725 •
www.climateearth.com

Date of Issue: March 11, 2014 **Period of Validity:** 5 Years (until March 11, 2019)

The Carbon Leadership Forum PCR: *North American Product Category Rules (PCR) for ISO 14025 Type III Environmental Product Declarations (EPDs) for Concrete*, Version 1.1 dated 12/4/2013, serves as the PCR for this EPD.
www.carbonleadershipforum.org

Independent verification of the declaration, according to ISO 14025:2006:
☐ internal ☒ external

Independent Verifier:
[TBD]

Figure 4. CEMEX-Produced Environmental Product Declaration for a Majority of the Concrete Mixes Used (Source: CEMEX)
图 4. CEMEX提供的用于大部分混凝土配比的环境产品证明 (CEMEX提供)

Mix Number 混合 编号	Compressive strength @ 28 days (psi) 压强 @28天 (psi)	Slump (in) 塌落高度 (in)
1564704	5,000	2
1412543	3,000	4
1412569	4,000	4
1412602	5,000	4
1412664	6,000	4
1412671	6,000	4
1412675	5,500	4
1412674	5,500	4
1529616	6,000	9
1412679	6,000	9
1412570	4,000	4
1412577	4,000	4

Table 1. Mixes with EPDs Prepared (Source: CEMEX)
图1. 带环境产品证明的混凝土配比 (CEMEX提供)

Impact category	Unit	Abbreviation	Impact assessment method
Life cycle inventory items			
Non-renewable primary energy consumption	MJ	nPE	Cumulative Energy Demand
Renewable primary energy consumption	MJ	rPE	Cumulative Energy Demand
Total primary energy consumption	MJ	tPE	Cumulative Energy Demand
Concrete batching water consumption	m^3	bCW	
Concrete washing water consumption	m^3	wCW	
Total concrete water consumption	m^3	tCW	
Non-renewable material resource consumption	kg	nMR	
Renewable material resource consumption	kg	rMR	
Hazardous waste production	kg	hWP	EDIP 2003
Non-hazardous waste production	kg	nWP	EDIP 2003
Impact categories			
Global warming potential	kg CO_2-eq	GWP	TRACI 2.1
Ozone depletion potential	kg CFC-11-eq	ODP	TRACI 2.1
Acidification potential	kg SO_2-eq	AP	TRACI 2.1
Eutrophication potential	kg N-eq	EP	TRACI 2.1
Photochemical ozone creation potential	kg O_3-eq	POCP	TRACI 2.1

Table 2. Required Environmental Impact Categories Included in CEMEX EPDs (Source: CEMEX)
图2. CEMEX环境产品证明中的环境影响等级 (CEMEX提供)

Important observations can be made from the Tally Phase I LCA results. First, the majority of the embodied carbon is found in the floor slabs. The next largest contributors are the foundation elements and core walls. In an effort to make the greatest impact on reducing embodied carbon in buildings, focusing reduction efforts proportionally to this distribution will yield the greatest results.

A second observation is that reducing concrete and rebar quantities through design optimization can have a very significant impact on reduction of carbon footprint. The two-stage LCA process is a way for design optimization, or lack thereof, to be accounted for within a sustainability review of the project.

Case Study Project A – Phase II LCA

For the phase II LCA, rebar quantities were updated from DD levels to values from a final contractor quantity take-off of the structural drawings, resulting in a 5% reduction in rebar. EPD values reported by CEMEX were also incorporated for a more accurate representation of true carbon footprint attributable to concrete (see Figure 7).

Despite variations between DD for final project quantities and industry average to final EPD concrete information, the Tally Phase I LCA agrees very closely with the Phase II LCA with project-specific EPDs. This suggests that the concrete mixes used on this project are on par with the industry-average values in Tally's database. It is important to note that while the structure's design was optimized to be as efficient as possible, carbon content was not a criterion in selecting the mixes used.

Case Study Project B, Seattle, Washington

Case Study Project B is a new 134-meter- (440-foot-) tall, 47,800-m² (515,000-ft²) performance-based seismic design of a 40-story apartment tower in downtown Seattle, Washington (see Figure 8). The project team includes GID Development (owner), Weber Thompson (architect), and Sellen (general contractor). The primary structural system is comprised of mild concrete slabs from basement to Level 5, which houses garage and retail space. Eight inch concrete post-tensioned slabs are provided at the remaining residential floors. The building's lateral system consists of a single concrete core rising the full height of the building. While primarily a concrete frame, a modest amount of structural steel and metal decking are used for elevator spreader beams, canopies, mechanical screens, and a leasing office. Construction began in August 2013, and completion is scheduled for December 2014.

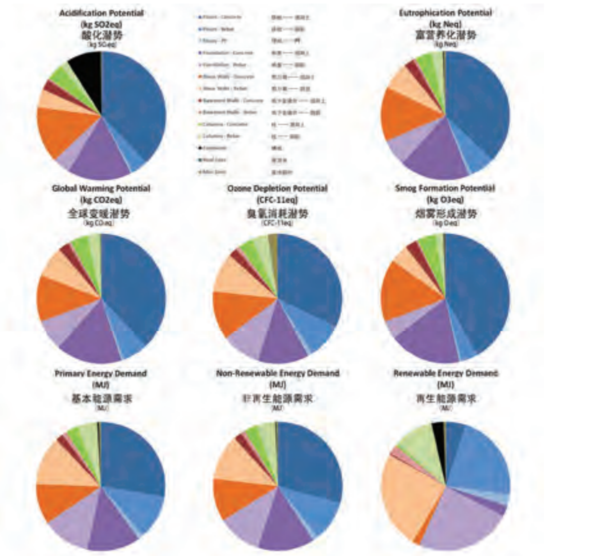

Figure 5. Environmental Impact Categories Reported from Tally (Source: Magnusson Klemencic Associates)
图5. Tally的环境影响等级报告 (Magnusson Klemencic Associates提供)

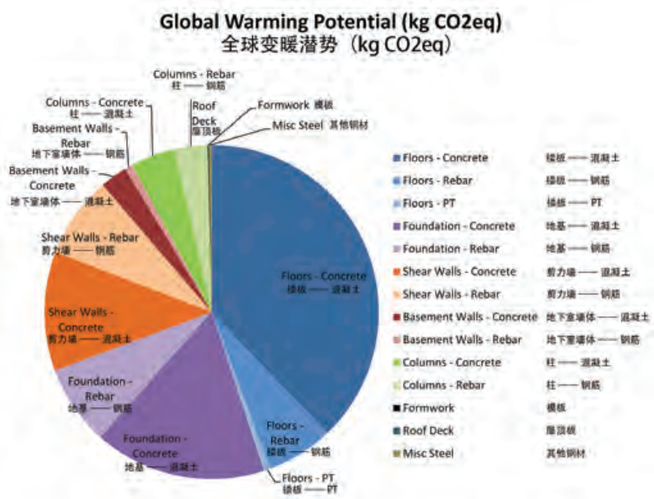

Figure 6. Global Warming Potential from LCA Performed with the Assistance of Tally (Source: Magnusson Klemencic Associates)
图6. 采用Tally作为辅助工具产生的生命周期分析的全球变暖潜势 (Magnusson Klemencic Associates提供)

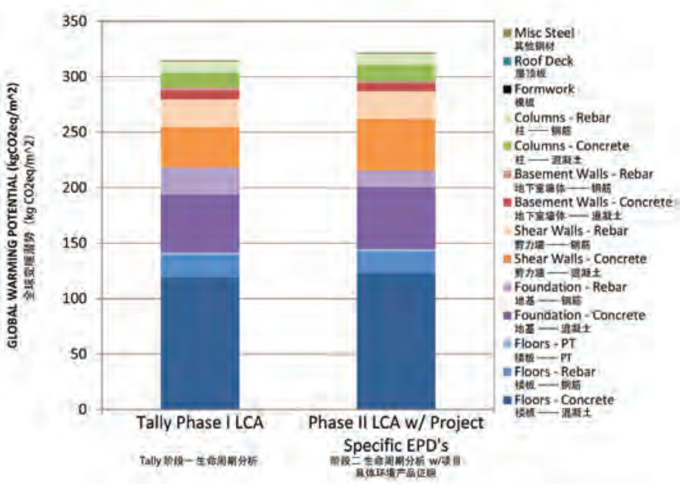

Figure 7. Case Study A – Phases I and II LCA Global Warming Potential Comparison (Source: Magnusson Klemencic Associates)
图7. 案例研究A – 第1阶段和第2阶段生命周期分析全球变暖潜势比较 (Magnusson Klemencic Associates提供)

Figure 8. Case Study B – Seattle, WA (Source: Weber Thompson)
图8. 案例研究B – 华盛顿州西雅图市 (Weber Thompson提供)

Case Study Project B – Materials

Concrete, rebar, and post-tensioning comprise the majority of project materials. The project mixes have 28-day specified cylinder design strengths of 27 MPa (4,000 psi) for basement walls, slabs on grade, and concrete on steel deck; 35 MPa (5,000 psi) for the mat foundation, mild reinforced slabs, and beams; 38MPa – 45 MPa (5,500 to 6,500 psi) for the post-tensioned slabs and beams; and 56-day strengths of 48-83 MPa (7,000-12,000 psi) for the columns and shear walls.

Case Study Project B – Phase I LCA

The Phase I LCA for Case Study Project B followed the same process as Case Study Project A. The structural systems for the two projects are similar, and the observations of carbon content per building component made at this phase mirror those of Study A (see Figure 9).

Case Study Project B – Phase II LCA

As part of this study, concrete material supplier CADMAN prepared preliminary EDPs for the 8- and 10-ksi mixes. CADMAN is in the process of providing third-party-validated EPDs for the balance of the project's concrete mixes (as the first concrete EPDs in the state of Washington), but the process is still ongoing. The preliminary EPDs were incorporated for this comparative study.

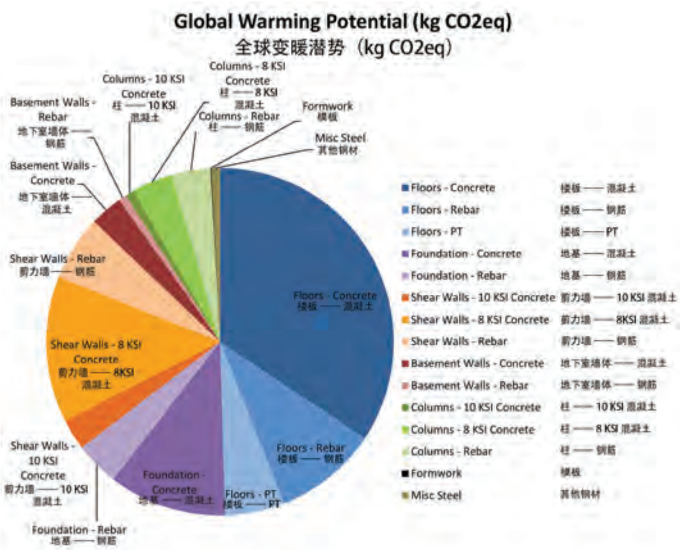

Figure 9. Global Warming Potential from LCA Performed with the Assistance of Tally (Source: Magnusson Klemencic Associates)
图9. 采用Tally作为辅助工具产生的生命周期分析的全球变暖潜势 (Magnusson Klemencic Associates提供)

根据本研究的目的，使用全球变暖潜势 (以等效二氧化碳公斤为单位) 作为更详细的重点 (参见图6) 。

从Tally第1阶段生命周期分析结果得到如下重要发现。首先，大多数内涵碳来源于楼板构件。下一位的来源是基础和核心筒墙。在试图减少建筑物内含碳的努力中，相应以上来源的比例分配精力将取得最大的效果。

其次，通过设计优化减少混凝土和钢筋用量对减少碳足迹的作用非常显著。两阶段生命周期分析过程是一种设计优化方法，或着退一步说，项目可持续性设计的审阅。

案例研究项目A – 第2阶段生命周期分析

在第2阶段生命周期分析中，用最终结构图纸合同钢筋用量替代初步设计阶段的钢筋用量，钢筋用量减少5%。同时，使用CEMEX提供的环境产品证明数据，以得到更准确的混凝土实际所含的碳足迹 (参见图7) 。

尽管初步设计阶段和项目最终的混凝土用量不同，工业平均值和最终混凝土环境产品证明数据也不同，Tally第2阶段生命周期分析结果与采用项目材料环境产品证明的第2阶段生命周期分析结果非常接近。这表明在这个项目中使用的混凝土配比接近Tally数据库中的行业平均值。值得注意的是，虽然结构设计进行了优化以使其尽可能高效，在选择混凝土配比时，碳含量并没有设定为一个标准。

案例研究项目B，华盛顿州西雅图市

案例研究项目B是华盛顿州西雅图市中心一个新建40层公寓，高134米，建筑面积47,800平方米，采用性能化抗震设计方法设计 (参见图8) 。项目团队包括GID Development (业主) ，Weber Thompson (建筑师) ，和Sellen (总承包商) 。地下室至5层为停车场和商业，采用钢筋混凝土楼板。其余的住宅楼层为8英寸后张法预应力混凝土楼板。侧向力体系为全高的钢筋混凝土核心筒。项目也使用了部分钢结构和压型钢板，用于电梯吊梁，雨蓬，设备格栅，和物业办公室。2013年8月开始施工，计划2014年12月完工。

案例研究项目B – 材料

项目结构材料主要是混凝土，钢筋和后张预应力主辅材。混凝土圆柱体强度为地下室墙、地面铺装、压型钢板楼板28天强度27 MPa(4,000 psi); 筏板基础、钢筋混凝土梁板35 MPa(5,000 psi); 后张预应力梁板38 MPa–45 MPa(5,500 to 6,500 psi); 柱和剪力墙56天强度48-83 MPa(7,000-12,000 psi)。

案例研究项目B – 第1阶段生命周期分析

案例研究项目B的第1阶段生命周期分析方法与案例研究项目A相同。两个项目的结构相似，在这个阶段发现的各种部件碳含量情况与案例研究项目A相同 (见图9) 。

案例研究项目B – 第2阶段生命周期分析

作为这项研究的一部分，混凝土供应商CADMAN为8-和10-ksi混凝土配比准备了初步环境产品证明。 CADMAN正在为项目的其余混凝土提供第三方认证的环境产品证明 (华盛顿州的第一个混凝土环境产品证明) 的过程。但这个过程仍在进行中，所以在这个比较研究中使用了初步环境产品证明。

要求提供钢筋和后张预应力材料的环境产品证明，但是没有得到。所以，对生产厂商所在地供电的碳足迹，运输和模板材料变化做了估算。假设模板为1/2英寸夹合板，可以重复使用10次。钢筋是由Nucor的西雅图厂制造，其显著优于行业平均水平，如结果所示。该工厂位于西雅图市范围内，所用的钢筋有90%的再生

EPD information was requested but not provided for the reinforcement and PT used on the project. However, accounting for the electrical supply carbon footprint at the point of manufacturing, transportation, and variations in formwork materials was estimated and incorporated. Formwork assumes 1/2-inch plywood forming with 10 cycles of re-use before replacement. Reinforcing bar is being supplied by Nucor's Seattle mill, a plant with significantly better-than-industry averages, as reflected in the results. The mill is within Seattle city limits, the rebar used has 90% recycled content, and the mill's electrical supply is approximately 95% hydro power (see Figure 10).

The Phase II LCA shows significantly lower embodied carbon relative to the Phase I study. This is in part due to the significantly lower embodied carbon in the reinforcing from the Nucor plant relative to the values assumed by Tally and the favorable aggregate supply in the CADMAN mix designs. Aggregate is a major variable that affects the cement content requirement of concrete mixes. Figure 11 highlights the column and shear wall variances from the Tally to EPD-specific information.

The CADMAN 10-ksi mix reports roughly 10% lower embodied carbon relative to the Tally database, while the 8-ksi mix reports a 25% lower embodied carbon. The embodied carbon of Nucor's Seattle plant is roughly 1/6 that of the values found in Tally.

Conclusions

LCA is not an exact science. It includes numerous variables that make proper assessment of the environmental impacts embodied within our built environment a challenge. To fully take hold, it is imperative that the LCA process be kept simple and easy to understand by the general public. New tools such as Tally are a major step forward for LCA, providing simplicity with increased accuracy. Since Tally is only as accurate as the project's Revit model and industry-average information, the onus is on the design team to maintain an accurate model, and to take steps in post processing to capture construction-stage input. As EPDs become more prevalent, thanks in part due to LEED v4, the quality of LCA information will become clearer.

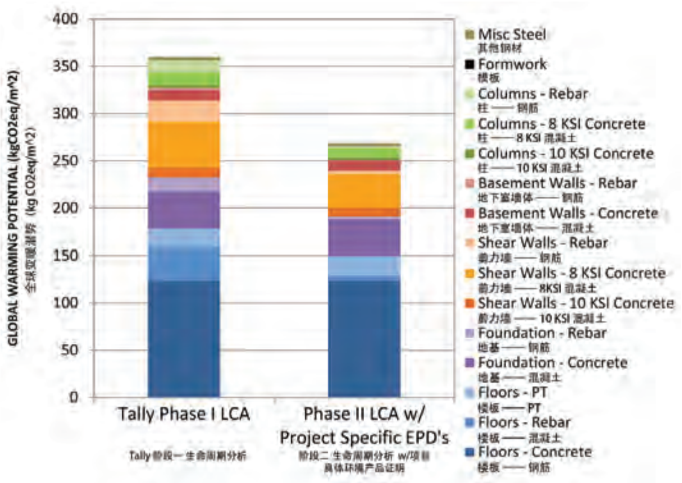

Figure 10. Case Study B – Phases I and II LCA Global Warming Potential Comparison (Source: Magnusson Klemencic Associates)
图10. 案例研究B –第1阶段和第2阶段生命周期分析全球变暖潜势比较 (Magnusson Klemencic Associates提供)

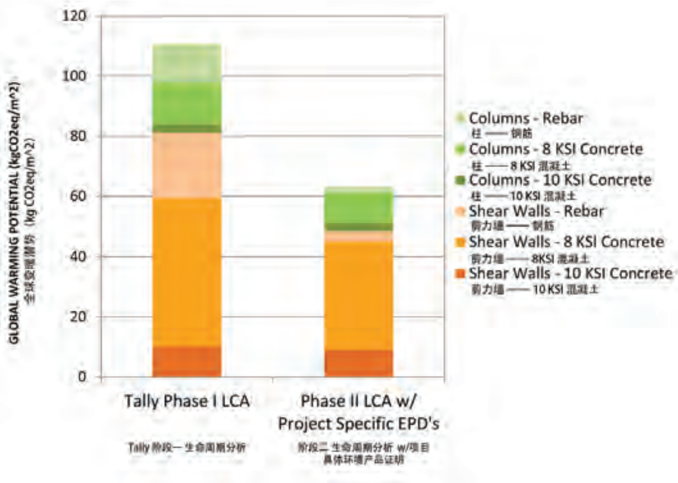

Figure 11. Case Study A – Phases I and II LCA Comparison – Columns and Shear Walls (Source: Magnusson Klemencic Associates
图11. 案例研究A – 第1阶段和第2阶段生命周期分析 – 柱和剪力墙 (Magnusson Klemencic Associates提供)

含量，并且工厂的电力供应约95%来自水力发电 (参见图10) 。

第2阶段生命周期分析结果的内涵碳明显低于第1阶段的结果。这部分是由于Nucor厂提供的钢筋的内涵碳明显低于Tally数据库中的数值，以及CADMAN提供的混凝土骨料较好。骨料是影响混凝土混合料中水泥含量的一个主要变量。图11表示了采用Tally和具体环境产品证明信息时柱和剪力墙内涵碳的变化。

CADMAN 10-ksi混凝土的内涵碳比Tally数据库约低10%，8-ksi混凝土的内涵碳低25%。Nucor西雅图工厂钢筋的内涵碳大约是Tally数据的1/6。

结论

生命周期分析不是一门精确的科学。它包括很多变量，使得正确地评估建筑的环境影响成为一个挑战。为了充分把握，当务之急是使生命周期分析的过程相对于普通大众简单易懂。新的工具，如Tally,提供了简单和更高的精度,使生命周期分析前进了一大步。由于Tally的准确度取决于项目的Revit模型和行业平均水平的信息，设计团队应建立和保持一个准确的模型，并采取必要的后处理步骤，获得施工阶段的信息。随着环境产品证明越来越被接受,生命周期分析信息的质量将变得更准确。这将归功于第4版LEED.

环境产品证明的采纳仍处于形成阶段，可以得到的结构材料环境产品证明很有限。在美国，混凝土，砌块和木材供应业正在迅速接受环境产品证明。而钢材供应业，除了阿塞洛-米塔尔公司从欧洲提供了信息，正在研究环境产品证明，但还没有完全接受。总的来说，所有环境产品证明的共同边界条件还没有形成共识。

由于生命周期分析的发展，它越来越接近成为设计决策过程可行的一部分。Tally把Gabi数据库整合进Revit，使之前进了一大步。但是，获得准确的生命周期分析信息，仍需要更多的和标准化的环境产品证明，并且生命周期分析评估需要包括至少两个阶段的过程，才能与项目设计过程联系在一起。

The production process for EPDs is still formative, with limited EPDs available for structural materials. Within the United States, the concrete, CMU, and timber supply industries are moving quickly to address EDPs, while the steel supply industry, with the exception of Arcelor Mittal's input from Europe, is studying EDPs but has yet to fully embrace them. Collectively, common boundary conditions for all of these EPDs have not been representatively agreed upon.

As the LCA process evolves, it gets closer to becoming a viable part of the design decision-making process. Tally is a major step forward, with the integration of Gabi databases into Revit. Accurate LCA information, though, still requires more and standardized EPDs, and the LCA evaluation process needs to include at least two phases for the process to become relevant to the project design process.

While LCA is not yet a regular tool within the design process, that time is not far off. Tally simplifies execution, and LCA case studies are greatly expanding our industry knowledge base. Beyond Tally, further information on the latest developments within LCA processes can be found within the recently published Life Cycle Assessment textbook[14], by Kate Simonen, Director of the Carbon Leadership Forum. This is suggested reading for those interested in further updates on the current state of the LCA field of practice.

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虽然生命周期分析还没有成为设计过程中的日常工具，但是那个时间已经不远了。Tally简化了分析过程，生命周期分析案例研究极大地扩展我们行业对之的理解。除了Tally之外，关于生命周期分析发展的进一步信息可以参见最近发表的生命周期评估课本[14]，作者是碳领袖论坛理事Kate Simonen。建议对生命周期分析实践的发展和现状感兴趣者阅读此书。

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[14] http://www.carbonleadershipforum.org/blog/lca-book-published.html