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Title: **Addressing Energy Efficiency and Complexity in Tall Buildings**

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Subject: MEP

Keywords: Energy
Energy Consumption
Life Cycle Analysis
MEP
Stack Effect
Sustainability

Publication Date: 2016

Original Publication: Cities to Megacities: Shaping Dense Vertical Urbanism

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

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Addressing Energy Efficiency and Complexity in Tall Buildings | 关于高层建筑能效及复杂性的探讨

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Abstract | 摘要

The energy systems in tall buildings are characterized by their high energy consumption and complexity. By reviewing the whole building life cycle – design, control, commissioning, and operation – this paper first introduces the challenges that we are facing in each stage of a building life cycle, and then provides cutting-edge technical solutions. Decentralized HVAC design, Hierarchical optimal control, PID auto-tuning, intelligent auto commissioning, and air flow management are some recommendable technologies that could help make building energy systems be simpler, more efficient, and more sustainable.

Keywords: Commissioning, Control, HVAC, Operation, Stack Effect and VWV

高层建筑的能源系统常常以高能耗及复杂度为特征。本文首先通过回顾建筑的全生命周期–设计、控制、调试及运营，介绍了在各个阶段我们所面临的挑战并在此基础上提出了最前沿的技术解决方案。分布式空调设计、分层分散最优控制、PID自动调节、智能自动调试以及气流组织控制都是本文所推荐的技术。这些技术使得能源系统向着更简单、更高效、更可持续的方向迈进。

关键词：调试、控制、空调、运营、烟囱效应、水多联机

Introduction

Cities, particularly in the developing world, are expanding quickly due to increasing populations. In the past decade, we have witnessed cities growing vertically at a dramatic pace, with the completed number of supertall and megatall buildings breaking the world record every year. With over 1.3 billion citizens and a rapidly urbanizing population, China constructs more skyscrapers than any other country globally. However, high-rise buildings, which are complex buildings, pose particular design and operation challenges for their systems, and the reality that they rely intensively on mechanical systems provides many challenges, among which energy and complexity are two factors that raise several concerns from the building industry.

Characterized by a large curtain wall façade, multiple functions, as well as complex mechanical systems, operators are mostly plagued by the high energy consumption of tall buildings, where HVAC becomes the largest energy end use and accounts for approximately 40 to 60 percent of total building energy consumption versus approximately 40 percent in small and middle size buildings (Huang, 2012).

The performance of traditional HVAC systems is sub-optimum in tall buildings because system complexity increases with building size, which leads to efficiency loss by, for instance,

简介

城市，尤其是发展中国家的城市,常常有着高速增长的人口。在过去的十来年中，我们注意到城市以惊人的速度在往垂直方向发展。建成超高层建筑的数量每年都在刷新世界纪录。而中国，作为一个拥有着超过13亿人口和高速城市化的国家，所建造的高层建筑超越了全球任何一个国家。然而，高层建筑，同时也是复杂建筑，对系统的设计及运营提出了新的挑战。事实上，由于高层建筑高度依赖于机械系统，建筑行业对此有很多争议。而在这些争议中，其高能耗和复杂性是引发最多关注的两个方面。

高层建筑以大面积玻璃幕墙、多用途建筑使用功能及复杂的机电系统以及高建筑能耗著称。在其建筑能耗中，空调能耗占比尤为主要，占到总体建筑能耗的40%到60%。而普通的公共建筑，其空调能耗仅为建筑能耗的40%。

为何传统的空调系统在高层建筑上的能耗不如人意呢？因为随着建筑面积的增加，系统的复杂性也增加。例如，长距离的冷热输送、风水系统不平衡、调试过程中系统功能性测试不充分、运行过程中设备故障不能及时察觉、无组织新风渗透等等，都会导致系统效率降低。此外，室内环境品质的好坏也直接影响人员的健康及工作效率。多项研究（Fisk，2000）（Piers MacNaughton，2015)表明一个不舒适的室内环境会严重减低人员的生产效率。因此，对于机电工程师而言，他们需要提供

the long distance needed for cooling and heating distribution, air and water imbalance, insufficient functional tests and commissioning, undetected equipment failures, turbulent outdoor air flow, and more. Besides, indoor environmental conditions maintained by mechanical systems directly influence the health and productivity of occupants. Many studies (Fisk, 2000) (Piers MacNaughton, 2015) have indicated that an undesirable indoor environment can significantly reduce productivity; therefore, MEP engineers are being pushed to provide system solutions that are more efficient on both energy and comfort, which in turn requires brave technical breakthroughs on system design, control, commissioning, and operation. Though challenging, this provides opportunities to introduce new technical solutions.

This article therefore addresses the question of what technologies could help us, in five years, 10 years, or in even further in the future, in the design and construction of more supertall and megatall buildings in a simpler, more efficient, and more sustainable way.

Decentralized Air Conditioning Systems

Current data indicates that more than 99 percent of tall buildings in China use a centralized chiller plant as the primary air-conditioning source (Cunyang Fan, 2014). Most tall buildings use a single energy center in the basement (e.g. Tianjin 117 (Antony Wood, 2014)); while an alternative approach is to build two energy centers in the basement as well as in one of the upper floors, respectively (e.g. Shanghai Tower (Antony Wood, 2014)). No matter the location of the energy center, for a traditional hydronic system, the increasing pumping distance required for all the mechanical equipment is important for tall buildings' energy consumption. These large distances require more pumping energy and, more importantly, buildings of over 35 to 40 stories typically incur efficiency loss due to a heat exchanger in pressure breaks, which are necessary to divide the chilled water loop into two or more separate loops at above 35 to 40 stories to avoid high pressures that can compromise conventional fittings and valves (Luke Leung, 2013). One pressure-breaking heat exchanger relay increases the chilled water supply temperature 1.5~2^{0}C. For a megatall building, when two pressure breaks are required, 3~4^{0}C supply temperature is lost, which in turn asks for the central chiller to produce water at lower temperature and thus decrease chiller efficiency significantly.

一个系统性的解决方案，能同时提高能效及舒适度水平。为实现这个目标，在系统设计、控制、调试及运营商的大胆技术革新是必不可少的。这带来的不仅仅是挑战，更是机会。

本文所阐述的，正是怎样的技术革新，可以在未来5年或者10年，帮助我们设计并建造更多、更简单、更高效、更可持续发展的高层及超高层建筑。

离散式空调系统

现有的数据(Cunyang Fan, 2014)表明中国超过99%的高层建筑使用中央冷冻机房提供空调冷热源。大部分的高层建筑采用布置于地下室的单一能源中心（例如，天津117大楼（Antony Wood, 2014））, 另外一种做法是设置两个能源中心，分别位于地下室和大楼中部（例如，上海中心（Antony Wood, 2014））。无论能源中心的位置如何，对于传统的水路系统而言，过长的冷热水输送距离是导致高层建筑能耗偏高的重要原因。这样长距离的水路输配系统耗费了更多的水泵功耗，但更重要的是，建筑每35到40层需要设置断压换热器，从而把水路分割成两个或者更多的独立的环路。这样做的原因是避免过高的压力从而损坏底层的设备和阀门(Luke Leung, 2013)。每一个断压换热器通常会增加冷冻水温度1.5~2^{0}C。对于一个超高层建筑而言，通常需要两次断压，也就是说会导致3~4^{0}C的温升。这也就意味着位于底层的冷机需要产生比常规系统更低的水温以保证大楼上部的除湿能力。这样做的结果是冷机效率严重降低。

面对能源输配的难题，寻找创新性的空调系统形式成为高层建筑工程及研发领域的热点话题，而其中最有前途的技术即离散式空调系统。离散式空调系统，例如变水流量系统（VWV）或者变制冷剂流量系统（VRF），通常由高效室外机、低噪声室内机以及整体系统控制器组成。室外机通常放置于设备层。对于高层建筑而言，每20层配备一个设备层。对于中低层建筑而言，室外机通放放置于屋顶。VWV和VRF的主要区别在于VWV为实内提供冷冻水而VRF将制冷剂直接通到室内。然而，VRF在高层建筑中的应用受限于两个重要因素。第一，系统效率随着最大布管长度的增加而衰减；第二，有毒制冷剂在室内潜在的泄漏风险。随着高层建筑对于室内空气品质和安全性关注的提升，VWV成为越来越被推崇的技术。

图1所示为一个典型的VWV系统架构图。不同于中央冷冻机房，离散式系统的压缩机沿建筑高度方向垂直分布，这种特性决定了当它应用于高层建筑时，不需要额外增加换热器。因此相对于中央冷冻机房而言，离散式空调系统可以运行在更高的蒸发温度下面，从而提高制冷循环的效率。也就是说，系统可以在提供项目制冷量的情况下减少电耗。

此外，按照传统的工程方式，空调系统设计、控制以及设备由不同的公司提供，所以项目的成败严重依赖于项目团队之间的合作程度。然而往往由于暖通设计师、楼控厂家以及设备制造商意见的认识差异导致系统复杂程度增加以及能耗效率降低。而分布式空调系统，作为集成的系统解决方案，通过减少中间环节，直接面向客户，从而能提供更高的控制效率，更少的现场施工以及更少的运行调试故障。

为了评估典型空调系统在高层建筑的能耗情况，联合技术研发中心开发了一个逐时计算模拟程序。和商业软件不同的是，这个模拟程序使用了真实的设备测试数据，而不是通用的性能曲线包括冷机、热泵、空调箱及室外机。图2所示为座落于上海的知名超高层建筑的模拟结果，结果表明分布式的VWV系统消耗最少的能耗（分别低于FCU及VAV系统大约6%和40%），而冰蓄冷系统花费最少的能耗费用（低于VWV大约29%）。

此外，对于分布式系统，其能耗还能通过优化控制从而进一步提升。正是由于分布式系统整体尺寸不大，因此比中央式系统更为灵活和快速响应。智能控制器可以通过感知人员的行为、房间负荷、二氧化碳浓度及房间湿度而调节系统运行。例如，在同样的上海高层建筑案例中，如果采用负荷和湿度响应式控制策略而重设冷冻水出水温度，可以实现额外15%的节能（图3）。

创新性控制

除了系统架构的突破，控制方法的突破是提高暖通空调系统性能的另一项有效措施。暖通空调系统性能包括多方面的指标，如操作性、可靠性、可扩展性、易调试性，以及房间舒适性和系统能效。

一项关键的技术是从系统优化控制层到部件控制层的集成架构，同时整合系统自动配置技术、故障检测和诊断技术、系统优化和数据分析技术等。

在系统优化控制层，目前常用的基于简单规则的控制方法已经被广泛应用于实际项目。其优势是良好的可操作性、可靠性和可扩展性，能很方便的应用于现有的常用控制器硬件。然而，这种控制方法对于HVAC系统各子系统间的优化协调比较薄弱，比如从建筑室内环境和HVAC空气侧子系统的相互协调，HVAC空气侧子系统和水侧子系统的相互协调。此外，系统的

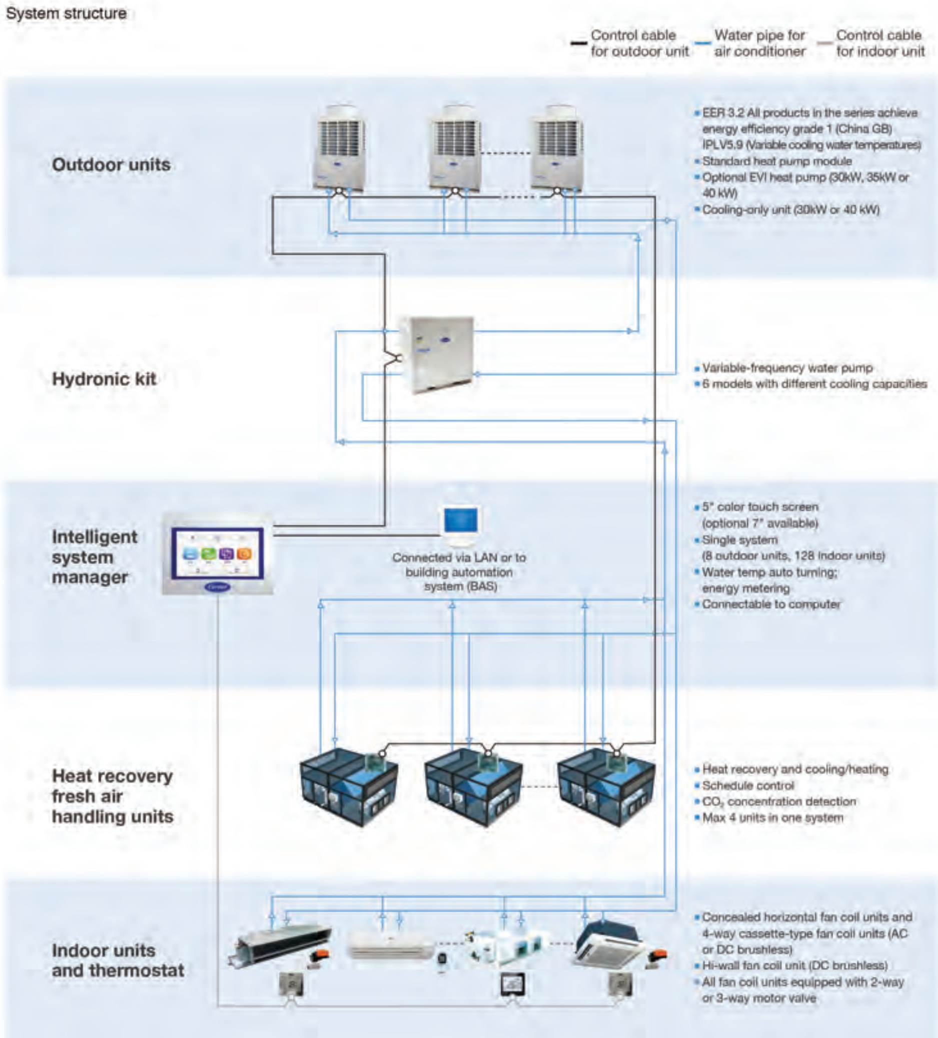

Figure 1. Typical structure of a decentralized system (Source: Carrier)
图1. 典型分布式空调系统架构图（来源：开利空调）

In the face of challenges on energy delivery, alternative HVAC systems for tall buildings are becoming hot topics in the engineering and research field, where the concept of decentralized HVAC systems is one of the most promising technologies. Decentralized HVAC systems, such as variable water flow (VWV) or variable refrigerant flow (VRF), normally consist of highly efficient modular heat pumps (Outdoor Units), low-noise fan-coil units (Indoor Units) and integrated system controllers. The ODUs are usually centralized on mechanical floors (for supertall or megatall buildings) for every 20 floors or on the roof (for low-rise or mid-rise buildings). The major difference between VWV and VRF is that the first system supplies chilled water while the latter one provides refrigerant directly to indoor units. However, the application of VRF in tall buildings is primarily constrained by two factors – the efficiency loss with the maximum piping length and the potential leakage of toxic refrigerant. Along with the increasing attention on indoor air quality and safety, VWV seems to be one of the most promising system solutions.

Figure 1 shows a typical VWV system structure. Instead of locating the chillers in the central chiller plant, the decentralized system distributes their compressors along the building height, which breaks the chilled water loop naturally without adding heat exchangers and thus allows higher evaporation temperature. This improves the efficiency of the refrigeration cycle, which means the system consumes less power when producing the same cooling capacities.

Moreover, in the traditional system design and construction approach, the HVAC system design, control and equipment are provided by different companies, so the success of a project is heavily determined by the collaborative level of the project teams; however, it always happens that the cognitive discrepancies among HVAC designers, building automatic control suppliers and equipment manufacturers give rise to the increasing complexity of HVAC systems and the loss of energy efficiency. As an integrated system solution, the decentralized system allows higher control efficiency and less on-site installation and commissioning issues.

An hourly simulation program has been developed to evaluate the energy performance of typical HVAC systems in tall buildings.

舒适性能和能效非常依赖于控制系统的调试，这需要经验丰富的工程师对于HVAC系统的长期运行跟踪。

模型预测控制（MPC）对各子系统进行建模并用于系统性能优化目标函数，进而求解优化问题从而实现整个系统能效或运行成本的最优控制。这一控制方法已经被有效应用于不同工业过程。Qin 和 Badgwell（Qin，2003)报告称，MPC在4000多个工业实例和现代化加工厂中得到有效应用。MPC最近的关键应用是在汽车和自主无人驾驶飞机和汽车自适应巡航控制系统中。然而，由于建筑HVAC系统的复杂性和多样性，对于MPC在建筑HVAC系统控制中的应用， 其主要挑战是如何应对使其易于实现并可扩展（经济实惠）。

研究团队开发了一套分层分散最优控制（HiDOpt）的优化控制方法，该控制方法具有和HVAC系统相同的拓扑结构和控制架构（分层和分散），能确保良好的扩展性，同时能在既有的控制器硬件上轻松实现（图4）。HiDOpt基于在线负荷预测、在线模型识别以及分层优化的架构，能实现HVAC空气侧和水侧的充分协调，同时能实现控制架构的自动部署。它省去了手动的模型校准以及控制参数的预调和重调，近乎完全不需要进行手动调试。

在一个中等规模建筑空气侧优化控制的实例中，测试表明，在保证同等舒适度的条件下，运用HiDOpt空气侧的优化控制使得AHU侧的制热需求降低了7%（图5）。对于大型高层建筑，由于HVAC系统相当复杂，运用现有控制策略会出现更多的能量浪费的情况，可以预见，将HiDOpt运用于大型系统可能会取得更好的节能性能，同时可节省更多的和更调试时间。

在HVAC部件控制层（例如，阀门位置及风扇转速的控制等），大量采用了PID（比例、积分、微分）控制，由一个需要保持在指定范围内的过程变量来驱动。由于负载的变化、室外气候环境的变化、设备性能的退化等因素，HVAC系统具有较强的非线性和时变特征。这使得，在系统初调阶段，PID参数需要调试，在系统运行阶段，PID参数需要重调，以保持所设计的控制性能。在现有系统的调试中，PID参数的调试一般由调试工程师手动完成，调试性能的好坏非常依赖于工程师的经验。调试不佳的PID控制会影响设备的稳定性和安全性，影响房间的舒适度，还可能会带来耗能的增加。据报道，经过良好调试的PID控制器可以减少2%–6%的执行机构磨损和原材料成本，能降低5%–15%的能源消耗（Kojic，2011年）。更重要的是，上层系统优化控制层的性能高度依赖于下层部件控制层是否能准确地将被控参数控制到其所给出的最优点，尤其是运行工况发生改变时。

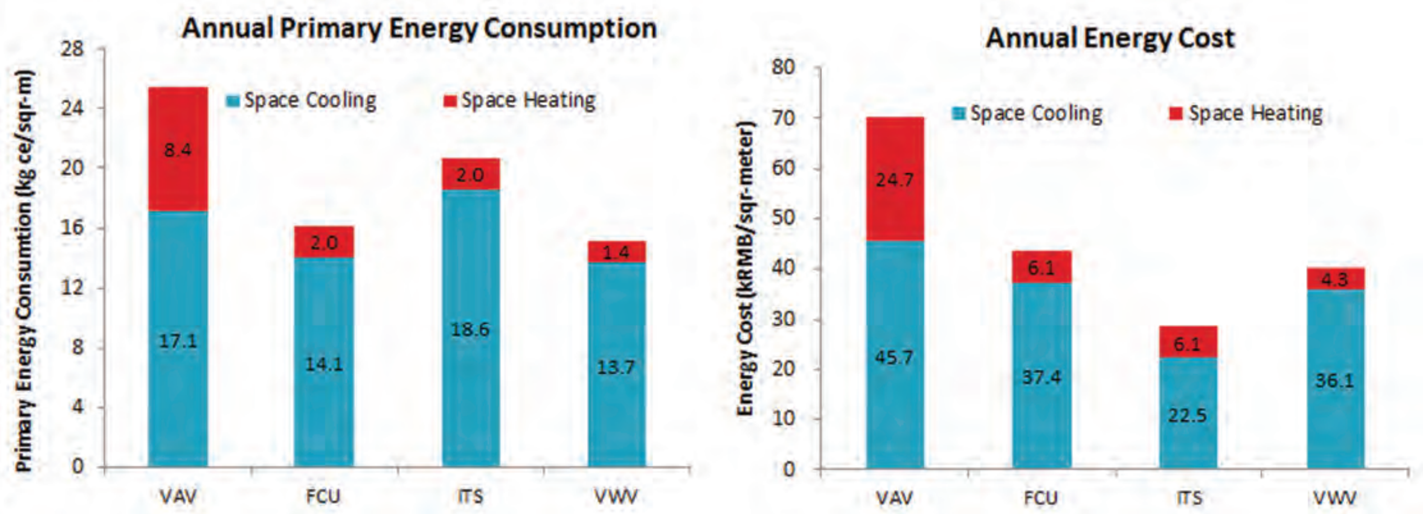

Figure 2. System energy performance for a megatall building in Shanghai (Source: United Technologies Research Center)
图2. 某上海超高层建筑的系统能耗比较图（来源：联合技术研发中心）

Instead of using generic performance data, this study adopted the actual manufacturers test data, including chillers, heat pumps, AHUs and ODUs, so that it represents the state-of-art equipment efficiency with ideal system controls. A well-known supertall building located in Shanghai was simulated and the results shown in Figure 2 demonstrate that the decentralized VWV system consumes the least energy (about six percent), and uses 40 percent less than FCU (Fan coil unit) and VAV (Variable air volume) systems, respectively; while the centralized ice storage system requires the minimum energy bill, about 29 percent less than VWV system.

Moreover, for decentralized systems, the performance could be further improved by optimizing the controls. Due to the small size of the system, decentralized systems are usually more flexible and responsive. A smart controller could automatically adjust the system operation based on occupancy behavior, room load, CO_2 concentrations, humidity, and more. For example, this case study of a tall building in Shanghai shows that a load and humidity responsive control on chilled water temperature will help reduce the energy power by 15 percent (Figure 3).

Novel Control Approaches

Besides the advanced HVAC configurations, advanced HVAC controls are another enabler for the best-in-class performance of HVAC systems. Performance of HVAC control can be measured by several characteristics including the operability, reliability, scalability, commissioning effort and, most importantly, comfort and energy efficiency.

A critical technology is an integrated control architecture that is supported by self-configuration, fault detection and

研究团队开发出了一套基于在线模型辨识和全局优化的PID自动调试算法，用于PID控制器的参数自整定。该算法会根据在线测试数据对被控对象的动态特性进行识别进而对PID参数进行自动调整。当系统控制性能不满足要求时，该算法将启动。经过该算法的自动调试，控制误差可降低50%–70%。该算法可同时对多个PID控制器进行调试。在算法中，考虑到了多个PID回路的耦合作用。将该技术运用到实际系统的调试中，预计能减少20%–50%的劳动力成本。在大型高层建筑中，有成千上万甚至更多的PID控制器，该技术的运用将能大大节省调试时间和劳动力成本。

图6所示为PID自动调试算法运用于某AHU（空气处理单元） 阀门的PID控制回路的自动测试。可以明显看出，未调试前，阀门控制十分不稳定，波动非常剧烈，这会导致阀门寿命的缩短以及房间温度控制不稳定。在激活PID自动调试算法后，阀门开度的控制稳定性显著提升，同时AHU送风温度的控制误差显著降低。

空调设备智能调试与运行

调试过程是以提高项目的交付质量为中心的过程。这个过程侧重于评估和记录调试系统和组件的计划，设计，安装，测试，操作和维护，以满足业主的项目要求（OPR）。对于建筑项目，调试是一个必要的步骤以支持设计，建造和最终的运营，来满足业主对能源，水，室内环境质量和耐用性的项目要求。提供室内舒适度的空调系统涉及到风水流量平衡，流体动力学，空气流的管理和设备的控制与协调，该系统在超高层建筑中则更为复杂，特别是在空气侧末端，数量可高达一万台。现有的设备和系统的安装实践和调试主要是由工程师人工处理，对于这样一个大量的手工重复工作，其质量是高度依赖于工程师的经验。因此，有必要以一个高度自动化的方式来验证安装和调试的质量，来保证调试的设备在全工况下的运行能够达到设计标准。同样，当建筑进入运营时，有必要定期检查设备的运行性能，以确定设备老化的水平，并为维护计划提供决策支持。

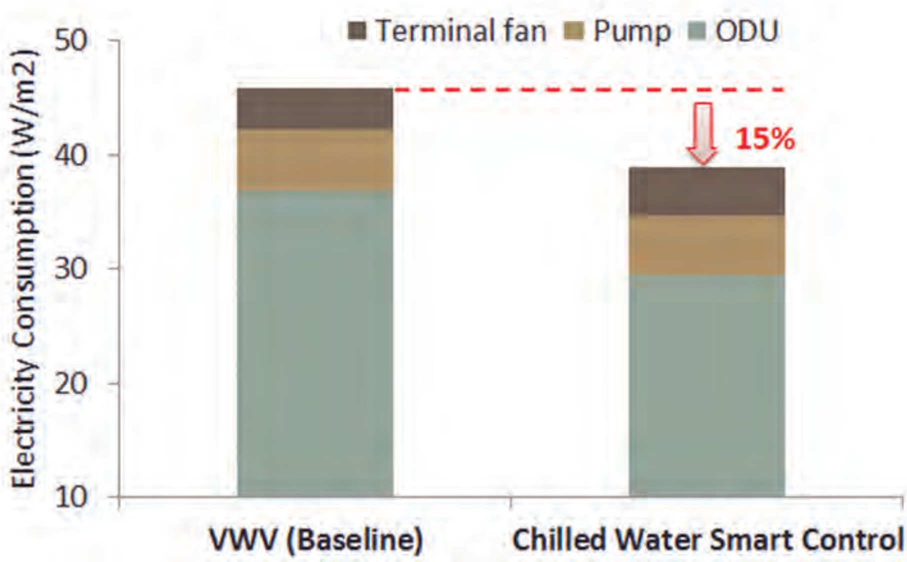

Figure3. Energy reduction by chilled water smart control for a tall building in Shanghai (Source: United Technologies Research Center)
图3. 上海某高层建筑通过采用冷冻水智能控制的能耗节约量（来源：联合技术研发中心）

diagnostics, systems optimization, and data analytics capabilities from supervisory to local control levels.

At the supervisory control level, current hierarchical rule-based controls are widely used in real applications. It has apparent advantages in terms of good operability, reliability and scalability, ensuring easy implementation in existing controller hardware, though it provides limited optimality in coordination between subsystems, such as, building to air-side HVAC coordination and air-side HVAC to water-side HVAC coordination. Furthermore, comfort performance and energy efficiency of the system highly relies on case-by-case tuning during commissioning, which requires large effort in terms of experienced engineers' labor and a significant time tracking of HVAC operation.

Model Predictive Control (MPC) considers the optimal coordination between subsystems by solving the optimization problem to minimize the system total cost (energy or dollar) based on modeling of all subsystems. It has been effectively used in a variety of industries. For example, Qin and Badgwell (Qin, 2003) reported successful use in more than 4,000 industrial applications and that in modern processing plants. Recent life-critical applications of MPC are adaptive cruise control in cars and autonomous drones and cars. The key challenge for MPC in buildings however, is how to make it deployable and scalable (and therefore affordable) given the complexity of the building and systems inside.

Hierarchical Decentralized Optimal control (HiDOpt) follows the same topology of current HVAC system and their control architecture (hierarchical and decentralized), ensuring good scalability and easy implementation in existing controller hardware (Figure 4). It is a self-deploying, advanced fully coordinated building air-side and water-side control, which is based on online load estimation, online model adaptation and decentralized optimization from layer to layer. It eliminates the need for manual model calibration and (re)tuning, with near-to-zero commissioning effort required.

In one medium-sized building field demo of HiDOpt, it showed seven percent AHU heating energy reduction without compromising comfort requirement when air-side HiDOpt operation was implemented (Figure 5). Given the system complexity and varying applications in tall buildings, it's expected the HiDOpt may show much better energy performance and more commissioning time saving.

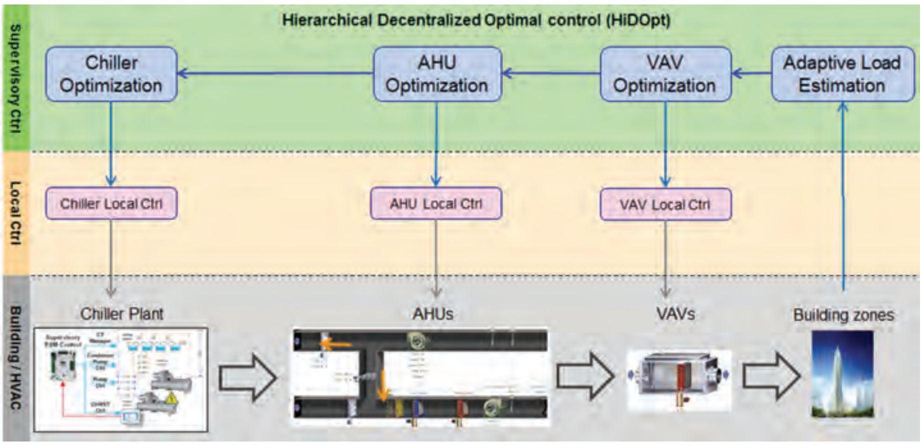

Figure 4. HiDOpt Architecture (Source: United Technologies Research Center)
图4. HiDOpt 控制架构（来源：联合技术研发中心）

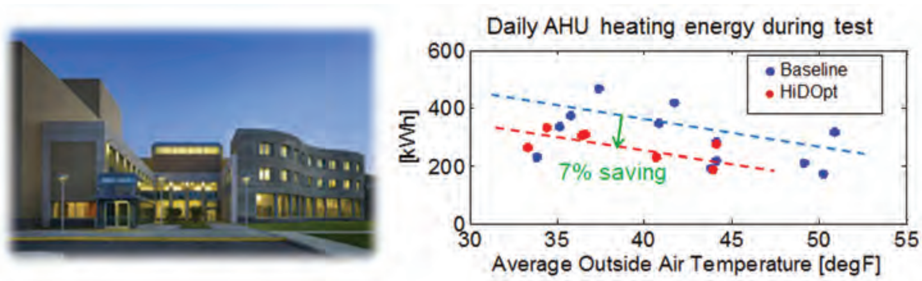

Figure 5. HiDOpt Demo Site: West Chester University, Swope School of Music Building and Performing Arts Center with a LEED Silver Rating (Source: United Technologies Research Center)
图5. HiDOpt演示实例：西切斯特大学斯沃普学院音乐大厦和表演艺术中心；LEED银评级（来源：联合技术研发中心）

At a local control level (such as to control valve positions or fan speeds), a majority of controllers in HVAC are PID controllers, driven by a need to keep a process variable within a specified range. Nonlinear and time-varying features of HVAC systems, due to load change, equipment performance degradation, outdoor weather variation, and more, require tuning (during the commissioning stage) and retuning (during the operation stage) of PID parameters to maintain the designed control performance. PID parameters are manually tuned in general, and the performance highly relies on field engineer experience. Poorly tuned PID loops will result in equipment stability and safety issues, comfort issues, and energy waste. It's reported that a well-tuned PID controller could reduce wear of actuator and raw material cost by two to six percent ((EEBPP), 2004) and reduce energy costs by five to 15 percent (Kojic, 2011). More importantly, a successful supervisory level control relies highly on the well-tuned local controller, so as to make sure the controlled variables are well maintained at the optimized set-points, in particular, when the design operation conditions are changed.

A PID auto-tuning algorithm based on online model identification and global optimization was developed. The algorithms will identify the system dynamics pattern based on monitored test data online and tune the PID parameters automatically. The algorithm will be initiated

新建的超高层建筑通常部署智能建筑系统，包括楼宇自动化系统（BAS），对本地或远程暖通设备系统进行监测和控制。在楼宇自动化系统架构上层，我们开发了空调设备智能调试与运行工具（图7）。

在调试阶段，首先会基于流体流量总和来设计设备的功能测试（如AHU），之后则根据设备按组顺序或同时来执行功能测试，开发的执行引擎可自动化利用与BAS网络服务数据接口来进行远程控制。测试完成后，所有的设备功能测试数据将采用数据分析引擎处理，通过故障的内在物理特征来提取测试设备的特征并归类，然后建议调试过程中的潜在故障源。因此调试质量既可在本地和远程审阅，也可以总动产生在线网页或离线的标准报告。

在运行阶段，首先会基于热物理和动力学对历史数据进行数据质量保证和处理，之后采用数据分析引擎进行分析。一旦有设备故障识别出，用户可以生成报告以进行维护，或者对有故障的设备进行特定的功能测试以进一步确认故障，因为功能测试在全工况下对设备运行检测，的数据质量可信度较高。

功能测试的设计与执行在与印度一栋经LEED白金认证的200,000平方英尺办公楼进行了示范，并应用数据分析算法对功能测试设备数据进行分析（图8），并得出特征提取归类与对应的故障源（图9）。识别出超过35个已知故障，之后建筑运营团

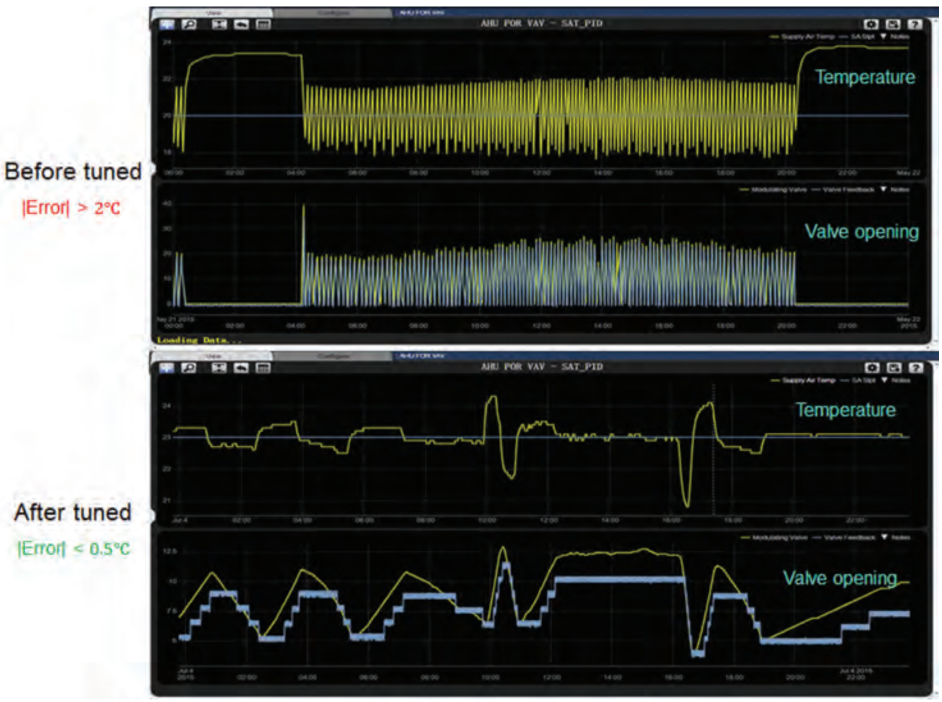

Figure 6. PID auto-tuning field demo for AHU (Source: United Technologies Research Center)
图6. 自动调试算法运用于某AHU 的阀门控制的PID参数自调试（来源：联合技术研发中心）

when the control performance doesn't meet the requirements. With the optimally tuned PID, it reduces control error by 50 to 70 percent. The algorithms can tune multiple PID loops simultaneously, and coupling between different PID loops is considered. It's expected to reduce commissioning time and labor cost by 20 to 50 percent. In tall buildings, there are thousands (or even more) of PID controllers for the whole system and significant saving of commissioning time and labor cost could be expected by applying this technology.

The PID auto-tuning algorithm was piloted in the field. Figure 6 is one field demo of this PID auto-tuning algorithm in a typical AHU valve PID controller. With the old PID parameters setting in the field (baseline), there were significant valve opening oscillations that lead to both reduced valve life and temperature fluctuations in the room. After activating the PID auto-tuning algorithm, the PID parameters were automatically tuned and the operation stability was significantly improved and control error of AHU supply air temperature was significantly reduced.

Intelligent HVAC Commissioning and Operation

The Commissioning Process is a quality-focused process for enhancing the delivery of a project. The process focuses upon evaluating and documenting that all of the commissioned systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the Owner's Project Requirements (OPR) (202-2013, 2013). For a building project, the commissioning is a necessary procedure to support the design, construction, and eventual operation that meets the building owner's project requirements for energy, water, indoor environmental quality, and durability. The HVAC system to deliver indoor thermal comfort which involves flow balance, fluid dynamics, air flow management and equipment controls and coordination; this system will become more complex for supertall and megatall buildings, especially the air-side terminals that could expand up to 10,000 units per building. Existing practice for the equipment and system installation and commissioning are mainly handled manually by the engineers, for such a large volume of units repeated manual work, its quality is highly dependent on the engineer's experience, so there is a need to verify the installation and commissioning quality in a highly automated fashion to warrant that the equipment operates as designed at full operating envelope during the commissioning stage. Similarly, when the building is in operation, there is a need to check the equipment's operational performance to determine degradation level and to provide decision support on maintenance scheduling.

Newly constructed supertall and megatall buildings usually deploy an intelligent building system that includes a building automation system (BAS) to monitor and control the HVAC equipment operation locally or remotely. Overlaying the sophisticated BAS, an intelligent

队对这些设备的故障进行了排除。实施7个月后，该楼的空气处理机组（AHU）能耗降低了20%以上（相当于1,575千瓦时 / 月）；同时，部分AHU回风管道中的二氧化碳含量从以前的1500ppm降低到设定点950 ppm，室内空气品质显著提升。

建筑气流组织控制

由于室内外温差引起的热压，驱动室内外空气的交流，这一被称作”烟囱效应“的现象在高层建筑中非常普遍。高层建筑中的各种不同竖向井道，比如说电梯井、楼梯井、以及各种各样管道井，相对于一般建筑中竖井，长度更大。强烈的“烟囱效应”在这类建筑中非常易于形成。这种效应会在建筑中造成各类问题，包括建筑入口层糟糕的热环境、由于空气泄露所额外增加的暖通系统耗能、影响门的正常运行 —— 电梯门、房间门。建筑越高，这些潜在的问题就可能会更加严重。“烟囱效应”因而成为了高层建筑中的急需解决的主要问题之一：影响建筑能耗、电梯运行安全、建筑舒适性。在高层建筑设计以及相应系统的运行过程中，需要将降低烟囱效应的策略考虑进去。现阶段，烟囱效应可以通过“被动策略”以及“主动策略”来降低。

“烟囱效应分析“

NIST CONTAM是一款被广泛接受的用于分析烟囱效应的工具。不同于简单的基于经验公式的分析方法，CONTAM仿真方法能够考虑复杂的建筑竖井结构，例如不同的电梯井布置和楼梯竖井布置。当然，这款工具要求专业的气流参数设置。另外，采用CONTAM来对一栋高层建筑的烟囱效应分析可能需要多天的建模时间。因此，在工程上对烟囱效应进行分析时，需要降低工具的学习难度，以及更高的仿真效率（图10）。

改进这一分析过程的方法是采用工程经验来简化参数设置，例如说对于门窗的泄露参数的设置；以及通过自动生成的方法来产生CONTAM的分析计算模型。UTRC开发的QuickContam工具就是这样的一款工具。它采用CONTAM作为其计算引擎来极大地提高仿真计算的效率。并且，采用这一工具可以进行敏度分析，进而分析出对烟囱效应产生影响的各种因素的重要关系，并且，也可以将它用于实施不确定性分析来分析某一烟囱效应引发事件的发生频率（图11）。

“被动策略”

“被动策略”是指那些被建筑设计团队用于减少烟囱效应发成几率的方法：设计额

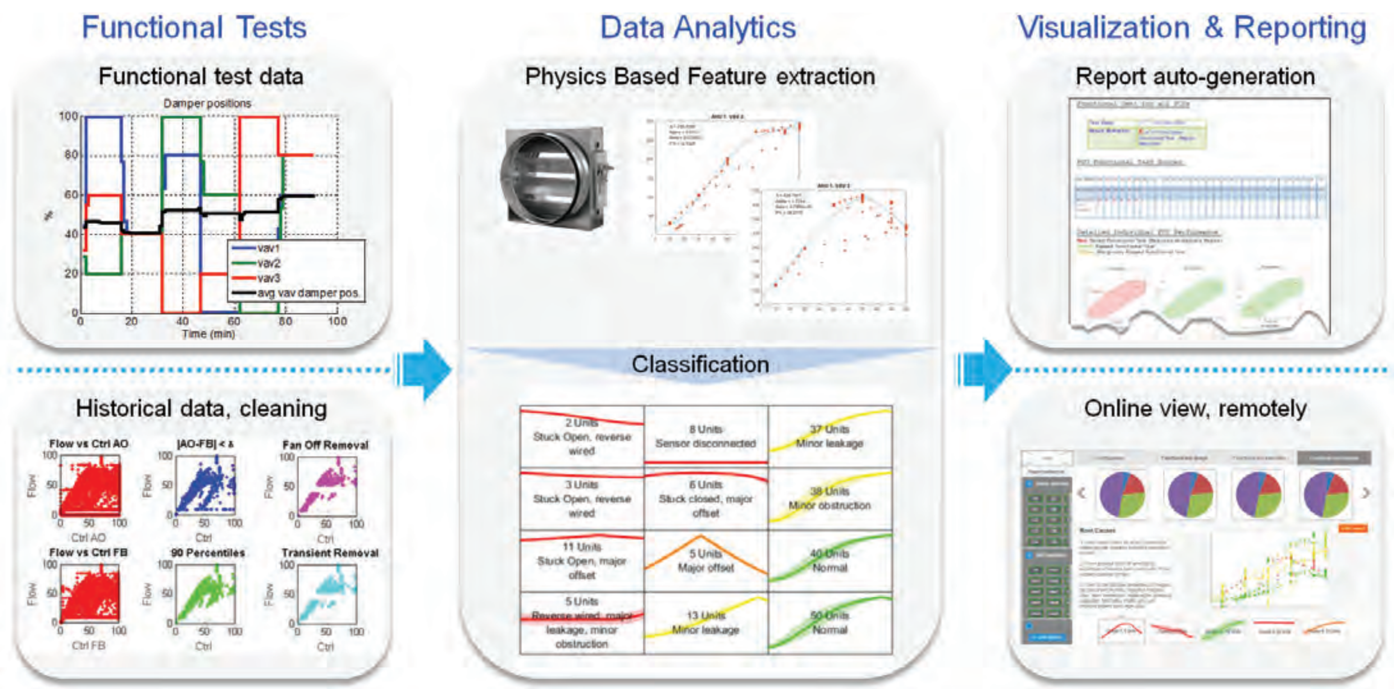

Figure 7. Intelligent commissioning and operation (Source: United Technologies Research Center)
图7. 智能调试与运行（来源：联合技术研发中心）

commissioning and operation tool was developed (Figure 7).

For commissioning, first the equipment functional tests were designed with flow capacity constraint of air supplier (like the air handling unit), then the equipment's functional test will be executed in group scenario sequentially or simultaneously; this execution engine is fully automated utilizing API to BAS web service for remote control. After tests are completed, all equipment functional test data will be applied to a data analytics engine to cluster abnormal equipment according to fault physics features, then potential root causes will be recommended. The commissioning quality can be viewed locally and remotely, online web or offline standard report.

For operation, historical data shall be cleaned based on physics before being applied to the data analytics engine. The engine will conduct same clustering and root causes recommendation, and follow up with report generation for facility maintenance guidance. This historical data analytics can be triggered periodically (such as monthly) for long-term equipment health tracking and monitoring.

The functional test design and execution were demonstrated in a 200,000-square-foot office building with LEED-PlatinumTM certification in India, and data analytics algorithms were applied to the functional test data (Figure 8) and the results are clustered with root causes (Figure 9). Based on the clustering, over 35 pre-existing faults were identified, and correction actions were taken by the facility operation team. After implementation the fault correction over seven months, this building's AHU energy

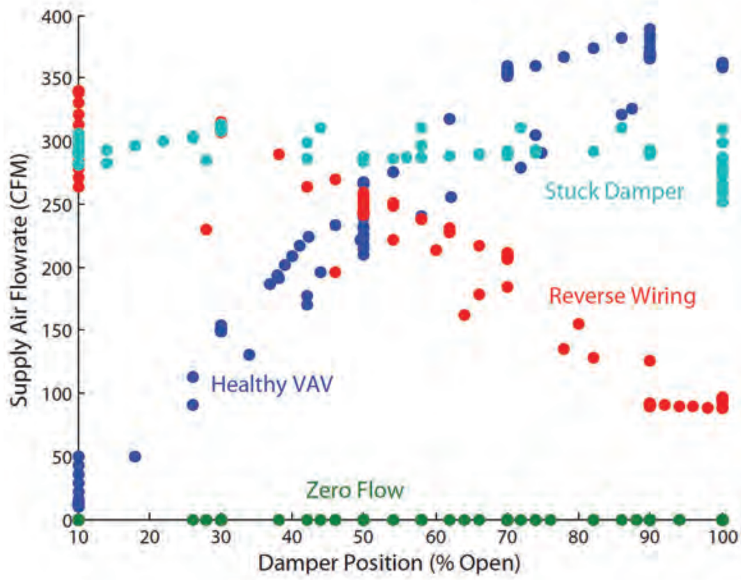

Figure 8. Functional test for variable air volume (VAV) (Source: United Technologies Research Center)
图8. 变风量系统功能性测试（来源：联合技术研发中心）

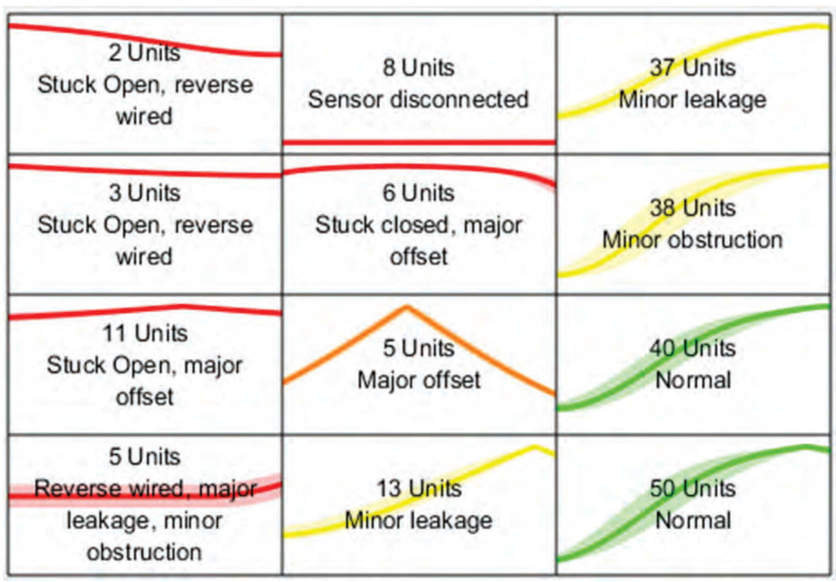

Figure 9. Root cause-based clustering (Source: United Technologies Research Center)
图9. 特征提取归类与对应的故障源（来源：联合技术研发中心）

consumption demonstrated >20 percent reduction (equivalent to 1,575 kW-hrs/month); also the CO2 levels in the AHU return ducts were decreased from previous 1500 ppm to design set-point of 950 ppm, which resulting significant elevation of the indoor air quality.

Air Flow Management

Temperature differences between indoors and outdoors cause stack pressure differences that drive airflows across the building envelope. This phenomenon is called "stack effect" and is quite typical in tall buildings. Tall buildings have many different vertical shafts, like the elevator hoistway, stairwell shafts, and mechanical wells. The long shafts provide great opportunity to form strong stack effect.

Problems caused by the stack effect include poor thermal comfort at the entrance level, extra HVAC energy consumption due to leakage, and difficult door operation – either elevator doors or the entrance door. These impacts become more significant in tall buildings. Stack effect has been seen as one of the main issues in tall buildings. The consequences caused by strong stack effect could affect energy consumption, elevator safety, and comfort level in buildings; therefore, tall building design and corresponding systems of operation have to understand stack effect and consider strategies to mitigate it. There are different ways to tackle the problem: "Passive" strategies and "Active" strategies (P. Weismantle, 2007).

Stack Effect Analysis

The NIST CONTAM (Walton, 2013) is a well-recognized tool to study stack effect. Better than simple equation-based calculation, CONTAM simulation can consider complex shafts diagram, like different elevator diagram and stair shaft design; however, the tool requires high airflow expertise for parameter settings. In addition, a tall building stack effect analysis using CONTAM would need several days to create a simulation model. Thus, an engineering stack effect analysis requires reduction of the learning curve and improvement on simulation efficiency (Figure 10).

One approach to improve the process involves defaulting parameter settings using engineering conventions, like settings for doors, leaks, and generating CONTAM project file automatically. QuickContam developed by UTRC is one tool that follows the approach. It

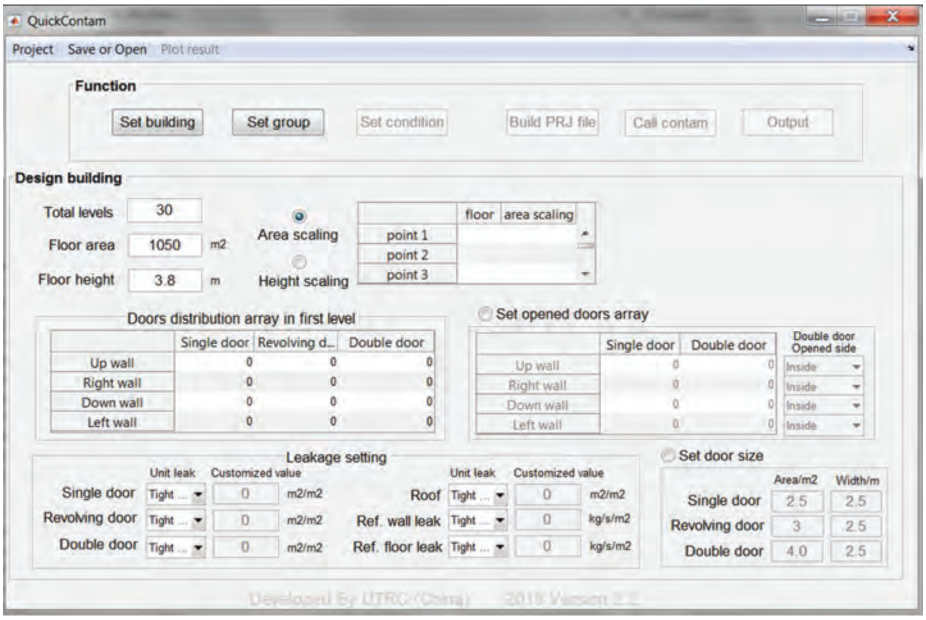

Figure 10. With NIST CONTAM as the simulation engine, the UTRC QuickContam tool can quickly set up a simulation model to conduct stack effect analysis (Source: United Technologies Research Center)
图10. 通过使用NIST COMTAM作为模拟引擎，UTRC的QuickContam工具能快速的建立起模型来进行烟囱效分析 （来源：联合技术研发中心）

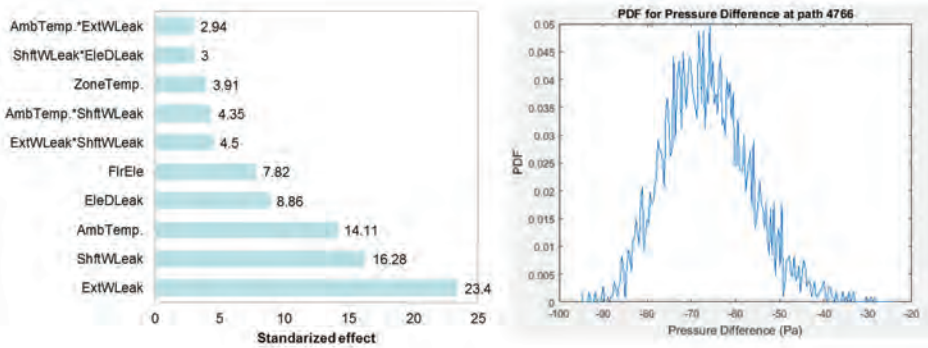

Figure 11. Enable sensitivity analysis and uncertainty quantification on stack effect analysis can help with effective mitigation (Source: United Technologies Research Center)
图11. 通过进行敏感性分析及不确定性量化分析能帮助降低烟囱效应（来源：联合技术研发中心）

uses CONTAM as the simulation engine and highly improves the simulation process. Also, it enables the possibility to conduct sensitivity analyses to rank influences from different factors on stack effect, and to analyze how frequent one occurrence caused by stack effect can occur (Figure 11).

Passive Strategies

In order to reduce occurrence chance of strong stack effect, the architecture design team takes "passive" measures to plan additional elements, or modify structure designs. These measures can be characterized to three types: "Augmentation," "Isolation," and "Segmentation."

Stack effect can be mitigated through improving the air tightness of building elements that are potentially on airflow paths. These augmented elements reduce air leakage, thus minimizing the flow caused by stack effect: reducing energy loss and pressure on elevator door.

外的建筑部件，改变建筑内部结构。这些方法主要分为三类：“增强”、“隔离”、“阻断”。

通过增强建筑围护结构的气密性，包括提高建筑外墙或玻璃幕墙的气密性、采用高气密性设计的大门，能够极大的减少通过这些围护结构的气流量。烟囱效应的影响因而能够大大的弱化：减少能耗损失、降低在电梯门上的风压。

另外一种有效的烟囱效应降低策略是“隔离”：在可能被“烟囱效应”影响的区域添加额外的建筑部件来阻断气流。这种设计包括门厅设置、压差隔离室、压差区域间设旋转门、以及双层门系统（图12）。

既然烟囱效应产生的一个重要条件是长竖井的存在，另外一种有效降低烟囱效应的方法就是将这些长竖井分隔成多个短井道。从烟囱效应的原理上看，将长竖井分隔成多个短竖井，能够有效降低高度效应，从而控制烟囱效应。例如在实际中，高层建筑的逃生楼梯会在避难层断开，从而可以避免强烈的烟囱效应所引起的烟气在楼层间的蔓延。另外，通过优化电梯组

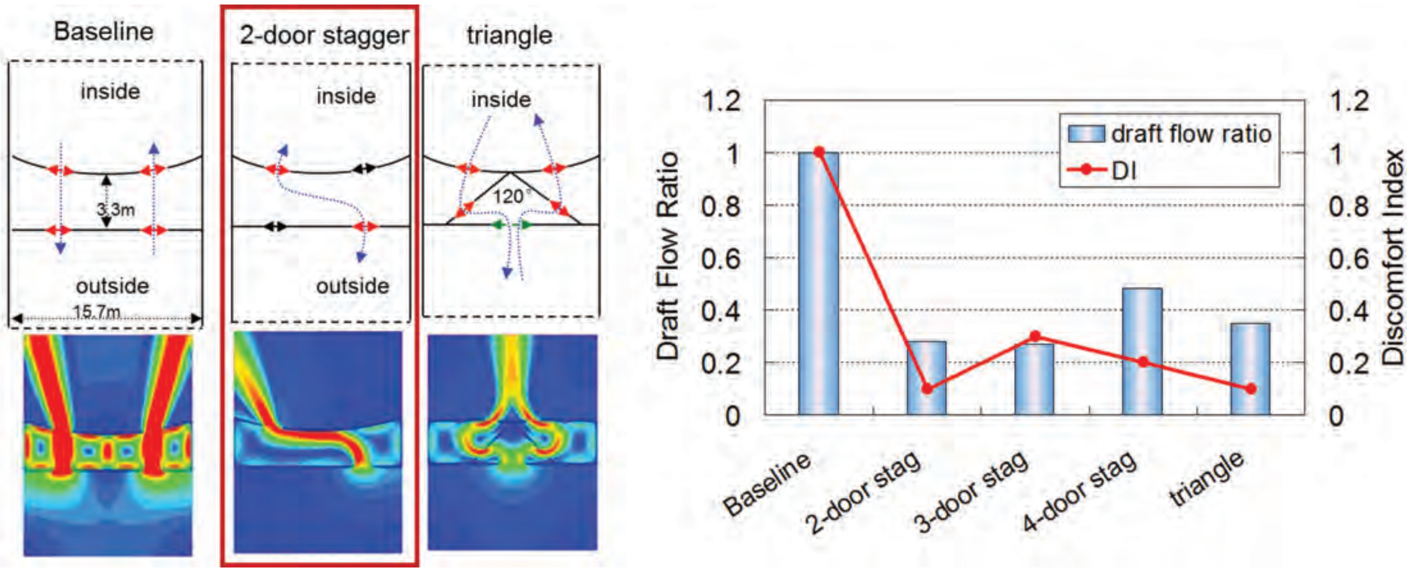

Figure 12. A case study on Shanghai World Financial Center: Through optimizing entrance door system, the draft flow caused by stack effect could be reduced efficiently, also improving comfort levels at the entrance lobby (Source: United Technologies Research Center)
图12. 上海环球金融中心案例分析：通过优化大门系统，因烟囱效应所引起的强烈的吹风感能够被有效降低，这也同样能够有效地改善门厅处的舒适感 （来源：联合技术研发中心）

Another efficient way for stack effect mitigation is the "isolation" – designing additional layers or barriers to the passage of air due to stack effect. Some example designs include the provision of vestibules, air locks, and revolving doors between areas of differential pressure, as well as the double-door system (Figure 12).

Since stack effect increases with long vertical shafts, it will be effective to mitigate it if the shafts can be split into short sections. Segmentation measure breaks the normal continuous element into shorter segments, therefore reducing the height in the stack effect equation. For instance, stair shafts in tall buildings are typically separated at areas of refuge floors. Optimizing elevator riser diagram by using shorter shafts is also a solution to avoid problems caused by stack effect.

Active Strategies

Besides above mentioned passive approach, the stack effect can also be mitigated through active designs. The "active" measures refer to actions taken in the mechanical system design. These measures are mainly focused on the elevator hoistway itself: through changing the pressure distribution in the hoistway, pressure differences between the hoistway and building open plan are reduced, and the stack effect can be mitigated. Some designs like air-conditioning or ventilating the hoistway are typical active approaches to mitigate stack effect.

There exists one way seen as active stack effect mitigation approach is to close the outdoor air dampers on lower floors during cold winter days, so to potentially avoid cold temperature in zone and reduce energy consumption. In fact, lack of outdoor air supply from HVAC system cannot pressurize the building zone sufficiently; thus, more uncontrolled outdoor air flow would be driven into the building caused by stack effect. Building openings, entrances, and HVAC system design should all take into account this unique phenomenon seen in every high-rise building.

Summary

Energy efficiency and complexity are two major factors that characterize the mechanical systems in tall buildings. The technologies in this article represent the cutting edge technologies in the whole building life cycle – design, control, commissioning and operation – that are leading the buildings towards a more efficient, simple and sustainable future.

Design

An alternative to traditional central plant design – decentralized VWV system – has proved its strong performances on energy efficiency and control flexibility. With short energy distribution distance, responsive control logics, safe chilled water loop, VWV tend to be one of the most promising system solutions in tall buildings.

Control

Hierarchical Decentralized Optimal control (HiDOpt) and PID auto-tuning represents the best-in-class self-deploying control technologies in system- and terminal-level application, respectively. The development of these advanced HVAC controls enables more reliable and easier system operation.

Commissioning and Operation

Intelligent commissioning and operation

分区设计来尽量使用短距离电梯井道，同样可以有效的避免严重的烟囱效应问题。

"主动策略"

除以上描述的被动策略，烟囱效应也可以通过主动策略来降低。"主动策略"通常是指建筑机电系统设计中所采用的烟囱效应降低方法。这些策略主要考虑的是电梯井道本身：通过改变电梯井道内的压力分布，来降低井道内外的压差，从而减少因烟囱效应导致的气流进入井道。像类似井道内空调，井道内通风的方法都可以被认为是降低烟囱效应的主动性方法。

有一种被认为是主动性策略方法是在寒冷冬季关闭建筑低层区域空调系统的新风系统，来降低烟囱效应。这种方法被认为能够避免因冷风的进入而使室内变冷，同时也能够降低建筑能耗。但事实上，由于空调系统缺少新风引入，无法给建筑内提供足够的压力以保证室内正压。因而，容易造成更多的不受控制的室外气流通过泄露进入室内，烟囱效应反而无法有效控制。在实际中，对于每一栋高层建筑的设计，应该充分地考虑这一独特的效应来设计建筑的各种开口，门窗，以及空气调节系统。

总结

高层建筑的机械系统常为以高能耗及复杂度为特征。本文所阐述的是建筑全生命周期 – 设计、控制、调试及运行 – 中最前沿的技术。这些技术能引导建筑走向更为高效、简单及可持续发展的未来。

设计

作为传统中央冷冻系统的替代方案–分布式VWV系统–在能效和控制灵活性上具有很好的性能。由于具备短距离能源输送、

technology allows the performance of the HVAC equipment to be auto tested, verified, and promptly documented, with no personnel required on-site. On the other hand, the air flow management technology mitigates the stack effect in tall buildings. Together, both of them drive the operation of tall buildings towards the direction of simplicity, health, and sustainability.

快速响应的控制逻辑、安全的冷冻水环路，VWV将逐步成为高层建筑领域最有前景的系统解决方案。

控制

分层分散最优控制（HiDOpt）和PID 自动调节算法代表了目前最前沿的自动部署式控制技术在系统层面及末端层面的应用。这些高级空调控制策略的开发有助于实现更为可靠并更为简单的系统运行。

调试与运行

智能调试与运行技术能自动测试、验证并快速报告空调设备的运行情况，不需要现场工作人员。在另一方面，气流组织控制技术能减少高层建筑的烟囱效应。这两项技术都将高层建筑的运营推向简单、健康并可持续发展的方向。

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