Smarter Cities and Their Innovation Challenges

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The transformation to smarter cities will require innovation in planning, management, and operations. Several ongoing projects around the world illustrate the opportunities and challenges of this transformation.

Cities are experiencing unprecedented socioeconomic crises. Urban growth and migration are putting significant stress on city infrastructure as demand outpaces supply for water, energy, transportation, healthcare, education, and safety. To reduce costs, improve efficiencies, and deliver the quality of life citizens expect while balancing budgets, cities are increasingly looking to information and communications technology (ICT) and new working practices.

The transformation to smarter cities will require innovation in planning, management, and operations. Several ongoing projects in Brazil, the US, Denmark, South Korea, and other countries illustrate the opportunities and challenges of this transformation.

NEED FOR SMARTER CITIES

There is an urgent need for cities worldwide to become smarter in how they manage their infrastructure and resources to cater to the existing and future needs of their citizenry. Concurrent trends in urbanization, economic growth, technological progress, and environmental sustainability are the drivers for this newfound urgency.

Urbanization

More than 50 percent of the world's population now lives in cities. By 2050, the UN forecasts this number to increase to 70 percent due to growth in the current urban population and migration from rural areas.[1] Some of this growth will be in 27 megacities with greater than 10 million people, but more than half of this growth will occur in cities that currently have fewer than 500,000 people. Urban infrastructure already experiencing stress will be hard-pressed to provide even basic services, while emerging cities will face greenfield development challenges.

Economic growth

The top 100 urban conglomerations currently account for 25 percent of the worldwide gross domestic product. By bringing people together, cities stimulate creativity and entrepreneurship, which further spurs economic activity. While the developed world has underinvested in its cities, the developing world by some estimates will need $40 trillion by 2030 for its new urban infrastructure, which presents tremendous innovation opportunities.

Technological progress

ICT advances have revolutionized all aspects of life. Two billion people use the Internet, and more than five billion are mobile subscribers.[2] There are 30 billion RFID tags embedded in our world and a billion transistors per human, each costing one ten-millionth of a cent.[3] This convergence of pervasive sensing and networking, wireless connectivity, and cheaper, faster, smaller computers has made it easier to intelligently control systems and empower people.

Environmental sustainability

There is evidence that human activity has caused unprecedented environmental change, and population growth will soon stress the world's natural resources to the breaking point. Global warming, air pollution, land degradation, declining per-capita availability of fresh water, food shortages, and reduced biodiversity are some of the starkest challenges. Top priorities for cities include sustain-

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ing water, energy, and food supplies, managing waste (95 percent of cities still dump raw sewage into their waters), and reducing greenhouse gas emissions.

Contrary to popular opinion, urban life is often greener than suburban and rural life: inhabitants consume less energy and space for living and use less energy for transportation. In developed societies, urban inhabitants are less dependent on fossil fuels and make more journeys on foot than those living in less densely populated areas.

SMARTER CITY TRANSFORMATION

It can take a decade for a city to become truly smart. Sometimes the impetus for transformation is recovery from a natural disaster, an impending large-scale event, or a sizable government investment. At other times visionary city leaders galvanize the citizenry and business community to channel their energy and resources into such a project.

Assessment

Once it has decided on transformation, a city must evaluate its needs and innovation opportunities, set clear objectives, prioritize development efforts, and establish metrics that let city planners, ICT consultants, and residents assess progress.

IBM and other organizations have created several tools to facilitate this process[4] including the Smarter City Assessment Tool, the Actionable Business Architecture, and the Municipal Reference Model. Researchers can use IBM's Component Business Model to partition a city into independent operational units, and they can apply its Smarter City Maturity Model to various domains ranging from resident-oriented services, such as social services and public safety, to structural functions, such as road maintenance and traffic management.

Assessment should be flexible enough to let cities choose the domains most important to them and provide some means of projecting costs and measuring progress—for example, how well various agencies are integrating operations and sharing data. Applying maturity models to numerous cities has also revealed common patterns that can help guide investment strategies and predict the outcome of adopting a particular approach. For example, investing heavily in road expansion without a smarter transit policy can reduce the use of public transportation.

A 'system of systems'

As Figure 1 shows, at the highest level, a smarter city integrates and optimizes a set of interdependent public and private systems to achieve a new level of effectiveness and efficiency. These systems are increasingly both producers of information and consumers of one another's information, although interactions can also be indirect. Hence, a smarter city can be viewed as a "system of systems."

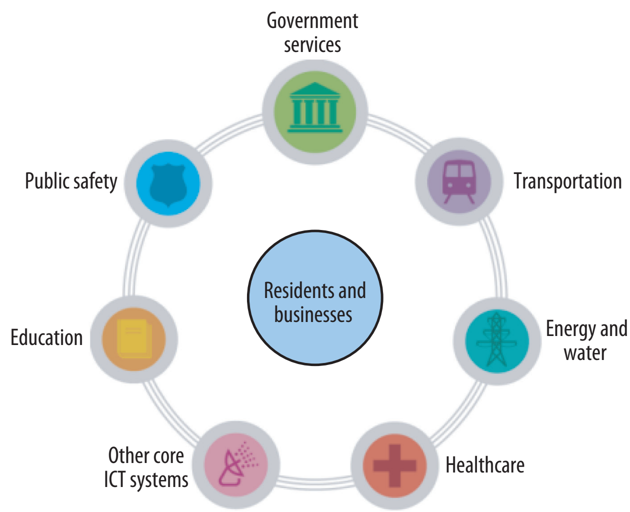

Figure 1. A smarter city constitutes a "system of systems"—a set of interdependent public and private systems that the city can integrate and optimize to achieve a new level of effectiveness and efficiency.

Smarter city transformation relies on the use of powerful analytical techniques to extract insights from real-world events to improve urban business processes. These processes can be broadly divided into planning, management, and operations.

Planning. A smarter city provides urban planners with tools to exploit various sources of information about human behavior to aid in the allocation of resources—land, water, transportation, and so on—as the city evolves. Holistic modeling of the city's ecosystem provides quantitative support for strategy development, performance evaluation, identification of emerging best practices, and integration of initiatives. Analyzing data from other comparable cities can help planners calibrate urban dynamics models and compare their relative progress.

Management. A smarter city can coordinate infrastructure management activities—the creation and maintenance of roads, equipment, and other assets—by providing cross-agency visibility of planned interventions. For example, the electrical utility's replacement of a cable under a street intersection might offer traffic managers an opportunity to save money by replacing a signal at the same location. By providing a time dimension, smarter city data can reveal historical views of each domain and enable managers to project its evolution.

Operations. A smarter city integrates multiple data sources to represent the interdependence of urban domains in real time. For example, electrical utilities can combine sophisticated models of near-term demand based on historical usage patterns (day of week, holidays, local weather, major events, and so on) with real-time traf-

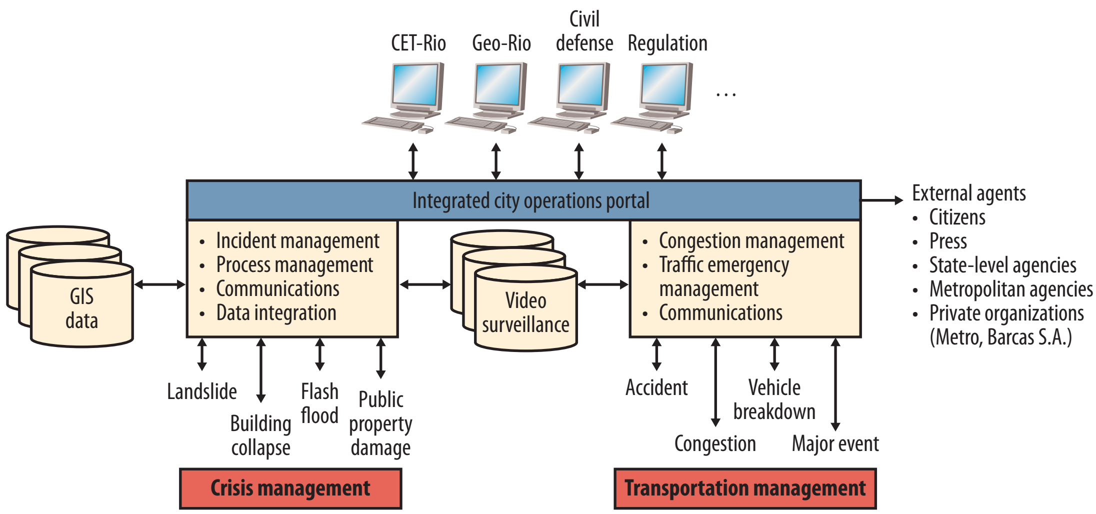

Figure 2. Rio de Janeiro's Operations Center integrates dynamic, real-time data and multiple systems to improve crisis and transportation management.

fic information that could impact future demand. Thus, awareness of a major delay in outbound commuter traffic in the early evening could let the utility project a delay in demand because those commuters will arrive home late. The utility could likewise use real-time weather data to predict the location of cables damaged in a rainstorm.

EXAMPLE SMARTER CITIES

Examples of cities of various size, geography, and economy illustrate different aspects of smarter city transformation.

Rio de Janeiro, Brazil

Every summer, Rio de Janeiro faces the consequences of intense rainfall, including landslides and flooding. In April 2010, the region endured one of the worst series of torrential rainstorms in decades, in which mudslides killed more than 200 people, left tens of thousands homeless, and caused more than $13 billion in damage (http://en.wikipedia.org/wiki/April_2010_Rio_de_Janeiro_floods_and_mudslides). The resulting chaos, loss of life, and destruction of property motivated state and city authorities to implement advanced ICT capabilities in Rio to better manage disasters and emergencies as well as planned events of national importance.

Using a substantial monetary investment resulting from the city's selection to host the 2014 World Cup and the 2016 Summer Olympics, and under the visionary leadership of Rio's mayor, Eduardo Paes, the city has embarked on an ambitious program to connect multiple systems to improve crisis and transportation management.

The Rio Operations Center[5] opened in December 2010. As Figure 2 shows, it includes an incident management system that will help the city to prepare for and respond to flood-related incidents and a process management system through which multiple agencies can make coordinated and intelligent decisions based on dynamic data from weather sensors, video surveillance, and field personnel, overlaid on a comprehensive geographic information system (GIS). As this system evolves, researchers can integrate data from transportation systems, buildings, and possibly energy, water, and other subsystems into the Rio Operations Center to create a true closed-loop system.

Dubuque, Iowa

The city of Dubuque is an example of a smarter city in which an economic crisis motivated a transformation. Following the demise of the wood-milling industry in the 1980s, this city of 60,000 has evolved into a vibrant hub of sustainable development by using ICT to optimize resources and operations for its citizens and city management. This has led to one of the fastest urban economic turnarounds in the US, with a diversified workforce and local industries working to make water, energy, and buildings sustainable.

In 2006, Dubuque created a sustainability model with three major themes: economic prosperity, sociocultural vibrancy, and environmental integrity. The model was based on 11 core principles including smart use of energy, water, and other resources; green buildings; reasonable mobility; and greater community knowledge.

Three years later, Dubuque partnered with IBM to become a living lab for smarter city sustainability management that monitors water and electricity consumption in homes using smart meters and provides guidelines and incentives to residents to optimize their individual consumption.[6] Figure 3 shows the citizen dashboard for integrated sustainability management.

Dubuque has been a pioneer in putting citizens at the center of smarter city transformation, a vital aspect that is often ignored. The city also integrates planning, management, and operations both to minimize its carbon footprint and to encourage economic growth.

Bornholm, Denmark

On Bornholm, Denmark, an island of 40,000 inhabitants, international researchers are developing a system that integrates electric vehicles (EVs) into the local power grid, which relies heavily on renewable wind power. As Figure 4 shows, the EDISON system—Electric Vehicles in a Distributed and Integrated Market Using Sustainable Energy and Open Networks (www.edison-net.dk)—includes a network of public and personal charging stations and integrated technologies to manage the charging of EVs as well as load balancing, billing, and so on.

In addition to reducing carbon dioxide emissions, EVs can act as supplemental storage devices that send power back to the grid when needed. Offshore wind power provides 20 percent of Denmark's electricity, and as part of a long-term strategy to increase that figure to 50 percent, the government hopes to deploy some 200,000 EVs nationwide by 2020.[7]

Songdo IBD, South Korea

Seoul, the capital of South Korea, already has an advanced ICT infrastructure that provides inexpensive, superfast broadband access to its more than 24 million citizens from virtually anywhere within the city limits. In addition to accelerating the country's economic growth, this universal connectivity has transformed governance, resulting in the world's most advanced and efficient e-government.[8] Among the many benefits of this transformation is greater transparency—the online disclosure of all bids for government contracts has significantly reduced corruption.

Work is now under way on the Songdo International Business District (www.songdo.com), a ubiquitous ecological (u-eco) city 40 miles west of Seoul on reclaimed land in the Incheon Free Economic Zone. When completed in 2015, Songdo IBD will include 80,000 apartments, 50 million square feet of office and retail space (including the 68-story Northeast Asia Trade Center, the tallest building in the country), a hospital, arts and convention centers, an

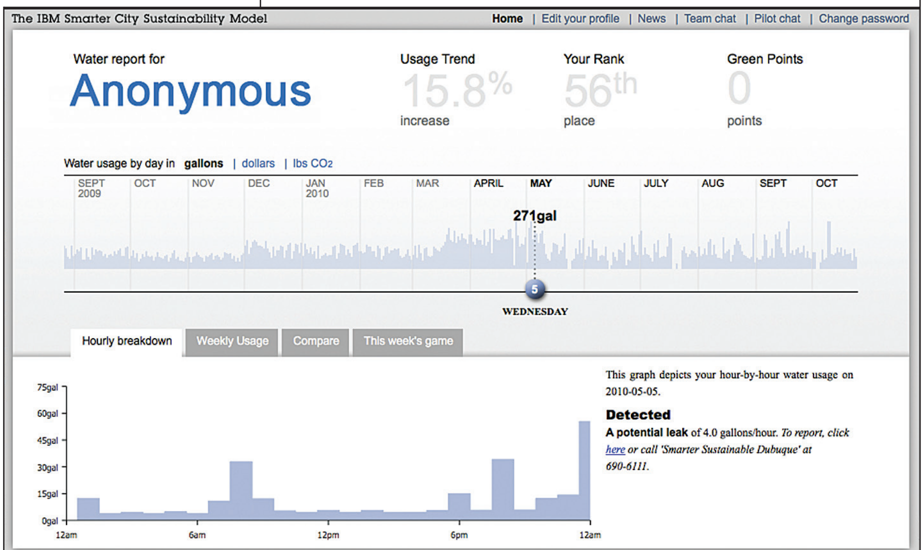

Figure 3. Citizen dashboard for integrated sustainability management in Dubuque, Iowa.

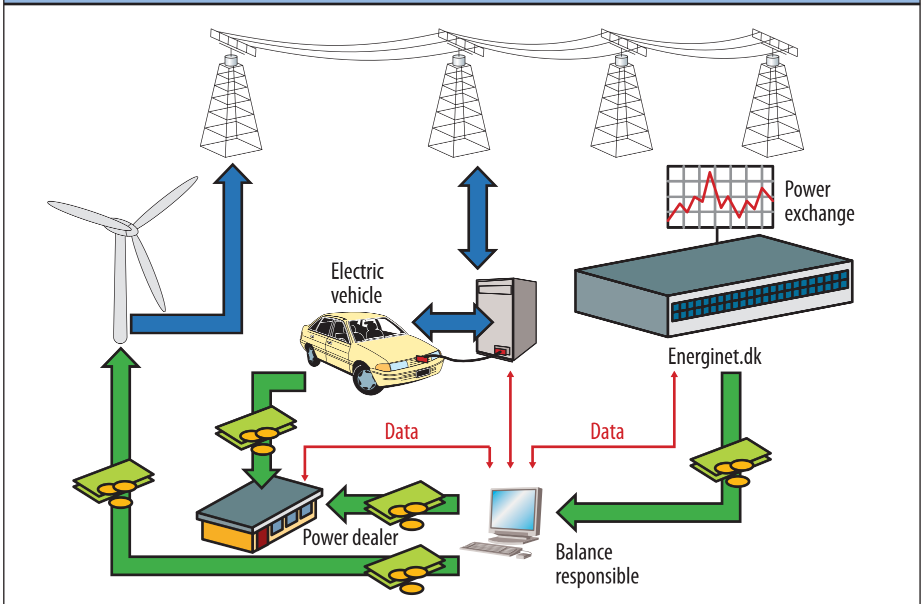

Figure 4. On the Danish island of Bornholm, the EDISON project—Electric Vehicles in a Distributed and Integrated Market Using Sustainable Energy and Open Networks—is developing a system that integrates electric vehicles into the local power grid, which relies heavily on renewable wind power.

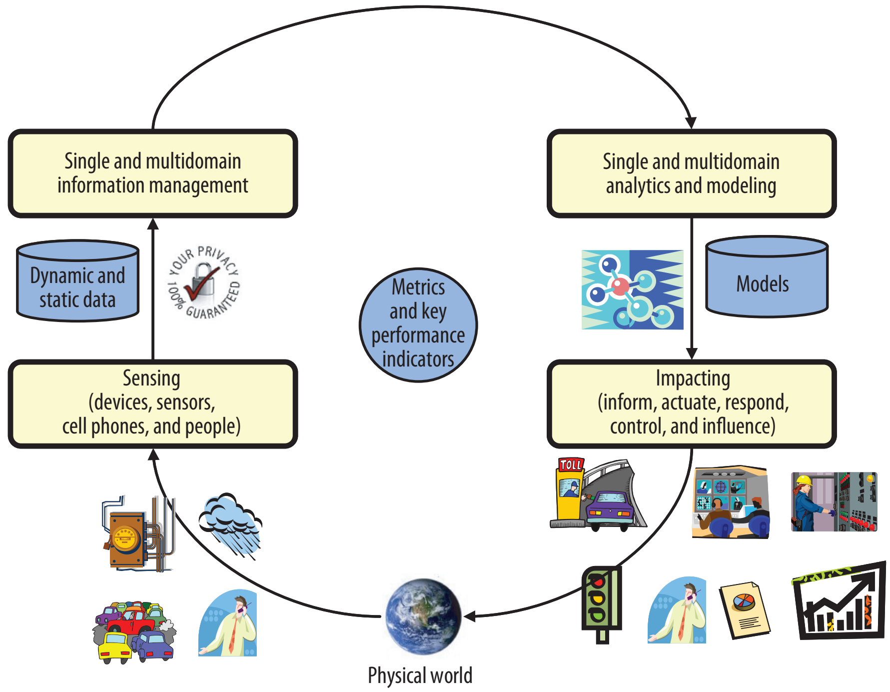

Figure 5. Smarter cities technology innovation framework. To optimize key metrics and performance indicators, all systems must be integrated in a closed loop.

academic complex, and 600 acres of open space, making it the largest private real-estate development in history.

A wide-area network of computers will link Songdo IBD's structures and offer citizens and businesses various digital services. For example, individual apartments feature panels in each room that control lighting, temperature, and access to media; 20,000 residential units will feature telepresence technology. A green, state-of-the-art datacenter will help manage all aspects of urban life, from traffic control to water and energy use to recycling.

Other smarter cities

Many other cities and regions around the world are using technology innovation to improve their planning, management, and operations.

Malta is creating the world's first countrywide smart grid, using ICT to optimize its water and energy systems.[9] Stockholm, Sweden, has implemented a system that automatically charges drivers a fee based on how much they drive (using control points outfitted with lasers and cameras) to reduce congestion and greenhouse gas emissions.[10] India's Gujarat International Finance Tec-City (http://gift-gujarat.in/index.aspx) is a greenfield development using advanced technology to, among other things, eliminate discharge waste and achieve 90 percent use of public transit. Portland, Oregon, is using a system dynamics model to discover and coordinate dependencies among key city systems. And Singapore is aspiring to become an innovative technology leader by using ICT to achieve water sustainability and to manage traffic and energy.

INNOVATION CHALLENGES

Figure 5 illustrates the ideal of a smarter city as a closed loop of interconnected city systems. These systems can be characterized by function: sensing, information management, analytics and modeling, and influencing outcomes. To optimize key metrics and performance indicators, all of these systems must be tightly integrated.

Sensing a city and its inhabitants

A city is full of sensors—smart water and electric meters, mobile phones, GPS devices, traffic sensors, parking meters, pipe sensors, weather sensors, building sensors, and so on. Even people can be sensors—using crowdsensing to gather intelligence on city operations is an emerging research area. The main innovation challenges in sensing a city and its inhabitants are trading off cost with quality and dual usage, and ensuring privacy and security.

Cost versus quality. Cheap, ubiquitous sensors can be used in large numbers, but their noisy, low-quality signals impose a nontrivial burden on analytics systems and might also require frequent calibration and diagnostic evaluation. In contrast, high-cost sensors with embedded intelligence can make analysis simpler and more accurate, and may be self-calibrating and -diagnosing, but cannot be installed in the quantities needed to cover large areas.

Cost versus dual usage. A sensor used for purposes for which it was not originally intended will not yield high-quality data, but replacing it with the proper sensor or augmenting it with another sensor can be prohibitively expensive.

Dubuque, for example, uses smart electric meters in homes to aggregate resource consumption at 15- or 60-minute intervals. Originally designed for billing and dynamic pricing, these meters are not as accurate as having a sensor on every electrical device. Disaggregating energy use for each house requires sophisticated analytics but is currently cheaper than instrumenting homes with a large number of localized sensors. This problem could be alleviated if future appliances have built-in functionality to report their energy consumption to home-area networks.

Another example is the use of mobile phones for location sensing. Mobile phones can be used to estimate users' locations through the data generated at cell towers. This is an inexpensive way to measure positional data and enables a plethora of smarter city applications such as traffic management and emergency response—a particularly attractive option for a developing economy—but its high range of error would require sophisticated analytics.

Privacy. The sensors that produce the best data and enable the most effective modeling are also the most intrusive, and thus more likely to make inhabitants of the environment being sensed uncomfortable. This is another reason why putting energy-monitoring devices on every home appliance is currently impractical.

Security. Significant research is needed to ensure that both sensors and actuators are secure when it comes to the acquisition, storage, and transmission of information. Tampering with or snooping on sensed data could result in nightmarish scenarios ranging from thieves knowing when residents are not at home to terrorists turning off a city's power and water. Cybersecurity must be taken to a new level before sensors can be deployed on a massive scale.

Managing information across all city systems

The main research challenges in managing smarter city data are the need for common information models and the ability to safely share information across multiple agencies within a city and among multiple cities in a metropolitan region.

Information models. To ensure end-to-end visibility while managing smarter city infrastructure and services, it is necessary to integrate data from disparate sources, each with its own sampling frequency, latency characteristics, and semantics. For example, information related to roads is scattered across many agencies including transportation, urban planning, public works, emergency services, public safety, and environmental management.

Creating and applying a unified information model makes it possible to obtain a more complete picture of urban activity. The ability to understand how combinations of factors contribute to, say, a rapid increase in the demand for water or an unusually high accident rate on a stretch of road in turn facilitates better operational decisions.

A principal technology base for managing spatial information and entities in cities is a GIS with associated databases and mapping tools. In the future, this model will be extended to include not only static data such as topography, land use, and the built environment but also dynamic information such as service delivery, resource consumption, and the movement of people (which can be used to infer behavior), vehicles, and freight.

Privacy, security, and access control. Securing data from sensed urban environments is a major research challenge. City datacenters constitute the largest potential single point of failure and thus require the most stringent security. Authorities must also design and implement privacy policies to prevent unauthorized access to data. In addition, access control mechanisms must be in place to ensure that visualization, analytics, and modeling applications do not misuse data. For example, mobile phone data used to sense traffic congestion with the explicit approval of the devices' owners should not be used to issue speeding citations.

Securing and controlling access to a plethora of data streams and applications will require a fairly agile, real-time implementation engine. New models are also needed to encourage the utmost transparency within required constraints.

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Standards and interoperability. Different cities and even different agencies within the same city adopt different models to manage information. Some industries, such as the electrical utility industry, have a well-developed set of standards, while others, such as the water utility industry, seem unaware of the concept. Initiatives like the Municipal Reference Model,[11] developed by the Municipal Information Systems Association of Canada, aim to incorporate the perspectives of the many stakeholders involved in urban infrastructure and services. More such models should be developed and refined through an open industry process.

Observing and understanding city activity

The availability of massive amounts of sensed information opens up fascinating opportunities to understand city activity through modeling and analytics. This will require real-time and batch analysis of heterogeneous data with cross-domain dependencies in the presence of significant uncertainty and variability.

System models. Models of city systems must be statistical as well as physical. For example, Dubuque and Malta model resource consumption at both the individual and community level, Stockholm models traffic congestion, and Denmark's EDISON project models wind power generation and EV-based energy storage. Traffic management, emergency response, and other such services in Rio rely on weather prediction models.

The challenge in building such models is the lack of ground-truth data to accurately calibrate and train them. Models need to be bootstrapped with existing data and adaptable to changes in the state of the city. Another set of challenges revolves around the difficulty of predicting human behavior—for example, how residents will respond to green incentives.

Analytics. By studying how its systems interact with one another and with users over a long period of time, a city can operate its infrastructure and services more effectively—the equivalent of a company applying enterprise resource planning. Recurring patterns, anomalies, and evolving events in models can reveal important insights, and "what if" scenarios can help in planning.

For example, Stockholm's traffic congestion models enable better road-use charging policies, Rio's fine-grained rainfall prediction models facilitate emergency planning and traffic management, Singapore is using sophisticated traffic models to optimize transportation operations, and Dubuque's energy consumption models help Iowa's utility board and energy independence office perform statewide energy policy planning.

Influencing outcomes

The ultimate goal of introducing smarter city technology is to optimize control of city systems and to offer citizens both a wider range of choices and real-time feedback to influence their behavior and thus obtain better outcomes.

Optimal system control. Conceptually, a smarter city can be viewed as an interdependent collection of closed-loop systems. At the physical engineering level, a closed-loop system can be likened to a process control system automatically (except in extreme cases) regulated through appropriate feedback and control. At the decision support level, a closed-loop system is automated to a limited degree through the application of rule-based models.

Optimizing resources across all systems as well as within each subsystem is a challenging problem that must address cross-domain and cross-system dependencies that may also be cyclic. In the EDISON project, for example, grid electricity capacity in part depends on how much power EVs store, but the energy they feed back to the grid depends on their usage, which in turn depends on traffic congestion. Managing energy generation and storage and managing vehicle use are each difficult, but optimizing the two systems together is a highly complex cross-domain resource optimization problem. Ensuring fail-safe operations of interdependent systems is also critical.

Human-city interaction. People are at the center of a city's transformation into a smarter city. They are important sources of data, both about themselves and about the physical world, and can become willing participants if they can easily provide the data—for example, through mobile phones—and if they see the value of the information resulting from their contribution. While information models and analytical algorithms can organize data, provide insights, and make simple decisions, it will be up to humans to make the complex decisions.

Modeling, understanding, and influencing human behavior, providing location-aware information and feedback, and cultivating trust in smarter city technologies are key challenges that will draw on work in psychology, user experience design, urban systems, location-aware services, game design and game theory, and social computing.

Research will focus on what information to present to users, when and how to present it, and what reactions to expect. It will also explore how to motivate positive behavioral change. For example, Dubuque matches 50 percent of the costs of fixing household water leaks if users report the leaks and follow through on repairs, and its insightful feedback on water consumption has increased conservation by 10 percent. Likewise, Seoul is using its citywide Internet connectivity to incentivize use of public transit by providing online information to drivers about insurance discounts, reduced-cost parking, and a tax break for leaving their cars at home one business day a week.

Cities must get smarter to address an array of emerging urbanization challenges, and as the projects highlighted in this article show, several distinct paths are available. The number of cities worldwide pursuing smarter transformation is growing rapidly. However, these efforts face many political, socioeconomic, and technical hurdles.

Changing the status quo is always difficult for city administrators, and smarter city initiatives often require extensive coordination, sponsorship, and support across multiple functional silos. The need to visibly demonstrate a continuous return on investment also presents a challenge. The technical obstacles will center on achieving system interoperability, ensuring security and privacy, accommodating a proliferation of sensors and devices, and adopting a new closed-loop human-computer interaction paradigm.

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