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Vertical Futures: Technologies That Will Shape the World

垂直未来：科技将改造世界

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An architect of innovative supertall towers and future cities, David Malott pioneered a global portfolio of iconic smart buildings as a design principal at KPF, including three of the world's ten tallest towers. Malott heads the design of the 600-meter-tall Ping An Finance Center rising in Shenzhen, China's fastest growing megacity and global innovation hub. He is the current Chairman of the Council on Tall Buildings and Urban Habitat, where he leads the CTBUH technologies research project, Vertical Futures.

David Malott是创新超高层建筑和未来城市建筑师，并作为KPF设计总裁开创了全球标志性智能建筑，包括世界十大最高建筑中的三座。Malott领导设计了位于深圳的600米高的平安金融中心，而深圳是中国发展最快的巨型城市以及全球创新中心。他现任世界高层建筑与都市人居学会主席，领导CTBUH有关垂直未来的技术研究项目。

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A multi-talented designer and aspiring futurist, Jordan Feinstein operates at the cutting-edge of architectural innovation and research. His exploration into the disruptive effects of technology in traditional architectural and urban processes led him to participate in the CTBUH Vertical Research projects, where he has played a lead role to investigate state-of-the-art technology in tall buildings and urban habitats.

Jordan Feinstein是一位多才多艺的设计师以及胸怀抱负的未来主义者，他位于建筑创新和研究的前沿。他对传统建筑和城市过程中技术破坏性影响的探索使他加入CTBUH垂直研究项目，其中他在高层建筑和城市栖息地的最先进技术的研究中起到了主导作用。

CTBUH Research Project
CTBUH研究项目
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Abstract | 摘要

We are at the cusp of a building revolution which, for the first time, won't be led by a developer, builder, architect, engineer, or urban planner. Technological innovation operating at unprecedented scale and speed is reshaping how buildings and cities are designed, constructed, and operated. Robotic construction, computer enhanced design, and augmented environments are a few examples that are disrupting traditional processes. This paper presents the initial results of Vertical Futures, a research project initiated by CTBUH and funded by the Henry C. Tuner Prize awarded to CTBUH in 2015. Following on CTBUH's 2014 "Roadmap on the Future Needs of Tall Buildings," the Future Technology Index aims to identify, audit, and classify the leading-edge technologies CTBUH members believe will transform tall buildings and future cities.

Keywords: Internet of Things, Responsive Environments, Robotics, Smart Cities, Sustainability, Technology

我们正处在一场建筑革命的风口浪尖，一场第一次不由开发商、建设者、建筑师、工程师或城市规划师领导的革命。空前规模和速度的技术创新正在重塑建筑和城市——重新设计、建造和运营。机械施工、计算机辅助设计和环境扩张是几个破坏传统过程的例子。本文介绍了垂直未来的初步结果，垂直未来研究项目由CTBUH发起，由Henry C. Tuner奖于2015年授予资助CTBUH。以下是CTBUH2014年的"高层建筑未来需求路线图"，未来技术指标（Future Technology Index）的目的是对那些CTBUH会员认为将改变高层建筑和未来城市的尖端技术进行确认、审计以及分类。

关键词：物联网、反应环境、机器人学、智慧城市、可持续性、技术

Introduction

The massive global interest in the development of advanced and innovative structures is unprecedented in the history of tall buildings. Teams from both academic institutions and professional practices are embarking on projects to advance fields in the architecture, engineering, construction, and operations of the urban habitat; and, for the first time, this development has brought in an industry previously unconnected to tall buildings and the urban habitat – technologists. Technology companies are now directly entering the field, forming specialized divisions to advance progress in the development of smart cities.

The staggering amount of research and development advancing high-rise buildings motivated the CTBUH, CIB, and UNESCO to create a "Roadmap on the Future Research Needs of Tall Buildings." From 2010 to 2014, this project sought to provide guidance on which research topics required priority attention – and which research gaps need to be filled – to progress tall buildings beyond their current state in the years to come.

前言

在先进、创新的高层建筑结构开发热情空前高涨的今天，学术团队和专业实践团队都致力于开展项目，推动高层建筑的建筑设计、工程、施工和运营领域的发展。就连原先同高层建筑和城市居住区没有交集的技术专家也加入到高层建筑结构的开发行列之中。科技企业更是直接进入高层建筑领域，形成推动智慧城市建设的特殊力量。

在大量研发的推动下，高层建筑发展迅速，促使世界高层都市建筑学会、国际建筑与建设研究创新理事会和联合国教科文组织制定了"高层建筑未来研究需求路线图"。在2010和2014年期间，项目尽力为需要优先进行的研究课题以及需要填补的研究缺口提供指导，以使高层建筑的发展在未来数年内更上一层楼。

根据研究路线图，世界高层都市建筑学会正在进行一项宏大的项目，旨在发现能够影响全球高层建筑和城市未来格局的创新技术。研究的部分经费来自特纳建设为了表彰世界高层都市建筑学会在高层建筑行业中的领导作用而颁发给世界高层都市建筑学会的2015年建设创新亨利.C特纳奖。

Following up on the Research Roadmap, the CTBUH is now conducting an ambitious project to identify the innovative technologies that will shape the future of tall buildings and cities around the world. This research is being funded in part through the 2015 Henry C. Turner Prize for Innovation in Construction, bestowed by Turner Construction on the CTBUH for its leadership role in the tall building industry.

For progress to be made, it is essential to understand the current best practices, developments in the pipeline, and cutting-edge ideas. The goals of this project are threefold: first, to survey the current state of technology and identify leading-edge applications and processes across the AEC-O spectrum; second, once this "Long List" of technologies is compiled, to classify each and establish the relationships between different fields of technology and AEC-O disciplines; and third, to establish metrics to evaluate each technology and identify which ones represent potentially disruptive developments. Values for these metrics will be calculated through a survey of CTBUH members, allowing a statistical analysis of these technologies and industry as a whole.

Traditional professional roles are morphing rapidly as advanced technology and capabilities require them to branch out and take advantage of many fields. Architects are now designing in virtual reality. Urban designers are considering networks of advanced sensors in their plans. Understanding the specific nature of these convergences and divergences is key to planning for the future of our industry.

The Technology Audit

The CTBUH has completed a systematic review of current technology and processes in the myriad fields related to tall buildings, culminating in a Long List of approximately 75 advanced technologies. A number of methods have been used to compile this list. First, a core research team was established to oversee the project, comprised of CTBUH members and industry representatives. The primary researchers then conducted a journalistic survey of all publically-known technologies. Over 100 publications, institutional websites, and academic portals were consulted in this search. Industry leaders and academic project leads have also been interviewed. Finally, an e-blast to CTBUH members with an open call for ideas surfaced many additional technologies for our final list. Overall, the list is thoroughly representative across AEC-O industries and includes a plethora of exciting developments.

Classification Methodology

To accurately compile and understand the many technologies surveyed, it is important to establish consistent classification guidelines. Two were adopted in order to best analyze current industry trends.

First, the World Intellectual Patent Organization (WIPO) uses a hierarchical classification of 35 technological fields within the five domains of Chemistry, Electrical Engineering, Instruments, Mechanical Engineering, and Other. WIPO classifications are broadly accepted by the global technological industry, as every patented technology must be categorized under one of their fields. It is, therefore, well-suited for classifying the technologies within the Long List.

Second, the CTBUH Research Roadmap identified eleven disciplines which together encompass AEC-O industries. These are:

1. Architecture and Interior Design
2. Building Materials and Products
3. Circulation: Vertical Transportation and Evacuation
4. Cladding and Skin
5. Construction and Project Management
6. Economics and Cost
7. Energy: Performance, Metrics, and Generation
8. Fire and Life Safety
9. Structural Performance, Multi-Hazard Design, and Geotechnics
10. Sustainable Design, Construction and Operation
11. Urban Design, City Planning, and Social Issues

Each of the technologies are assigned to the industry discipline of greatest relevance – in many instances, two or more. This leads to a predictable challenge at this stage of the research: as disciplines modernize, the fields of technology they encompass multiply, leading to an increasing amount of overlap between disciplines as a whole. Traditional

掌握最新的最佳做法，酝酿中的发展和先进的理念是取得进步的必要条件。项目有三个目标。 一是调查技术现状，发现建筑设计、工程、施工和运营各环节的尖端应用和工艺。 二是在确定技术“初选清单”以后，对技术和建筑设计、工程、施工及运营专业的各个领域进行分类，关联不同领域。

先进技术和能力要求传统的职业角色扩展范围，利用多个领域的优势，传统的职业角色因此而迅速转变。建筑师正在虚拟现实中进行设计。城市设计师正在方案中考虑中先进传感器网络。了解这些聚合与离散的特性是未来行业规划的关键。 三是建立技术评价指标，识别有颠覆性发展潜力的技术。指标值将通过对世界高层都市建筑学会会员的调查计算确定，以便对技术和行业进行整体性的统计分析。

技术审核

世界高层都市建筑学会系统性地审核了大量高层建筑领域的最新技术和工艺，最后采用多种方法拟定了约有75项先进技术的“初选清单”。首先成立一个由世界高层都市建筑学会会员和行业代表组成的核心研究团队负责项目监督。初级研究员对所有公开技术进行了新闻调查。研究查阅了100多份出版物、机构网站和学术门户网站，访问了众多行业领袖和学术项目领导。最后给世界高层都市建筑学会的会员群发公开创意征集邮件，为最终清单另外征集到多项技术。总的来说，清单充分地代表了建筑设计、工程、施工和运营行业，包含大量的重大发展。

分类方法

为了准确地编制和理解大量调查过的技术，必须制定统一的分类指南。采用两种分类方法分析行业的最新发展趋势。

一是世界知权产权组织使用的分级分类法（简称“WIPO分类法”），共有化学、电气工程、仪表、机械工程、其他五大类35个技术领域。WIPO分类法是全球科技行业普遍接受的分类方法，每一项专利技术必须归入一个领域。WIPO分类系统似乎比较适合用于对“初选清单”中的技术进行分类。

二是世界高层都市建筑学会研究路线图，共确定了11个包含建筑设计、工程、施工和运营行业的专业，具体如下：

1. 建筑设计和室内设计
2. 建筑材料和产品

definitions blur as change across all industries is driven by the same factors, such as significant leaps in materials, manufacturing, and computational abilities. For example, advanced environmental sensor technologies, rarely considered in the last decade by any field other than fire and life safety, are rapidly transforming the disciplines of architecture, circulation, urban design, structural performance, and construction. As they benefit from the same base technological fields, the disciplines themselves become more convergent.

Across the AEC-O spectrum, we observed technologies affecting tall buildings in a number of fields including biotechnology, chemical engineering, civil engineering, computer technology, control systems, digital communication, electrical machinery, engineering, environmental technology, molecular chemistry, materials, mechanical elements, metallurgy, polymers, special machines, transport, and wireless communication.

Observed Technological Trends Within Disciplines

Through the compilation and completion of the Long List, we have noticed fascinating trends in many disciplines. These are qualitative observations of the bulk of the research as to movements within industries.

Architecture and Interior Design:
Architecture is rapidly transforming as a discipline in order to take advantage of advanced algorithms in the design process and previously impossible structures created out of new materials (Figure 1). More than ever, an architect's job encompasses a holistic understanding of many fields and their individual capabilities, including computer technology, mechanical elements, wireless communications, and advanced engineering. Designs are developed parametrically through code, and then engineered to be prefabricated by robots. Technologies are emerging to allow buildings which can actively transform themselves to adapt to shifts in the environment, people flow within them, noise levels, and even the stress level of its occupants (Figure 2).

Building Materials and Products:
The many industries creating building materials and products are being transformed by advanced manufacturing processes enabling new polymers and alloys. Many of the advances in this field are, however exciting, still in their infancy. Materials that can

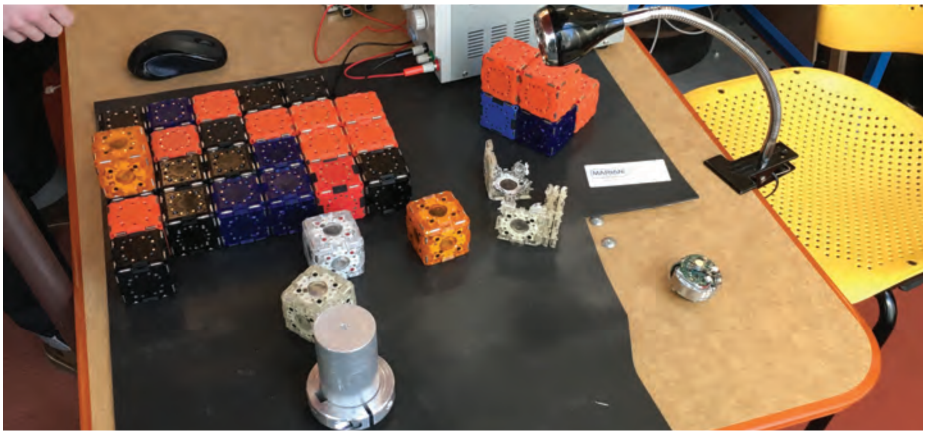

Figure 1. M-Blocks are small cubes (5 centimeters per side) that have no external actuators, yet they manage to move and even jump. (Source: John Romanishin)
图1. M-Blocks是边长5厘米的小方块，这些方块没有外部驱动器但能移动甚至跳跃。（来源：John Romanishin）

3. 动线：垂直交通和疏散
4. 包覆层和外皮
5. 施工和项目管理
6. 经济成本
7. 能源：绩效、指标和发电
8. 火灾和生命安全
9. 结构性能、多灾害设计和土工
10. 可持续设计、施工和运营
11. 城市设计、城市规划和社会问题

每一项技术归入一个最相关的行业专业，多数情况下归入两个以上的相关行业专业。由此可见本阶段研究工作的艰巨：随着专业的日益现代化，专业所包含的技术领域迅速增加，专业之间的重叠现象总体日益严重。材料、制造和计算能力的巨大进步带来了各行各业的变化，传统的定义日益模糊。以先进的环境传感技术为例，十年前除了火灾和生命安全很少有专业会把这项技术纳入考虑，今天却在迅速改变建筑设计、动线、城市设计、结构性能及施工专业。得益于同一基础技术领域的事实使这些专业本身的聚合程度也有所提高。

在建筑设计、工程、施工和运营的各个环节，技术影响着高层建筑的多个领域，包括生物技术、化学工程、土木工程、计算机技术、控制系统、数字通信、电机、工程、环境技术、分子化学、材料、机械零件、冶金、高分子、特殊机械、交通及无线通信。

专业的技术趋势

随着初选清单的编制和完成，我们发现了多个专业的良好趋势，这是对大量行业趋势识别研究工作的定性观察。

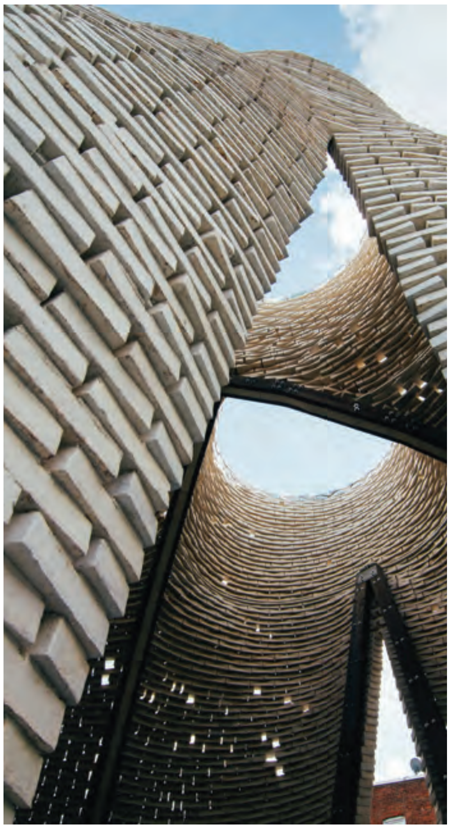

Figure 2. Hy-Fi, an installation by New York architects The Living, is the first tall structure built with bricks "grown" from mushrooms. (Source: David Benjamin)
图2. Hy-Fi是第一座用真菌砖垒成的高塔，由纽约The Living建筑事务所设计。（来源：David Benjamin）

建筑设计和室内设计：
乘着设计中先进算法的东风，建筑设计迅速转化升级，利用新材料创造前所未有的结构（图1）。建筑师在工作中需要理解的东西和需要掌握的个人能力超过了以往任何时候，包括计算机技术、机械零件、无线通信和高级工作。通过代码进行参数化设计，经过工程化后由机器人进行预制。不断涌现的技术使建筑能够自主改变，适应环境变化、内部人流变化、噪声变化乃至住户的压力水平变化（图2）。

建筑材料和产品：
先进的制造工艺带来全新的高分子和合金，改变着众多建筑材料和产品生产行业。建筑材料和产品行业的很多进步虽然

change shape, density, opacity, and rigidity are in the pipeline, and promise to elevate the bar for feasible designs and inspire entirely new concepts of what buildings are capable of (Figure 3).

Circulation: Vertical Transportation and Evacuation:
Circulation is a discipline which is actively taking giant leaps in capabilities. Arrays of sensors and cameras are already being installed within buildings to track "People Flow" and adjust circulation apparati (elevators, escalators, and signage) accordingly. Elevator efficiency is climbing to new heights through a combination of intelligent algorithms and advanced machinery. In the very near future, architects will be able to pick between carbon fiber ribbons, which allow elevators to travel up to 1,000 meters in a single shaft, and magnetically-propelled cabs which need no cable at all and can even travel horizontally, dramatically increasing core efficiency in towers and allowing for previously unfeasible designs.

Cladding and Skin:
The façade is undergoing a revolution. Once a simple shell protecting the interior environment from the elements, advances in enclosures are now one of the leading factors transforming tall buildings, especially in the area of energy efficiency. Integrated solar and wind capture technologies allow the curtain wall to generate a portion of the energy needed for building operations. Novel, water-filled ceramic tubing allows for passive cooling, significantly decreasing the energy required for HVAC systems. Plants integrated into open-air passages through the building enclosure actively improve interior air quality and provide a weather barrier, reducing the need for manufactured solutions. In the future, intelligent, reactive materials will allow façades to open and close like pores in skin. This could allow a system which passively increases airflow through surfaces in direct sunlight, then closes it off when the sun moves on. Unlike some of the other disciplines on this list, many of these advances have either already been utilized in projects, albeit some at a smaller scale, or have prototypes working successfully.

Construction and Project Management:
Prefabrication has seen resurgence in the world of construction, allowing for significantly lower-cost "unitized" projects with high-quality control. 3-D printing is already on its way to high adoption and utility, and recent advances in the material qualities are allowing for even structural elements of towers to be printed. Even more transformative advances in advanced robotics are in the pipeline, which are poised to redefine the construction industry like no other. Robots are already becoming prevalent in construction processes, working alongside humans in an assistive and collaborative fashion. One day, an intelligent fleet of thousands of crawling, climbing, and flying

可喜，但目前仍然处于初级阶段。能够改变形状、密度、透明度和硬度的材料尚在酝酿之中，一旦推出无疑将使可行性设计更上一层楼，为我们带来灵感，形成全新的建筑功能概念（图3）。

动线：垂直交通和疏散
动线专业的能力取得了长足的进步。大楼都安装了传感器和摄像头阵列，以跟踪“人流”，相应调节动线装置（电梯、电动扶梯和引导标示）。智能算法和先进机械的结合使用大幅提高了电梯效率。建筑师有望在不久的将来把碳纤维带（能让电梯在一个井道中行驶1000米）和磁性推动轿厢（不需要电缆，甚至能横向行驶）纳入选择范围，从而极大地提高大楼的核心效率，实现前所未有的设计。

包覆层和外皮：
外立面正经历着一场革命。技术进步使外立面超越了简单的外壳功能，具有室内环境保护功能，围护结构是改变高层建筑的主要因素，在能效方面的改变尤为显著。太阳能风能集成捕获技术使幕墙具备了发电功能，满足大楼的部分运行电力需求。全新的充水陶瓷管被动供冷极大地降低了暖通系统的能耗要求。通过建筑围护结构融入开放式风道的绿植有效地改善了室内空气质量，形成气候屏障，减少了制成品的使用需求。未来的智能反应材料将使外立面像毛孔一样张开和闭合，系统在太阳直射时被动增加表面气流，在太阳光移开后关闭气流。不同于清单中的某些其他专业，本专业的很多先进技术要么已经投入项目使用（尽管规模较小），要么已经有成功运转的原型。

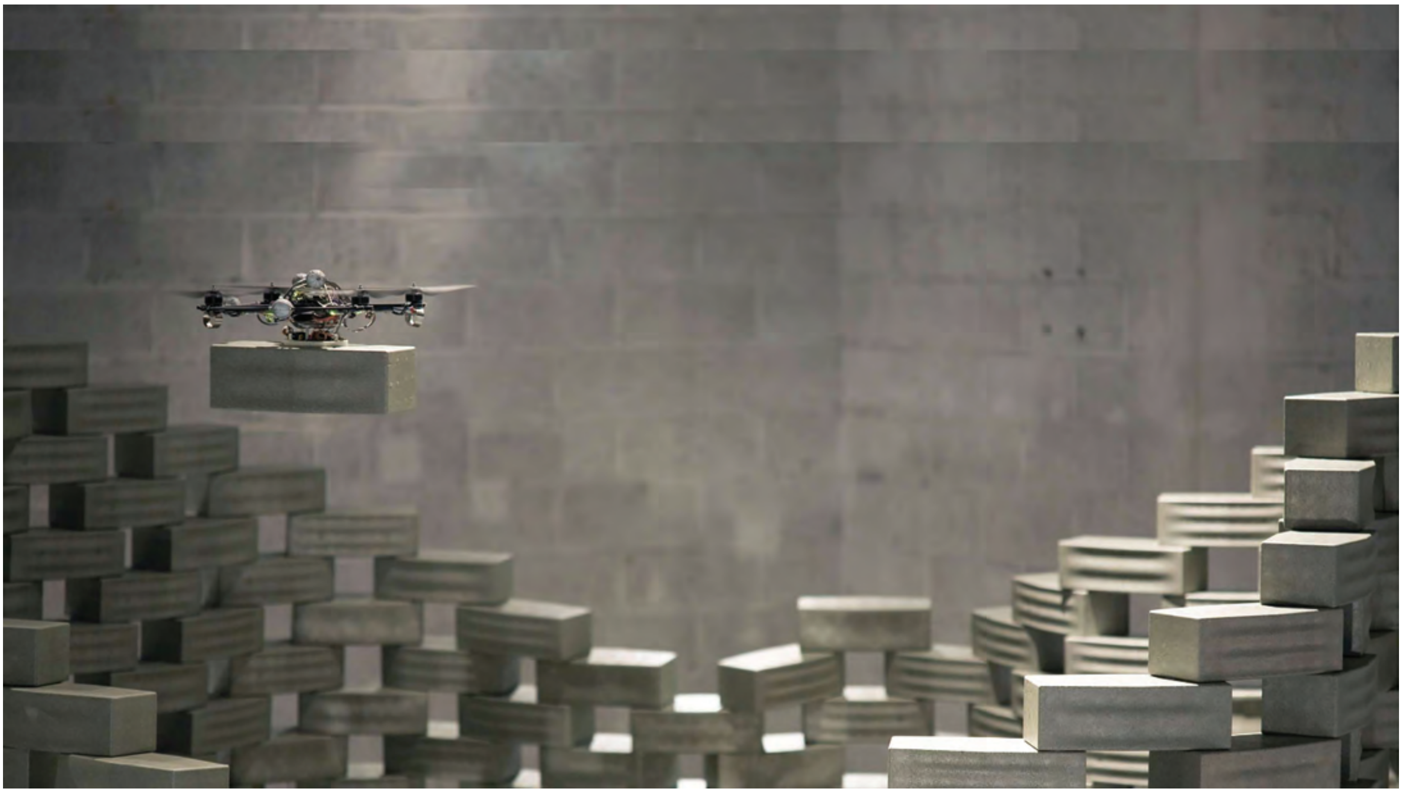

Figure 3. Flight Assembled Architecture by Gramazio & Kohler: A swarm of flying drones assemble a tower made of polystyrene bricks in Orleans, France. (Source: Gramazio & Kohler)
图3. 由Gramazio & Kohler建筑事务所设计的飞机组装式建筑：一群无人机在法国奥尔良用聚苯乙烯砖组装一座高塔。（来源：Gramazio & Kohler）

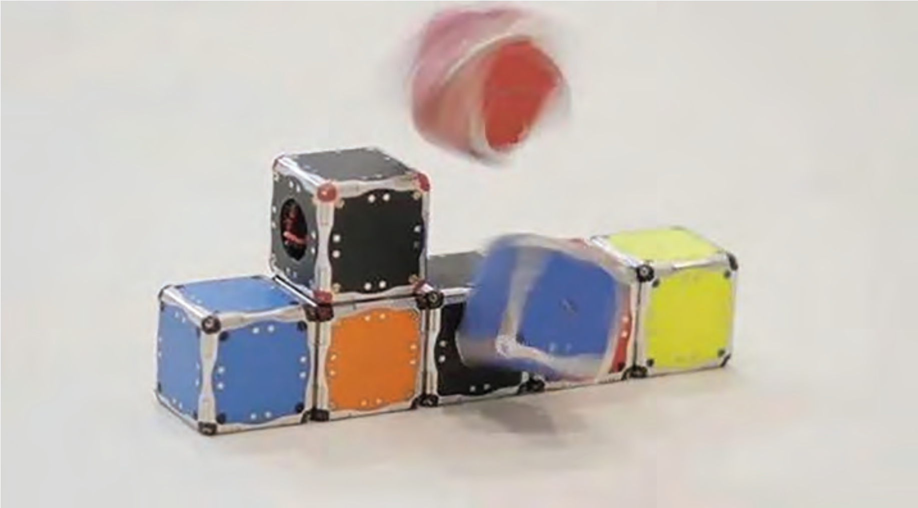

Figure 4. Although early in their development, future iterations of M-Blocks will be able to self-assemble into complex configurations, possibly paving the way for advanced construction techniques. (Source: John Romanishin)
图4. M-Blocks还处在发展的早期，未来的M-Blocks将能够自动组装复杂结构，为先进的施工技术铺平道路。（来源: John Romanishin）

robots could construct a building with little human involvement (Figure 4). Multiple research teams are even looking into ways that the structural components of the buildings themselves could be intelligent, climbing autonomously into place before permanently affixing themselves. Disaster relief could involve dropping piles of these components into dangerous areas, where they would self-assemble into shelters in a short amount of time. While not on the immediate horizon, substantial investment in research and development of advanced robotics is a prelude to active integration in many industries, including construction, in the future.

Structural Performance, Multi-Hazard Design, and Geotechnics:
Structural engineering is gradually becoming more integrated with other elements of tall buildings. Towers are increasingly making use of façade systems as means of structural rigidity and support. That, along with the increasing design freedom achieved from advanced algorithms and materials, is bringing new opportunities to structural construction and its integration with the aesthetics of a project. Moving forward, developments in 3-D-printed concrete and steel structural components will increase capabilities further, as both are already being investigated to allow for stronger and more efficient designs (Figure 5). Ways to improve the material efficiency of metals are also coming along, including injecting materials into open-cell foam, leaving behind an impressively strong and lightweight lattice when the foam is dissolved.

Sustainable Design, Construction, and Operation:
Within the timeframe of the Research Roadmap, sustainable design has evolved from hot buzzword to a fundamental goal. Increasing the worldwide focus on environmental sustainability, plus the cost benefits of increased energy efficiency, have led to an explosion of new sustainable ideas, technologies, and practices. Concrete can now be manufactured with sequestered carbon dioxide from energy-production emissions. A number of new treatments and manufacturing processes have recently reintroduced timber to the world of tall buildings, and there are multiple projects in the pipeline, some reaching up to 40 stories, which use timber as their primary structural

施工和项目管理:
建筑业的预制复兴产生了成本大幅下降，控制品质优良的“单元化”项目。三维打印即将得到广泛的采纳和使用，材料质量方面的研究进展使均匀的大楼结构构件的打印成为可能。酝酿中的高级机器人方面的革命性进展将超越任何其他技术进展，改变建筑业的格局（图4）。机器人已经全面参与建设进程，辅助或协同人类工作。未来的某一天，会有成千上万的爬行机器人、爬升机器人和飞行机器人组成的智能机器人施工队完成大楼建设，几乎不需要人类参与。有一些研究团队甚至开始研究让建筑结构构件智能化，自动爬进相关位置，自行永久固定的方法。救灾时可以把这种构件大量放入危险区域，让它们在短时间内自行组装成避难处。大量的高级机器人研发投资虽然不会在近期内引发变革，但会拉开未来机器人进入包括建筑业在内的各行各业的序幕。

结构性能、多灾害设计和土工:
结构工程与高层建筑的其他元素日益融合。用外立面系统实现结构刚度和支撑是大楼建设的趋势。这项技术加上先进算法和先进材料实现的设计自由度的提升进一步解放了结构施工，使结构施工能够兼顾项目美观。已经有人开始研究如何用三维打印混凝土和钢结构构件实现更高效、更优秀的设计，发展下去，三维打印混凝土和钢结构构件将进一步提升建设能力（图5）。有很多改进金属材料效率的方法正在研究当中，包括在开孔泡沫塑料中注入材料，在泡沫溶解后留下质地坚固的轻型格架。

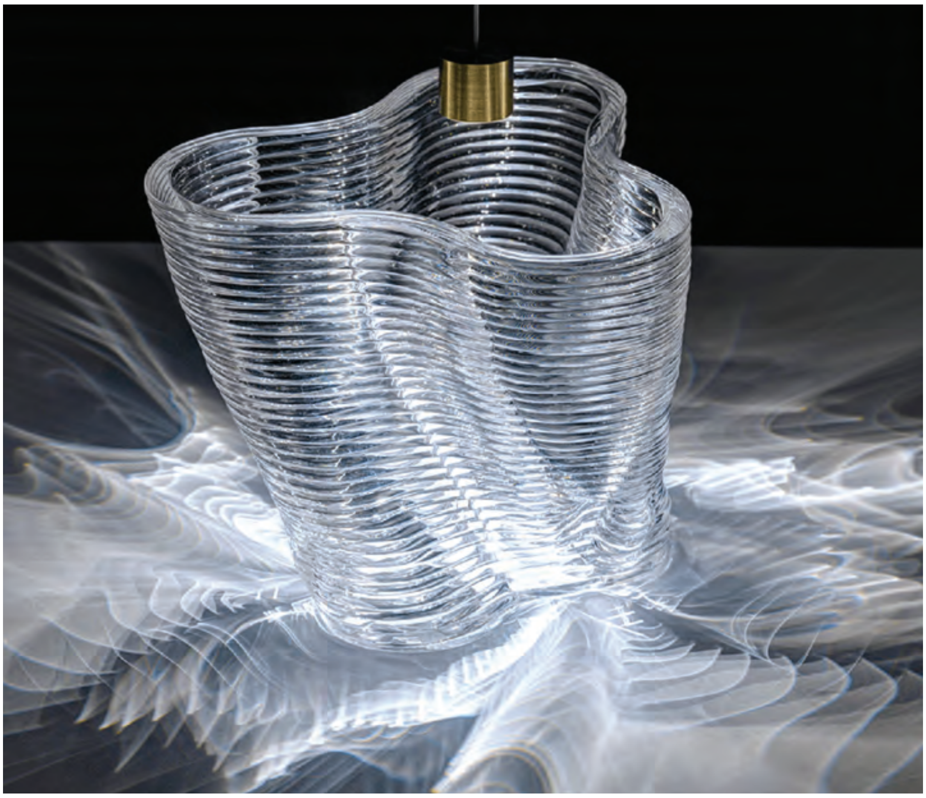

Figure 5. The project synthesizes modern technologies, with age-old established glass tools and technologies producing novel glass structures with numerous potential applications. (Source: MIT Media Lab)
图5. 该项目综合了现代技术、古老的玻璃工具以及具有许多潜在应用的新的玻璃结构技术。（来源: MIT Media Lab）

component (Figure 6). Other grown materials like fungus are being developed into building components. New materials like titanium dioxide curtain wall coating actively remove pollutants from the atmosphere by oxidizing organic matter and creating water vapor and carbon dioxide. This discipline is benefitting from an increasing overlap with cladding and skin, as many advances there also serve the interests of energy efficiency.

Urban Design, City Planning, and Social Issues:
Urban design has emerged as one of the most active fields undergoing significant transformation. Many large firms have designated teams utilizing intelligent algorithms to consider factors including urban density, environmental exposure, and equity in their site analyses (Figure 7). Any urban planning now needs to consider the increasingly numerous array of sensor networks which will allow cities to actively adapt to changing parameters. For example, an intelligent, city-wide network could reroute additional public transportation to areas with suddenly increased people flow. These ideas are so promising that governments and the private sector are actively investing hundreds of billions of dollars into the development of smart cities. Like many other disciplines, the practice of urban design has increased its necessary skill sets, as expertise in computational analysis and wireless hardware technologies is quickly becoming a prerequisite for best-practice work.

Proposed Analytical Metrics And Next Steps

The utility of this Long List of technologies comes not only from maintaining a holistic survey of technological capabilities, but from the opportunity it provides to analyze and cross-evaluate the merits of each in order to identify the most promising developments in the pipeline. To perform this analysis, we propose assigning four metrics to each technology: prevalence, scalability, deviance, and value.

Prevalence is a calculation of the current market saturation and adoption rate of the technology. Is the technology currently used by a high percentage of its potential market? Market saturation is a commonly accepted metric in business-analytics for the success of a product.

Scalability is the potential for a technology to be adopted on a substantial scale. It is another prevalent metric used in economic analyses of the viability of a new product, as

Figure 6. The Tamedia Office Building by Shigeru Ban Architects in Zurich, Switzerland, features a timber main structural system rising seven floors. Composite timber beam structures can achieve heights of 50-meters or more. (Source: Shigeru Ban Architects)
图6. 位于瑞士苏黎世的Tamedia办公大楼是一座7层的木质建筑，由坂茂建筑设计事务所设计。其连锁木结构可达到50米或更高的高度。（来源：Shigeru Ban Architects）

Figure 7. The Next Tokyo project aimed to solve key problems in population density and address rising sea levels with a futuristic city rising from Tokyo Bay. (Source: KPF)
图7. 下一个东京项目旨在解决人口密度的关键问题，并为从东京湾崛起的未来城市解决海平面上升的问题。（来源：FPF）

可持续设计、施工和运营：
可持续设计在研究路线图的相关期限内从一个热门词汇演变成一个基本目标。现在，世界各国都越来越重视可持续性及能效提升带来的成本效益，全新的可持续性创意、技术和实践大量涌现。现在可以用发电排放物生产整合的二氧化碳混凝土。一些新的处理工艺和制造工艺让木材回归高层建筑，很多筹备中的项目（其中有些项目高达40层）以木材作为主要的结构构件（图6）。此外人们还在研究将真菌等活材料纳入建筑构件的技术。二氧化钛幕墙涂层等新材料能氧化有机物，生成水蒸汽和二氧化碳，从而有效地清除大气污染物。本专业与覆盖层和外皮专业日渐重合，得益于覆盖层和外皮专业的众多能效技术。

城市设计、城市规划和社会问题：
城市设计成为正在经历重大变化的最活跃的领域之一。很多大企业明确要求自己的团队利用智能算法衡量城市密度、环境风险及基地分析公平性等因素（图7）。现代城市规划必须考虑不断增加的大量的传感器阵列网络，这些网络能让城市有效适应不断变化的指标。例如，智能全市网络能重新规划路线，安排增加的公交前往人流骤增区域。由于创意前景良好，政府和私人领域争相投入数千亿美元开发智慧城市。随着计算机分析和无线硬件技术成为城市设计最佳实践工作的先决条件，城市设计的技能要求同其他专业一样水涨船高。

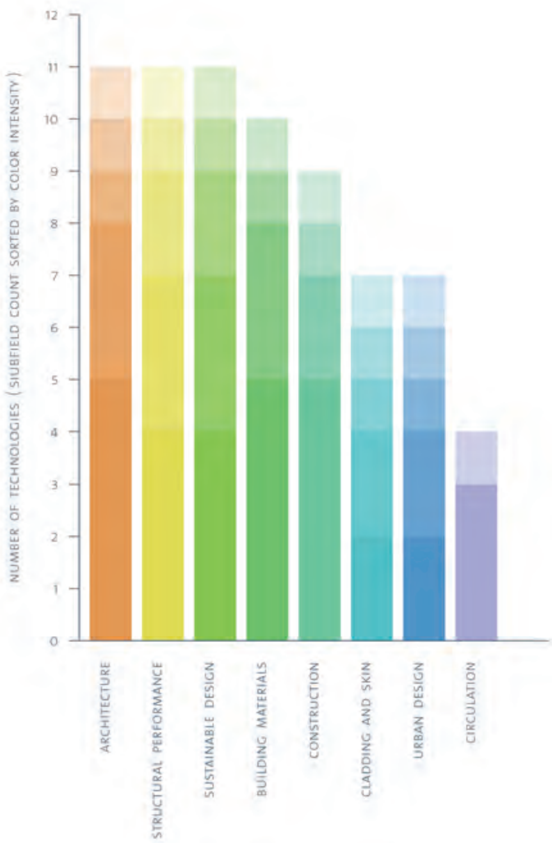

Figure 8. A summary of the technological survey's findings. (Source: CTBUH)
图8. 技术调查的调查结果摘要。（来源：CTBUH）

understanding its potential market size is key to evaluating its potential value and impact.

Deviance is a measure of the novelty of the technology. How different is it from the current best-practices? Deviance is an established and valuable metric used to evaluate the importance of work presented in academic journals, making it ideally suited for our analysis of new technologies.

Value is our final metric. Simply put, is this technology a good solution to a problem? Value proposition is a significant factor considered by potential investors in new technologies: if a new idea doesn't provide a better solution to a problem than the existing option, it is unlikely that customers will switch.

These four established metrics are valuable because we can utilize them to calculate two grades for each technology: maturity and impact.

Maturity will be calculated for each technology with the following equation:

Maturity = Prevalence * (1 / Deviance)

If a technology is mature, it follows that it is will have a high adoption rate among its potential market. A mature technology will also see a low deviance, as it has already been improved and optimized over many iterations and is no longer changing in a significant way from generation to generation.

Impact will be calculated for each technology with the following equation:

Impact = Deviance * Value * Scalability

If a technology has a high chance of being significantly impactful on an industry, it should be highly deviant from current solutions, have the potential for a massive user base, and be an excellent solution to a problem.

The values for each of the four metrics will be attained through standardized questions on a survey emailed out to the CTBUH member network. The individual numbers assigned to a technology on each survey will be unitized, and then averaged across the entire answer set. This will allow substantial statistical analyses of the technologies individually, and across fields as a whole. Most interestingly, we believe this analysis will enable the identification of technologies with the potential to be significant in the future (Figure 8).

We will assign a technology with a low **Maturity** grade but a high **Impact** grade as one that the AEC-O community believes has the ability to become "the next big thing." These insights will be invaluable as they identify what each industry should be considering and pivoting towards, and how we should be adjusting our thinking about what tall buildings will become as we reach ever higher, and our urban habitats grow ever smarter, in the years to come.

拟议分析指标及下阶段工作

本技术初选清单的用途不仅在于维持全面的技术能力调查，还在于分析、交叉评价各项指标，发现酝酿中的最有前景的技术发展。为执行分析，我们提议为每一项技术指定四项指标：普遍性、可扩展性、变异性、价值。

普遍性是技术的当前市场饱和度与采用率估计。技术目前是否在潜在市场上有高比率的使用？市场饱和度是普遍接受的商业分析指标，用于确定产品的成功与否。

可扩展性是技术的大规模采用潜力。了解潜在市场规模是评价新品潜在价值和影响力的关键，因此可扩展性是新品可行性经济分析中的另一个常用指标。

变异性是技术的新颖性指标。技术与现行最佳实践有什么区别？变异性是一项成熟、有用的指标，用于评价学术期刊所述作品的重要性，非常适合此处的新技术分析。

价值是终极指标。简单来说，技术是否能很好地解决问题？价值主张是潜在投资者考虑是否投资新技术的重要因素。如果新创意不能比现有方法更好地解决问题，那客户就不大可能改用新方法。

这四项指标可用于计算技术的两项分类：成熟度和影响力，非常有用。

用以下公式计算每一项技术的**成熟度**：

成熟度＝普遍性*（1/变异性）

一项成熟的技术会在潜在市场达到较高的采用率。成熟的技术历经多次改进和优化，代与代之间的变化不大，变异性也较小。

用以下公式计算每一项技术的**影响力**：

影响力＝变异性*价值*可扩展性

可能对行业有重大的影响技术应该与当前方案有很大的差异，有可能得到广泛的使用，能够很好地解决问题。

关于四个指标的值，我们将通过电子邮件向世界高层都市建筑学会的会员网络发送标准问题，通过调查确定指标值。在各项调查中对每一项技术所赋的值将进行统一，然后取全部回答的平均值，以实现各项技术及领域整体的实证统计分析。最有意思的地方在于分析有助于我们发现具有未来潜力的技术（图8）。

我们会指定一项**成熟度**评分低，**影响力**评分高的技术，世界高层都市建筑学会认为这样的技术可能成为下一个大热门。这些看法非常可贵，能让各行各业明白未来的考虑因素和努力方向，帮助我们转变观念，在大楼越造越高，城市居住区越来越智能的未来重塑高层建筑功能。