Foundations for Smarter Cities

C. Harrison
B. Eckman
R. Hamilton
P. Hartswick
J. Kalagnanam
J. Paraszczak
P. Williams

This paper describes the information technology (IT) foundation and principles for Smarter Cities™. Smarter Cities are urban areas that exploit operational data, such as that arising from traffic congestion, power consumption statistics, and public safety events, to optimize the operation of city services. The foundational concepts are instrumented, interconnected, and intelligent. ***Instrumented*** *refers to sources of near-real-time real-world data from both physical and virtual sensors.* ***Interconnected*** *means the integration of those data into an enterprise computing platform and the communication of such information among the various city services.* ***Intelligent*** *refers to the inclusion of complex analytics, modeling, optimization, and visualization in the operational business processes to make better operational decisions. This approach enables the adaptation of city services to the behavior of the inhabitants, which permits the optimal use of the available physical infrastructure and resources, for example, in sensing and controlling consumption of energy and water, managing waste processing and transportation systems, and applying optimization to achieve new efficiencies among these resources. Additional roles exist in intelligent interaction between the city and its inhabitants and further contribute to operational efficiency while maintaining or enhancing quality of life.*

Introduction

Cities are arguably the most important social, economic, cultural, and defensive structures that humankind has ever produced. The importance of technology in improving the operational efficiency and quality of life in cities has long been recognized. Earth and stone works were built as early as Neolithic times [1] to provide defense against enemies and protection against weather. Some 3,000 years ago, Persian engineers dug a Qanat [2], a long tunnel connecting a well to its outflow many miles away. Iran still has some 20,000 of these structures, and until recently, this ancient example of forward thinking still provided the entire water supply for Teheran—a city of one million inhabitants. Around the world, similar innovations were followed by sewer systems that dramatically improved public health, canal and railway systems that greatly expanded the scalability of cities, and finally telecommunications—telegraph and telephone—that allowed virtual mobility within and between cities. Now, following the benefit achieved by civil, mechanical, and electrical engineering, we begin to see the potential benefits that can be achieved through the application of information technology (IT). This paper describes the types of challenges that IT can address and how IT can be applied to them.

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Problems in contemporary cities

The technology advances noted above and many others have made cities creative, vibrant, healthy, and secure places to live. United Nations estimates [3] indicate that 50% of the world's population now resides in urban areas, population growth will continue in many of these, and the pace of urbanization is increasing. The coastal cities of China, such as Shanghai, are visible examples of these trends. On the other hand, developed economies that have been heavily affected by the globalization of their historical industries are faced with declining populations and the loss of their younger generations to more vibrant environments. The industrial cities of the Midwestern United States, such as Dubuque or Detroit, are examples of the latter. The trends noted above create an increasing number of challenges. A broad range of urban resources and services, including road and transportation system capacity, electrical power, effluent emission, fresh water, public health, and public safety, are subject to increasing pressure.

In India, China, and other emerging economies, we see large-scale migrations from rural areas to cities as globalization leads these countries to make the transition from agrarian or industrial economies to postindustrial economies [4]. Many of these countries also face continued growth in their populations through the middle century, indicating that stresses will continue to increase on physical infrastructure and city services such as electrical and water utilities, networks of roads and bridges, public safety, and air quality.

Conversely, in more developed economies, many industrial and manufacturing cities of the Industrial Age have seen their economic bases eroded through the economic globalization that took place in the late twentieth century [5]. These cities now face an urgent need to redevelop their infrastructures to globally compete. To be globally competitive implies creating a desirable place for educated professionals to live and work, attracting new high-growth industries, and ensuring both continued external investment and a strong tax base. Sustaining or improving the quality of life through improvements in city services and resources is a foundation for such competitiveness.

The development of new cities, as well as the redevelopment of existing ones, is occurring at a time when environmental sustainability is becoming a major consideration for national and local governments and, thus, is also increasingly becoming a key factor in the attractiveness of a city. See, for example, among many others, the Applied Solutions Coalition [6]. High-density areas such as cities are efficient from the point of energy consumption, since, for example, they encourage walking instead of the use of vehicles for much movement of people and since the sharing of much physical infrastructure reduces the embodied carbon dioxide per capita and improves the efficiency of resource consumption. See, for example, the Congress for the New Urbanism [7]. On the other hand, high-density areas increase the risk of propagation of disease and may increase the prevalence of crime.

Smarter Cities

One working definition of a Smarter City is "connecting the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city." Thus, the Smarter City continues the long-standing practice of improving the operational efficiency and quality of life of a city by building on advances in IT. In a Smarter City, the traditional concept of a physical city infrastructure is extended to a *virtual city infrastructure*, an integrated framework that will allow cities to gather, integrate, analyze, optimize, and make decisions based on detailed operational data. This infrastructure includes deployed sensors, both distributed and centralized processing capability, transmission bandwidth, and accompanying software models and presentation logic to support human decision makers. Our hope is that this virtual city infrastructure and the enhanced decision making that it enables will have a major impact on life in the city, equal to that of many of the major historical innovations in urban infrastructure.

Our concept of Smarter Cities emerged from a 2008 study known as the Instrumented Planet [8]. The central observations of this study were that, in many aspects (although not all), Earth is becoming increasingly instrumented, that pervasive networks are available to collect real-world sensor data, and that inexpensive computing power is available to analyze such data. Furthermore, this study indicates that significant benefits could be achieved by using those data to connect physical events to advanced analytic capabilities, with resultant improvements in intelligent integrated city control and management systems. We refer to such systems in general as Smarter Planet* systems [9], of which Smarter Cities are a major subset. As a result of the Instrumented Planet work, IBM has defined its view of a Smarter Planet system through three IT characteristics or dimensions, as follows.

- *Instrumented*—Instrumentation enables the capture and integration of live real-world data through the use of sensors, kiosks, meters, personal devices, appliances, cameras, smart phones, implanted medical devices, the web, and other similar data-acquisition systems, including social networks as networks of human sensors. The combination of instrumented and interconnected systems effectively connects the physical world to the virtual world.
- *Interconnected*—Information obtained from instrumentation data is integrated throughout an end-to-end process, system, organization, industry, or value chain. In addition, such data may be interconnected across multiple processes, systems, organizations, industries, or value chains. Interconnection may also bring together information that exists in an unstructured way or *en masse* and not associated with a system in particular. For example, Web 2.0 interconnectivity across social networks, search engine queries, and other such logical constructs offers meaningful information but exists across a mesh of physically distributed systems.
- *Intelligent*—The analysis of this interconnected information must yield new insights that drive decisions and actions that improve process outcomes or system, organization, and industry value chains. Such outcomes must fundamentally change the end-user experience or ecosystem, that is, they must demonstrate tangible value-add. The best examples will also have intelligence that is near real time, forward looking, or predictive.

This paper describes some of the major needs of contemporary cities and how the IBM vision of a Smarter City can meet those needs. This paper is organized as follows: First, we present our decomposition of the roles of IT into instrumented, interconnected, and intelligent systems. We give simple examples to illustrate each of these aspects in turn and conclude with some of the many open issues in this new application space for IT. Second, we present more detailed motivating examples drawn from actual project experience. These include traffic control and demand

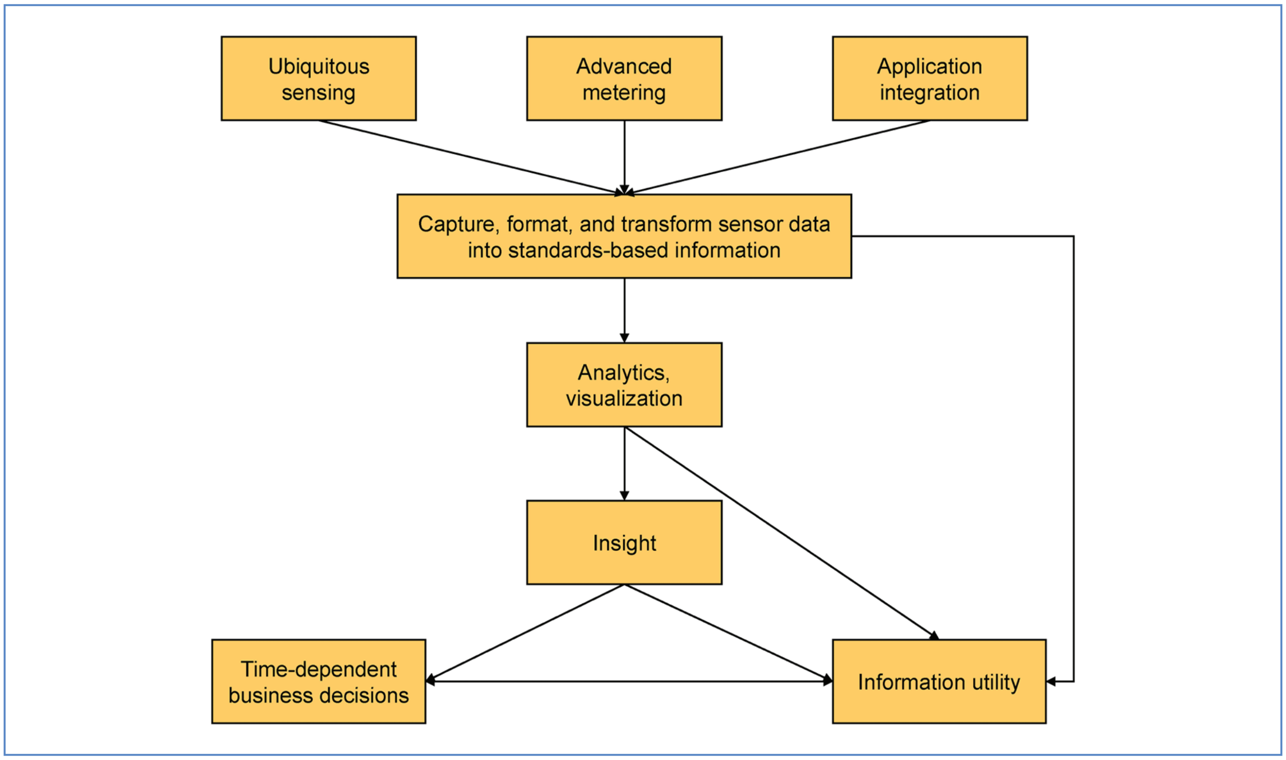

Figure 1

Conceptual flow of data and information in an instrumented world system, beginning with real-world data and ending with insight that drives decision making. The information utility concept (bottom right) indicates that multiple clients may exist for the various insights that the system can produce.

balancing, electrical energy usage and pricing management, crime and public safety, the structural health of city infrastructure, air pollution, extreme water events, and entrepreneurial issues. Third, we consider how the technical outcomes from these Smarter City solutions bring value to the city's residents and businesses. Fourth, we outline the needs for further research and experimentation. Finally, we summarize the contributions of this paper.

IT aspects of the Smarter City

In this section, we further describe the features of key IT aspects, as shown in **Figure 1**, and provide simple examples to illustrate their roles.

Instrumented

By *instrumented*, we mean not only systems of sensors and meters that measure some physical parameter such as pressure, flow, and temperature but also software in IT systems that extracts some diagnostic information about an enterprise business process, for example, the price of electrical energy. Such data are acquired in a time-dependent manner, which may be under a hard real-time constraint or under some more relaxed constraint. We refer to these as "live data." Thus, an instrumented system has access to sources of live data that describe the operations of both physical and virtual systems of the city. In some cases, an instrumented system also contains digitally addressable controls or actuators that can be remotely adjusted. In many cases, the sensors and actuators are not directly accessible to remote users or systems but are integrated into a process control or supervisory control and data-acquisition (SCADA) system that provides indirect access to the sensor data or actuator controls.

Current Smarter City designs mainly focus on the collection of data from real or virtual sensors and relatively little on controlling the corresponding actuators. This is because, in current implementations, the response of the Smarter City systems back into the real world is mediated through human operators in the existing individual system control centers. See the section "Intelligent" for a discussion of how this loop may be closed.

The Instrumented Planet study showed that urban environments around the world are increasingly rich in such instrumentation and that the rates of sensing and adjustment are also strongly increasing. This is also the space that has widely been explored under the heading "Internet of Things" [10]. In the telecommunication industry, these are also known as machine-to-machine (M2M) systems [11].

Such instrumentation includes the following:

- video surveillance cameras;
- loop detectors embedded in roads;
- RF identification (RFID) detectors for tolls on roads, bridges, and tunnels;
- RFID detectors for payment systems for public transportation, parking, and other municipal services;
- water-level monitors in sewers and other tunnels;
- water-quality sensors;
- instrumented fixed infrastructure such as levees, electrical distribution systems, and traffic management systems;
- smart electric and water meters;
- telematics systems on road and rail vehicles;
- position-reporting systems based on the GPS on vehicles, including taxis, buses, and trucks;
- GPS position-reporting systems in mobile telephones;
- mobile telephone and public wireless local area network base stations.

According to ABI Research [12], 21 million telematics units were to be installed between 2008 and 2010 for fleet management purposes, as well as 27 million telemetry units for asset management, and six billion RFID tags for inventory and supply chain management. A large fraction of the world's four billion mobile telephones [13] are in urban areas. The number of mobile Internet devices reached 450 million in 2009 and is expected to reach 900 million by 2013 [14, 15].

In many ways, the world is well provided with instrumentation. A notable exception is in the area of water supply, where the utilities are in some areas underinvested in live monitoring of the sources and transport of water due to institutional conservatism and the lack of effective pricing of water itself. The level of leakage of water from local distribution pipes, ranging up to 60% in extreme cases, is one indicator of this [16].

In other areas such as energy and water management, the level of sensing is also dramatically growing, particularly when considering that automated utility meters are an aspect of remote sensing. The potential for mobile devices, for example, mobile telephones, to act as location sensors significantly adds to this trend, augmenting the spatial mesh across which sensors are placed.

Unconventional forms of sensing are also emerging. The ubiquity of mobile telephones with cameras and video functions, together with online social networking services such as YouTube** and Facebook**, is providing an informal stream of information about city events, such as accidents or incidents. Engineering companies are also using video cameras and microphones to capture visual and acoustic signatures for the behavior of a system, such as an elevator, that can trigger maintenance or repair processes.

A key observation of the Instrumented Planet study was that such instrumentation is often installed for some transactional purpose, typically billing a user for some service, but this produces as a side effect a stream of detailed information about the consumption of resources or the movement of people, vehicles, and events within the city. As a consequence, the frequencies of monitoring and adjustment are dramatically increasing. What was once monthly is now weekly; weekly, daily; daily, hourly; and hourly, continuous. This is particularly true where the parameter being measured is dynamic and fast moving such as traffic or energy consumption. However, even relatively static physical infrastructures such as levees are increasingly the subject of real-time monitoring for structural health and signs of failure, for example, as with the "Calibration Levee" ("IJkdijk") project in The Netherlands [17].

In other examples, the requirements of integrating highly distributed microgenerators with highly variable power outputs into the conventional power grid [18] are increasing the frequency of monitoring and adjustment. Water agencies are finding that they can save significant amounts of energy and money by continuously adjusting and optimizing pumping levels and configurations, while traditionally, such frequent adjustments were attempted only rarely.

Interconnected

By *interconnected*, we mean not only the ability to connect instrumented systems physically via public and private networks within the city but also the ability to connect together logically the many IT software systems used by the city's agencies to manage the operation of the city's services. **Figure 2** shows some of the possible configurations of sensing systems that collect data from real-world sensors. **Figure 3** shows a hierarchical model of the interconnection of systems and services within the city.

As a result of the four billion mobile telephones worldwide, wireless networks provide coverage of high fractions of many populations, well over 90% in developed countries [19]. These networks have shown steady increases in link bandwidth and total capacity and decreases in bandwidth charges [20], as well as support for connectionless services such as the IP over public wireless local area networks, and are now being adopted for M2M communications with sensing systems.

Some sensors are constrained, for example, by lower power consumption requirements, to use simplified networking protocols [21]; these are illustrated in the edge clouds for Figure 2. Such sensors require a local gateway that can capture their short-range signals and convert the data packets into the IP for the backhaul to the processing center. Other instrumentation, notably smart electricity meters, may produce such high volumes of data that some distributed processing close to the data sources will be required to avoid high networking costs.

The security and integrity aspects of such networks have received little study. The systems we describe in this paper

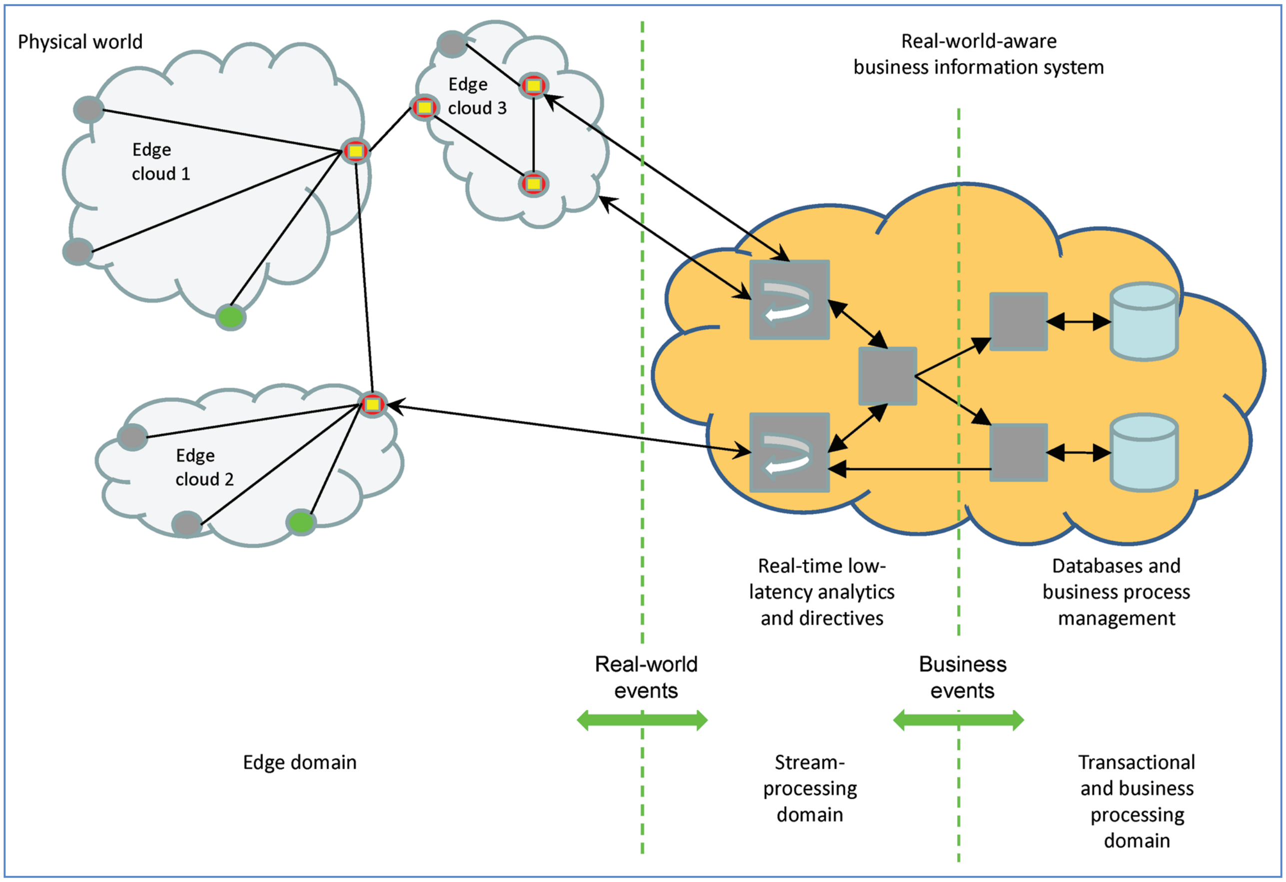

Figure 2

Conceptual sensing infrastructure and processing infrastructure.

are coupled to critical physical infrastructure, although at present, the coupling is relatively loose. This implies the need for redundant paths, encrypted links, verification of the two parties, and message queuing support, among other things. Methods to create such high-integrity network services over public "best efforts" networks are being developed [22].

The interconnection of multiple city services is an application of contemporary enterprise application integration to local government systems. It is a striking feature of the way that most cities are managed that, although city agencies have adopted some form of IT-based management system for their services, very few of them have the ability to exchange information. This appears to reflect the historical independence of such agencies and is reminiscent of the isolated operational towers of enterprises before the 1990s, when enterprise resource planning was broadly adopted to provide integrated management.

Today, the basic IT principle for interconnection is the service-oriented architecture (SOA) [23]. Here, the unit of application functionality is the "service" and is fairly coarse grained compared with the fine-grained objects of object-oriented programming. Thus, a service could be, for example, a geographic information system (GIS) that provides the spatial database for the city's assets. These services communicate through a standard application protocol based on a common semantic model—that is, a common vocabulary for describing attribute–value pairs that is meaningful for the service provided. Application functionality that was not created for an SOA environment, for example, a sensor platform, can be encapsulated to map its functions into the SOA environment.

The SOA approach is a powerful method for the interconnection of city services, although it does not guarantee that this can automatically be achieved. City services may have been designed with incompatible semantics, which may be dealt with through a kind of translation service. A more difficult problem is that services may have different application protocol models. For example, most services will be stateful and may have different expectations of the sequences of messages required to change from one state to another.

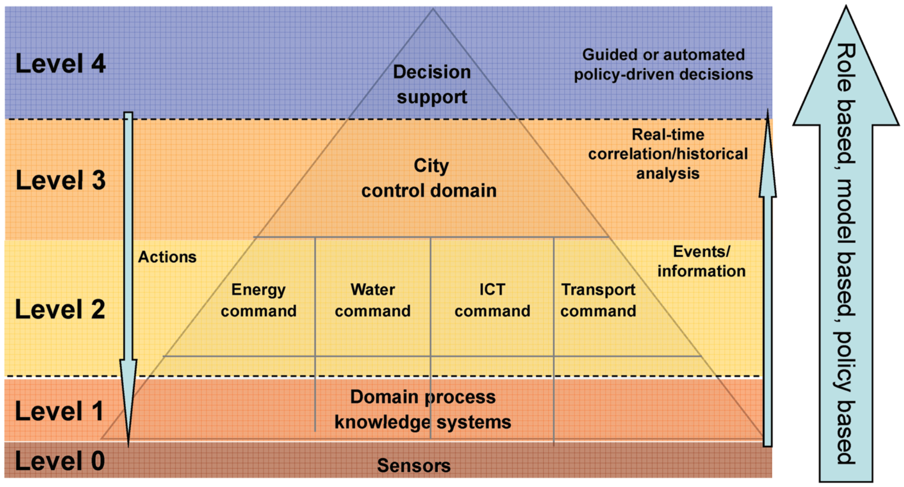

Figure 3

The layered structure of interconnection is the Smarter Planet Command Systems. The primary flows of information are upward and downward within individual city services within Levels 1 and 2. Level 3 provides horizontal communication capabilities and is the enablement layer the "systems of systems" view of the city.

SOA is a message-passing system in which services engage in pairwise conversations. SOA services can also publish messages or events for reception by other interested services that have subscribed to that class of messages. Although the SOA environment may be virtualized across multiple processors to improve computing performance, complex event rates in an SOA environment are limited to the order of 1,000 per second. Currently, this appears to be adequate for most city services, although smart metering systems may eventually exceed this limit. Consider, for example, a city with three million smart electrical meters that communicate every 5 minutes, and the result is a sustained rate of 100,000 events per second. The processing of such information streams will need to be performed outside the SOA environment, for example, in the IBM InfoSphere* Streams environment [24].

Intelligent

To recap, instrumented systems are the sources of live data that represent the operation of the city's physical infrastructure and services. The information from these live data is brought into an SOA environment that is rich in enterprise computing resources, such as GIS, and in which live data and other information can be exchanged among multiple city services. The flow of such live information within a single city service drives the execution of the business processes of that service. For example, a live information stream may contain an alarm indicating the failure of a street light. When this alarm message is published in the SOA environment, it can trigger a business rule that leads to the generation of a work order to replace the defective light bulb, using the GIS to determine the street location of the failed light.

An intelligent system extends this model to analyzing, modeling, optimizing, and visualizing the operation of the service. For example, the intelligent system might look at the spatial correlation of light failures and note that there are districts in the city with unusually high failure rates. Alternatively, it might look at the list of current work orders and determine an optimal route for a repair truck to minimize journey time or fuel consumption, or it might find temporal correlations among such failures, such that the failure of a particular light or a group of lights is a leading indicator for the imminent failure of another light or lights. It can then create a predictive model for early replacement rather than simply waiting for the lights to fail.

Local governments are administered through policies, some of which are based in law. These are implemented as business rules with varying priorities that act as constraints on the business processes, for example, during optimization. For example, a policy might require that street lights be repaired within 48 hours of a failure being registered. The optimizer might then defer repair actions for failures reported today until the day after tomorrow.

These kinds of complex analytics have existed in some cases for many years, but they have been used offline and with limited frequency. What has changed is a major reduction in the computational cost of running such analytics and the increasing availability of live data. These factors have enabled such analytics to become part of the online business process model so that these processes now become "intelligent."

A further step that is enabled by interconnection is the creation of analytics that look at information from two or more city services such as water and transportation or that include externalities such as a weather stream. This enables the operation of cross-service business processes. A simple example is the spatial matching of work orders that require the excavation of the same section of a street for both water mains and traffic signals. A more complex scenario is the notification of the public safety service of a broken water main that results in the redirection of traffic away from the affected district.

Achieving the promise of Smarter Cities as a system-of-systems model requires the integration of a wide variety and large volume of information, as well as the application of a correspondingly wide variety of analytics and simulations to interpret this information, make predictions based on it, and optimize business processes that act on it. This intelligent integrative modeling framework requires the following features.

1. An infrastructure that provides a flexible extensible modeling framework for defining and running multistep analytic simulations. Unlike other extant modeling frameworks, this framework is intended to support use by nonexpert modelers. This requires the division of extant (typically monolithic) discipline-specific models into atomic model components and the identification of patterns of such models. Cross-disciplinary simulations may then be expressed as dataflows specified as compositions of components.

Since models can be built on different or even conflicting assumptions and definitions of key terms, not all compositions of components represent scientifically valid simulations. It is critical to disallow "frankenmodels," compositions of incompatible components that produce scientifically invalid simulations. This requires a rich metadata specification for representing model semantics and expressing rules and constraints for combining model components. Additional requirements include a software environment for modeling framework development, as well as an adapter strategy for non-Java** code (e.g., FORTRAN and Python) that still enables efficient simulation runs, including parallelization of component execution. An example of work toward such a framework in the hydrology field is given in Eckman et al. [25].

2. Autocalibration capabilities are required to enable this framework to be used by nonexpert modelers. Models typically have a number of parameters and initial conditions whose values must be calibrated on specific data sets. This is typically manually done by assigning values to the parameters such that the model outcomes are sufficiently close to observed data for a particular data set. Ideally, this process is repeated for each new model on each new data set. Some researchers also perform the next step of verification—using the same parameter settings on a different data set, and comparing the outcomes with observed data. Manual calibration and verification are time consuming and error prone. Autocalibration promises to be a great improvement and a necessary feature of a "plug-and-play" modeling framework.
3. Visualization is a key element of the infrastructure, both to convey complex data effectively and to enable nonexpert users to make full use of the relevant features of the infrastructure. A visualization environment with a strong data model is needed to enable visualizations, model results, and allow relevant data all to be handled similarly.
4. Open standards must be the foundation for the modeling framework, making use of existing standards where appropriate. Examples include WaterML [26], the Open Geospatial Consortium standards (OGC.org), the Extensible Business Reporting Language (XBRL.org), and the Open Model Integration Environment (OpenMI.org). This also implies working with recognized organizations to extend existing standards and develop new standards where necessary.

Instrumented, interconnected, intelligent city

The concepts of instrumented, interconnected, and intelligent provide a useful reference model for designing the application of IT to address problems in urban environments and, to some extent, guide separation-of-concerns work in such designs. We have found that the application of IT to the operation and management of city services is a largely unexplored area. In particular, many of the semantic standards we would like to use in creating IT platforms based on open industry standards do not exist. We and others have efforts underway to develop such semantics and, where possible, to publish them through industry bodies [27].

This model is incomplete, however, in the sense that it misses the final step in helping to solve a city problem. That is, the outcomes from instrumented, interconnected, and intelligent systems must result in better and actionable operational or management decisions. In our current thinking, these decisions are often made by a human operator or manager looking at the information provided through the IT-based execution of the business process and coming to a better conclusion about what needs to be done. That decision can then be communicated to the operational teams in charge of the city services that are implicated. In other cases, there may be a closed loop in which the IT-based business process at a minimum communicates its conclusions to the implicated city services or, going further, makes recommendations to these systems for action.

Table 1 Systems for energy management (Smart Grid).

Instrumented	Consumer electricity meters and submeters; energy flowmeters for distributed electricity generation; consumer flowmeters for district heating and cooling; microgenerators; building management systems; consumer portals; energy service companies (ESCO); plug-in electric vehicles.
Interconnected	Back-haul of data from the above sensors; integration with services for industrial production management, district heating and cooling, transportation, public safety, water, and weather.
Intelligent	Planning for deployment of electric vehicles and distributed generation; real-time demand modeling and energy pricing to achieve peak smoothing; energy allocation to critical services, e.g., water management.

Some cities wish to use this approach to create a city command center or operations center. We have, for example, built a Real-Time Crime Center for New York City that brings together in one place all live information related to crimes in progress from a variety of city agencies [28]. This has proven very effective in fighting street crime in New York City. The ability to capture an integrated view of what is going on throughout the city is appealing to some city managers, whereas others dislike the sense of broadly applying "command and control" principles to operating services in democratically governed cities. There are also issues concerning the hierarchy of authority within the city agencies that fall outside the scope of the IT solution; nevertheless, the IT solution must be able to appropriately communicate its outcomes to the city services.

As illustrated in Figure 1, the accumulation of information in the Smarter City also lends itself to the creation of information utility services. An information utility generates a feed on information for its subscribers that is developed from the analysis of one or more incoming feeds of real-world information. The concept originated in the financial service industry, for example, in calculating live values for a stock index such as the Dow Jones Index from the live values of its component stocks. These services will add further value to the city by providing residents and businesses with specific derivative information.

In the following section, we consider a few of the problems and challenges faced by cities that motivate this novel application of IT and give examples of how the instrumented, interconnected, and intelligent framework applies.

IT for a Smarter City

In this section, we describe some of the challenges of contemporary cities that may be effectively addressed by a Smarter City approach. While the examples we cite are not intended to be an exhaustive list of challenges that can be met using a virtual city infrastructure, they are representative of our experiences to date.

City services have several defining characteristics: They are either physical systems based on thermodynamics and other physical principles, or they are social systems based on the behavior of many individual inhabitants, or they are both. Physical systems imply that the IT solutions take into account the underlying physical laws that constrain the operation of the system and that are the basis for optimizing the operation. Social systems imply that the IT solutions take into account the operation and rights or privileges of the users, as well as the mutability of their individual behaviors under various influences. The examples given here illustrate these defining characteristics.

Demand management for electrical energy

The development of the Smart Grid [29] involves a similar process of embedding instrumentation, interconnection, and intelligence in the generation, transmission, and distribution infrastructure, as indicated in **Table 1**. Cities include large fractions of the distribution network, and here, advanced meters are being installed in large numbers that will measure consumption at endpoints, broadcast the real-time energy price, and monitor the production of electricity from microgenerators such as rooftop photovoltaic panels and the reselling of such power to the grid. This will fundamentally alter the nature of the electric grid—from today's model of centralized production supplying power conditionally to unaware consumers, to distributed production resources such as wind and solar, providing power to pervasive storage and demand-aware consumers. Another important aspect is the introduction of continuous information flow between producers and end users, which allows the real-time signaling of price and consumption costs, thereby shifting or shaving demand. That is, by providing feedback to the consumer, the consumer is motivated to make energy consumption decisions, for example, when to dry clothes or what temperature to set for an air-conditioning system. The motivation may be intended to produce a temporary reduction in energy consumption, for example, by tolerating a slightly warmer building or to defer

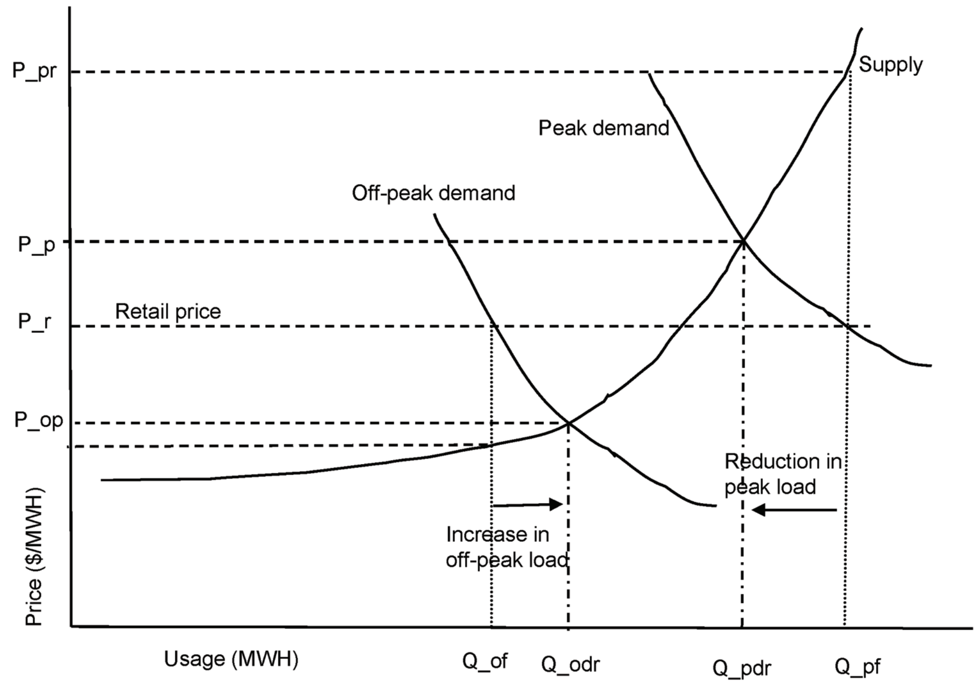

Figure 4

Schematic of demand response to price. The peak and off-peak demand curves represent aggregated demand from the customers served during the current trading period, and the supply curve represents the utility's offer price. The experiment shows the shift of energy demand from peak to off-peak periods.

consumption, for example, by stopping refrigeration in a supermarket for 20 minutes. This is known as *demand response* or *demand modulation* [30]. **Figure 4** shows an economic model for demand response in which energy demand can be controlled by the utility simply by adjusting the real-time price, for example, resetting the price every 5 minutes. In this example, each consumer has, in effect, defined a price–demand curve for energy needs, and it has been shown both theoretically and experimentally [31] that this has a significant effect in terms of smoothing demand peaks.

This fundamental shift to distributed energy resources has major implications for the operation and management of the electric transmission and distribution grid. We focus on the distribution grid, since this is where issues of energy management relate to the continuous interaction between end users and producers. We need to pay special attention to the customer ecosystem that is expected to dramatically change as different distributed sources or microgenerators become prevalent at the customer level. A key issue is the link between customer behavior and use and how this has an impact on the operations at the generation planning level. This is illustrated in Figure 4 in detail.

At any level of the network, we could potentially have renewable generation in terms of photovoltaic cells on rooftops or storage batteries in the basement or small farms at the feeder network level. To plan electrical power generation for any period during a day, we need to be able to estimate the total demand at, e.g., the feeder network level. A key component to estimate the aggregate demand at the feeder network is to estimate the energy demand at a building level, which, in turn, depends on several factors:

- Time of day and day of week.
- Weather (temperature and humidity).
- Information signals (such as load-sensitive pricing).

Assuming we have demand response at a building level as a function of weather, time of day, and information signals, we can estimate the aggregate demand at different levels of the feeder network. However, the demand response has uncertainty associated with it since the response is based on a behavioral response. An important question relates to the design of price (information) signals that would lead the desired level or shape of the demand in time.

The next thread for this research is to characterize the demand response at the building level. The energy load for a building can be estimated using statistical analysis of historical use data. However, we need to augment this by causal modeling to capture the physical models that estimate the changes in the energy load for a building given the weather (e.g., temperature and wind), size of the building, and location (e.g., south facing versus north facing) using computational fluid dynamics models.

Another aspect of the load depends on customer behavior based on principles of behavioral economics. To quantitatively estimate the behavioral aspects and their impact, we need to estimate the price elasticity of demand. An important component of the building energy demand model is the quantitative estimation of the elasticity of energy demand at the end-user level. Once we have such an estimate, we can use it in a control mechanism to schedule energy use through pricing (or *dynamic demand management*) at a building level.

This application of instrumented, interconnected, and intelligent systems to energy management is an excellent example of the value that can be created through a "systems of systems view" of the problem. The encouraging outcomes from a small pilot of this approach [31] in the Olympic peninsula of Washington State by the GridWise Alliance during 2007 and 2008 will further be studied through a much larger pilot [32].

Water supply and extreme water events

The Sonoma County Water Agency (SCWA) is responsible for managing the health of the Russian River and supplying water to 600,000 people [33]. In so doing, it has to balance the demands of the river, containing three endangered salmonid species, with the needs of the area's world-famous wine industry and its population. The agency is a water wholesaler; it manages supplies that it then sells to retail water contractors in the area such as the cities of Santa Rosa, Windsor, Rohnert Park, Petaluma, and Cotati (there are nine contractors in all). It does this through a storage and conveyance system, which includes two reservoirs, the river itself, the world's largest river-bank natural filtration system, and approximately 70 miles of pipeline to distribute the water to the retailers. At present, while SCWA provides some data about its operations to its retail contractors, and the latter reciprocate to some degree, neither side exchanges enough data, with sufficient frequency, to enable integrated management of the conveyance system. As a consequence, each entity makes its own decisions, with the resulting potential for inefficiencies in energy usage and water supply. In addition, SCWA's decisions about water availability and the status of the Russian River determine the amount it makes available for its retail contractors. However, the agency is constrained by a significant "choke point" in the system: The rate of release from one of the two reservoirs has to be carefully controlled, as an excessive flow will damage its ecosystem and flush down the river the species that SCWA is legally mandated to protect. As an additional dimension, the activities of the wine industry, in particular in withdrawing water for spraying vines to protect against heat or frost, can lead to severe fluctuations in river levels—again, risking damage to the ecosystem. While SCWA can release more water into the river from its reservoirs to help maintain these levels, it needs a longer warning period to do this. As it attempts to balance these demands and constraints, the decisions made by SCWA have proved highly contentious in the past, and there is an accepted need for a greater level of transparency in how it makes them.

A further dimension of the issue is that the Russian River is prone to damaging flash floods, and as such, its behavior must be carefully monitored and managed. SCWA wants to capture excess winter water and store this underground in one or more of four groundwater basins in its area, for future use. Two of these are affected by saltwater incursion from the sea; thus, there is an additional need to maintain freshwater pressure underground, to stop saltwater incursion.

Finally, like the rest of California, the region has experienced a severe drought in the last few years that has exacerbated all of the issues above, as well as the political stakes surrounding the decisions that need to be made. It is expected that as climate change has an increasing impact, this pattern is likely to be repeated in the future.

IBM has recently embarked on a long-term program with SCWA designed to help address these issues. The general aspects are shown in **Table 2**.

The program has three integrated elements.

1. A management system for the transmission pipeline that integrates continuous information on flows, tank levels, and pumping activity from the SCADA systems operated by SCWA and its contractors, to create a single operating picture of the pipeline such that water supply activity can be coordinated more easily. In the future, this will also allow each organization to collaborate in such areas as detailed pump optimization and leak detection, to maximize energy and water efficiency.
2. A Russian River "console," showing the status of the Russian River: its flow, depth, aspects of its water quality, extraction levels, and ecosystem health indicators. These data would be made available to all affected entities and will also include additional feeds from the U.S. Geographic Service (USGS) stream gauges, external weather forecasts, and other sources.
3. In the longer term, a water accounting system that tracks all "puts" and "takes" from each water resource (including the four groundwater basins) to provide a continuous picture of the status of all resources in the area. This will be built by integrating multiple existing models (e.g., models of the reservoirs, the groundwater basin, the transmission system, and the Russian River)

Table 2 Systems for water management.

Instrumented	Water consumption meters, flowmeters, pressure meters, energy consumption meters (pumping), water treatment monitors, water purity sensors, physical security monitors, river height sensors, dam height sensors, levee movement sensors.
Interconnected	Back-haul of data from the above sensors. Integration with services for transportation agencies, public safety, energy, buildings, weather, and climate; also, integration with other water management agencies within the same watershed or aquifer.
Intelligent	Planning for water release from upstream dams and allocation of water among rights holders; planning for combined sewer overflow systems; dynamic control of water reserves (if permitted); predictive modeling for water use restrictions; modeling of diffusion of pollution plumes and saltwater intrusion; modeling of fish populations; modeling and prediction of extreme water events (oceans, rivers); optimization of water pumping and water treatment.

with data on evaporation–transpiration, human usage, rainfall, and so on.

The current phase of the work consists of a pilot trial with SCWA and three of its retail contractors (Santa Rosa, Cotati, and Rohnert Park) combining elements of projects 1 and 2 above. The pilot implementation consists of additional telemetered meters installed by Badger Meters to enable a more "granular" picture of the transmission system, integration of SCADA data from each organization, and the addition of basic data on the Russian River from the USGS stream gauges, plus weather forecasts. Facilities such as chat and bulletin boards will also be provided. For the pilot, the integrated data will be available via a separate secure Web site. In the longer run, it is intended that the data will be visible through the SCADA system itself in each organization. If the pilot is successful, it will be expanded to include all ten contractors, and an additional function will be added. At the same time, work will begin to create the full Russian River console.

Demand balancing in urban roadways

Traffic congestion in many cities is increasingly alarmingly. For example, in Stockholm, in 2004, the number of cars entering the city was about half a million per day and steadily increasing. The average commute time in 2005 rose by 18% from the previous year [34]. Cars idling in traffic jams increase greenhouse gas (GHG) emissions, but simply choosing alternative longer commuting routes can also increase fossil fuel consumption and GHG emissions. Solutions are needed that provide greater road availability and decreased GHG emissions and that meet other important constraints, such as avoiding certain roads at certain times because of construction, poor road surface condition, residential neighborhoods, schools, and wildlife.

First steps toward the solution of this problem have been taken in a number of cities. In Stockholm, by providing a mechanism for charging for entry and thus defining a value of entry, the Stockholm City government implemented a road charging system trial, resulting in a reduction of traffic by 25% over a period of 6 months and a reduction of carbon emissions of approximately 15%. By providing the sensing and response mechanisms, the city was able to mitigate the problems of the increasing traffic and to increase ridership on public transport by approximately 6% [34]. The Singapore Land Transportation Authority (LTA) constructed the first electronic road pricing (ERP) system in 1975 [35]. In 2006, the LTA contacted the IBM Math Sciences Group to ask if the mountains of data produced by the ERP system could be used to make predictions about imminent congestion on the city's roads. The ERP system does not provide perfect visibility into traffic flows on all principal streets, and alternate means were required to fill in the gaps. However, it was quickly shown from historical data that predictions of imminent congestion can be made with high confidence (85% accuracy) up to 1 hour before congestion actually occurs. This is sufficient time for the flow of traffic in the affected area to be changed by altering the operation of traffic lights and the prices charged for entering the district. The modeling and prediction assets produced from this work were packaged into the IBM Traffic Prediction Tool [36, 37].

These solutions, known as *road-usage charging* or *congestion management systems*, are examples of how IT can provide a feedback mechanism between the capacity and demand for use of a public resource, in this case the city road system. The key aspects are given in **Table 3**. The feedback loop is closed in these cases by providing a price signal that changes the consumers' behavior, but other methods are possible, as we show later in this paper.

Table 3 Systems for traffic management.

Instrumented	Contact strips, inductive loops, RFID, video, lasers, payment cards, turnstiles, access gates.
Interconnected	Back-haul of data from the above sensors; integration with services for multiple transportation agencies, public safety, water, energy, and weather.
Intelligent	Planning of multi-modal transportation services; modeling of congestion, pollution, and effects of road closing or restriction; optimal pricing for congestion management, dynamic scheduling of public transportation and on-demand vehicles for end-to-end journey efficiency, dynamic use of multi-modal transportation options.

In part, congestion arises from a market failure, since there is no price signal to modulate user behavior, and from a lack of live information that would enable users to make better decisions about their journeys. Despite innovation in mass transit and urban design, municipalities increasingly recognize the need to shape traffic demand for congestion reduction. Fortunately, intelligence governing such systems may introduce far greater efficiencies than now experienced. IBM is exploring different solutions and recognizes that balancing demand is not merely a question of "vehicular quantity" but includes other environmental variables. Branching out from solutions developed for Stockholm, London, and elsewhere, new research enables local governments to explore multiple options.

Price signals available to the traffic management system include fixed and variable transit fees. Fixed transit fees can be based on distance or origin, vehicle occupancy, or route capacity. Variable rate transit fees can be based on current traffic congestion or density, on individual vehicle emission characteristics, or on ambient environmental conditions. These tools allow the traffic managers to drive toward city policies for abatement of GHG emissions, encouraging the use of alternate routes, discouraging long commutes, and so forth.

In summary, these are just a few possibilities for balancing demand, based on either pure congestion statistics or inclusion of other ambient environmental or societal factors. Other possibilities exist, to be developed within the rubric of the Smarter City initiative. These examples illustrate the new capabilities that can be enabled through the introduction of instrumented, interconnected, and intelligent systems in urban areas.

Further work

The Smarter City is a novel area for the application of IT, and there is much to be learned and much to be accomplished. Some of these are briefly described here.

The semantic model for conversations with the IT representations of urban infrastructure is incomplete, and there are no open industry standards for the model. IBM and others have internal models of similar systems, but we see clearly that the semantic model for all possible city services is extremely large. Moreover, it is not obvious which industry bodies could most effectively adopt and advocate such standards.

We are dealing here with critical local and national infrastructures. The systems we describe in this paper are generally only loosely coupled to the underlying physical infrastructure and rely on the judgment of human operators for adjustments. However, we are potentially introducing loopholes for the entry of malware into the SCADA systems that are tightly coupled to the underlying infrastructure. There is a need to assess how to formally apply systems engineering principles to the design, implementation, testing, deployment, operation, and lifecycle management of these systems, which may have very long lives.

Our discussion here has exclusively focused on the physical and economic modeling aspects of city systems and services. Much work is required to develop social models that provide equivalent predictive capabilities for the behaviors of individuals, groups, communities, or the entire city. **Figure 5** shows early thinking on how these two sets of models will interact within the Smarter City platform.

Our ability to accurately forecast the outcomes from the creation of Smarter City systems is limited. While we can be concrete about the technical achievements of the instrumented, interconnected, and intelligent systems themselves, we have little insight into how, in general, these will translate into assessments of quality of life or into the attractiveness of the city for human and financial capital. This is a long-standing problem of investment in physical infrastructure that virtual infrastructure also inherits. Unlike physical infrastructure investments, however, we can be sure that these approaches will be less expensive, quicker to implement, and easier to adapt.

Although our focus is on the operation and management of city infrastructure, it seems likely that these approaches will have an impact of the conduct of urban planning, potentially turning this from a modeling-based discipline to one more based on simulations. To the end, the accumulation of

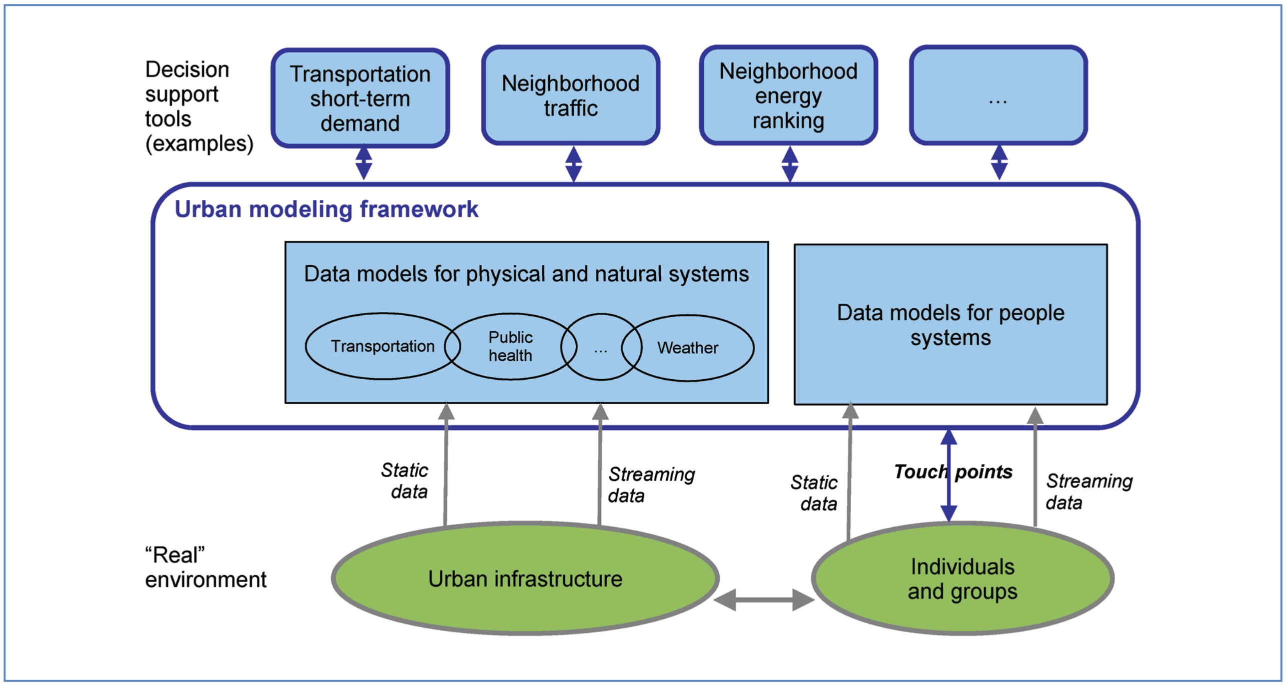

Figure 5

Integration of behavioral models at the community, and the individual level is a powerful means to derive accurate predictions of short-term demands for energy, water, transportation, and other urban resources, thereby allowing cross-resource optimization of the city's operation. It also offers the means for more direct engagement of individuals and communities in the planning and operation of the city.

databases of operational data in standard formats appears highly desirable. This intersects with a trend toward open government in which central and local government agencies publish a variety of data [38]. IBM opened a Web site in March 2010 that is intended to provide tools to enable city managers and planners to visualize, analyze, and compare such data sets [39].

We currently see growing commercial and academic interest in Smarter Cities as evidenced by this and other papers in this issue of the *IBM Journal*. We look forward to seeing these and many other problems being addressed in coming years.

Summary

In urban environments, myriad sensors and pervasive networks provide surprising volumes of information about the activities underway. These sources, together with technical advances in application integration techniques and in the affordability of complex analytical computation, are converging to enable the development of intelligent online systems for the operation of individual city services and for their integration into an intelligent system of systems. The central thinking behind the IBM Smarter City initiative is to take advantage of these rich sources of information to help make better cities. This particularly applies to how the physical infrastructure of the city supports the needs of the citizens for safety, employment, comfort, mobility, and community. Creating the Smarter City implies capturing and accelerating these flows of information both vertically, within the operation of a given infrastructure system, and also horizontally, among the many different infrastructure systems and using this information to manage the operations with a specific objective in mind, such as minimal energy usage or maximum citizen comfort.

While the original sensing and networking elements may have been deployed for reasons of automation, or convenience, or to provide a new service, the ability to derive high-value information from them enables us to address concerns that are becoming acute in countries around the world. These concerns are driven by population growth and rapid urbanization in the Middle East and Asia, by the need to deal with constraints on physical resources and capacity in the Western world, by the need to reinvent economic bases that have been eroded through the migration or decay of industry, and by the real challenges of rising sea levels and other aspects of climate change through the world.

The integrating and transformative power of IT enables the leverage of these information flows to achieve improved efficiency in the utilization of existing infrastructures that would be enormously expensive and disruptive to achieve by extending the infrastructure itself. Likewise, they enable new thinking about how to manage public infrastructure services—making them dynamically responsive to the citizen's activities. Not least, these approaches can lead to reductions in the consumption of energy and water and, hence, to the attainment of a city's sustainability goals; many of these reductions will come from closely tailoring consumption to actual need and from offering city managers ways to promote more sustainable behaviors.

While our work is rooted in technology, it is closely bound to many social implications and must therefore respect the rights and interests of the citizens, as well as being aligned with the work of architects, urban planners, and city governments. It is interesting to compare the Smarter City definition we give in the introduction with the stated goal of the City of Cleveland, Ohio [40]: "We are committed to improving the quality of life in the City of Cleveland by strengthening our neighborhoods, delivering superior services, embracing the diversity of our citizens, and making Cleveland a desirable, safe city in which to live, work, raise a family, shop, study, play, and grow old." It is an ambitious new space in which to apply IT.

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Colin Harrison *IBM Corporation, Armonk, NY 10504 USA (harrisco@us.ibm.com)*. Dr. Harrison received a B.Sc.(Eng.) and a Ph.D. degree from Imperial College, London, both in electrical engineering. He is a director in the IBM Enterprise Initiatives team, working on smart cities and cloud computing. He was previously Director of Strategic Innovation for the IBM IT services in Europe and Director of Global Services Research in the IBM Research Division. He has enjoyed a career with IBM that has led from micromagnetics to medical imaging, parallel computing, mobile networking, intelligent agents, telecommunications services, and knowledge management. From 1997 to 2001, he was the worldwide leader in developing the application of research skills to the IBM services businesses. Dr. Harrison is a Fellow of the IET, a Senior Member of the IEEE, a member of the IBM Academy of Technology, and an IBM Master Inventor. Prior to joining IBM, he worked at CERN in Geneva developing the SPS accelerator and at EMI Central Research Laboratories in London, where he led the development of the first clinically useful magnetic resonance imaging system in the world.

Barbara Eckman *(barbarae@alumni.princeton.edu)*. Dr. Eckman received M.S.(Eng.) and Ph.D. degrees from the University of Pennsylvania. Senior partner and founder at Gulph Scientific Computing Consultants, she is a former Senior Technical Staff Member at IBM in West Chester, PA. Most recently, she was the Technical Lead and Visionary for Water for Tomorrow, a collaboration on river basin modeling with The Nature Conservancy, and the Chief Architect of the IBM Big Green Innovations effort. She is an alumna of the IBM Academy of Technology. Before joining Big Green Innovations, Dr. Eckman's 20-year focus was in biomedical computing and bioinformatics, where she is an internationally recognized expert in heterogeneous database and application integration. In 2003 she received an IBM Outstanding Technical Achievement Award for her work on extending DB2*, the IBM relational database management system, with bioinformatics-specific features and functions. Dr. Eckman is an author of two filed patents (pending), 20 peer-reviewed articles, and numerous technical reports. She is a member of the American Geophysical Union, the International Society for Computational Biology, and the Association for Computing Machinery, Special Interest Group on Management of Data (ACM SIGMOD).

Rick Hamilton *IBM Corporation, Charlottesville, VA 22903 USA (rh@us.ibm.com)*. Mr. Hamilton received a B.S. degree in electrical engineering from the University of Tennessee, an M.S. degree in engineering management from Southern Methodist University, and an M.S. degree in electrical engineering from the University of Texas. He is an Executive IT Architect with more than 20 years of diverse information technology experience. He works on innovation and intellectual property matters focusing on emerging technologies, and is a frequent speaker on these topics across North America, Europe, and Asia. Mr. Hamilton is a named inventor on more than 700 U.S. patent applications for innovations in software, services, and hardware, the highest such number in IBM history.

Perry Hartswick *IBM Corporation, Hopewell Junction, NY 12533 USA (hartsp@us.ibm.com)*. Mr. Hartswick is an IBM Distinguished Engineer. His current assignment is as the Chief Architect for IBM Big Green Innovations. He is directly responsible for the solution architecture being used worldwide, as well as the direct applicability of the architecture to specific business opportunities. Perry is responsible for driving technology into all areas of controls, monitors, feedback, and management systems. He continues to expand his areas of influence by developing solutions such as Sense and Respond for alarm handling and asset management. He also continues to act as the systems architect for IBM Photovoltaic Research as well as providing architectural leadership for the IBM Industrial Sector in controls, management and optimization.

Jayant Kalagnanam *IBM Research Division, T. J. Watson Research Center, Yorktown Heights, NY 10598 USA (jayant@us.ibm.com)*. Dr. Kalagnanam has a Ph.D. degree from the Department of Engineering and Public Policy at Carnegie Mellon University in 1991. He is a Senior Manager in the Mathematical Sciences Department and has been at the IBM T. J. Watson Research Center as a Research Staff Member since 1996. Before joining IBM Research, he worked as a Research Faculty at the Department of Engineering and Public Policy at Carnegie Mellon University where he developed large cost minimization models for designing and retrofitting utilities with new technologies. After joining IBM Research, Dr. Kalagnanam worked on developing optimization models for production planning and scheduling in the context of manufacturing for various industries including steel, semiconductor, and electric utilities. He has been involved in the design and development of optimization solutions that have been deployed in plants and are in daily use. He has filed over a dozen patents and published more than 30 articles in peer-reviewed journals and conferences in the area of production modeling.

Jurij Paraszczak *IBM Research Division, T. J. Watson Research Center, Yorktown Heights, NY 10598 USA (jurij@us.ibm.com).*
Dr. Paraszczak is Director of IBM Research Industry Solutions and the Global Research leader of Green Technologies and Smarter Cities focusing on methods of managing the lifecycle of resources including water, energy and carbon. In this role, he is responsible for integrating research capabilities in, materials and processes, IT innovation, modeling and optimization to implement sustainable solutions for IBM customers in industries as diverse as retail, telecom, automotive, financial markets, government and many others. In addition, he manages a team of specialists who help develop IBM Research innovations in IT technology for customer solutions in many industries. Dr. Paraszczak has more than 55 publications in various areas of telecommunications, technology, and systems and more than 18 patents in a wide variety of fields including communications, plasma chemistry, microlithography, materials manipulation and chip fabrication, packaging systems, media delivery, and characterization.

Peter Williams *IBM Corporation, Danville, CA 94506 USA (peter.r.williams@us.ibm.com)*. Dr. Williams holds a Ph.D. degree that was awarded by the School of Management at the University of Bath, England, in 1986. He is the Chief Technical Officer for the IBM Big Green Innovations incubator, whose role is to create environmentally focused businesses for IBM. He is responsible for assembling, maintaining, and developing the portfolio of businesses included, and technologies used. Dr. Williams holds the title of IBM Distinguished Engineer. By background, he is a management consultant with more than 20 years of experience of bringing technology and business issues together to develop novel solutions and business models. A native of the United Kingdom, he has lived in the United States since 1999.