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Smart cities of the future

M. Batty[1,a], K.W. Axhausen[2], F. Giannotti[3], A. Pozdnoukhov[4], A. Bazzani[5], M. Wachowicz[6], G. Ouzounis[7], and Y. Portugali[8]

[1] Centre for Advanced Spatial Analysis (CASA), University College London, 90, Tottenham Court Road, London W1N 6TR, UK
[2] IVT, ETH, Wolfgang-Pauli-Strasse 15, HIL F31.1, 8093 Zrich, Switzerland
[3] KDD Lab, Istituto ISTI, Area della Ricerca CNR di Pisa, Universit di Pisa, via G., Moruzzi 1, 56124 Pisa, Italy
[4] National Centre for Geocomputation, Iontas Building, NUI Maynooth, Co., Kildare, Ireland
[5] Department of Physics and National Institute of Nuclear Physics, University of Bologna, via Irnerio 46, 40126 Bologna, Italy
[6] University of New Brunswick, Department of Geodesy and Geomatics Engineering, 15 Dineen Drive, PO Box 4400, Fredericton, NB, Canada, E3B 5A
[7] Geo-Spatial Information Analysis for Global Security and Stability, Institute for the Security and Protection of the Citizen (IPSC), Joint Research Centre, European Commission, T.P., 267, via E. Fermi 2749, 21027 Ispra, Italy
[8] Tel-Aviv University, Department of Geography and the Human Environment, Tel Aviv 69978, Israel

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Abstract. Here we sketch the rudiments of what constitutes a smart city which we define as a city in which ICT is merged with traditional infrastructures, coordinated and integrated using new digital technologies. We first sketch our vision defining seven goals which concern: developing a new understanding of urban problems; effective and feasible ways to coordinate urban technologies; models and methods for using urban data across spatial and temporal scales; developing new technologies for communication and dissemination; developing new forms of urban governance and organisation; defining critical problems relating to cities, transport, and energy; and identifying risk, uncertainty, and hazards in the smart city. To this, we add six research challenges: to relate the infrastructure of smart cities to their operational functioning and planning through management, control and optimisation; to explore the notion of the city as a laboratory for innovation; to provide portfolios of urban simulation which inform future designs; to develop technologies that ensure equity, fairness and realise a better quality of city life; to develop technologies that ensure informed participation and create shared knowledge for democratic city governance; and to ensure greater and more effective mobility and access to opportunities for

[a] e-mail: m.batty@ucl.ac.uk

urban populations. We begin by defining the state of the art, explaining the science of smart cities. We define six scenarios based on new cities badging themselves as smart, older cities regenerating themselves as smart, the development of science parks, tech cities, and technopoles focused on high technologies, the development of urban services using contemporary ICT, the use of ICT to develop new urban intelligence functions, and the development of online and mobile forms of participation. Seven project areas are then proposed: Integrated Databases for the Smart City, Sensing, Networking and the Impact of New Social Media, Modelling Network Performance, Mobility and Travel Behaviour, Modelling Urban Land Use, Transport and Economic Interactions, Modelling Urban Transactional Activities in Labour and Housing Markets, Decision Support as Urban Intelligence, Participatory Governance and Planning Structures for the Smart City. Finally we anticipate the paradigm shifts that will occur in this research and define a series of key demonstrators which we believe are important to progressing a science of smart cities.

1 Our visionary approach

For much of the 20th century, the idea that a city could be smart was a science fiction that was pictured in the popular media but quite suddenly with the massive proliferation of computable devices across many scales and with a modicum of intelligence being embedded into such devices, the prospect that a city might become smart, sentient even, is fast becoming the new reality. The convergence of information and communication technologies is producing urban environments that are quite different from anything that we have experienced hitherto. Cities are becoming smart not only in terms of the way we can automate routine functions serving individual persons, buildings, traffic systems but in ways that enable us to monitor, understand, analyse and plan the city to improve the efficiency, equity and quality of life for its citizens in real time. This is changing the way we are able to plan across multiple time scales, raising the prospect that cities can be made smarter in the long term by continuous reflection in the short term.

Smart cities are often pictured as constellations of instruments across many scales that are connected through multiple networks which provide continuous data regarding the movements of people and materials in terms of the flow of decisions about the physical and social form of the city. Cities however can only be smart if there are intelligence functions that are able to integrate and synthesise this data to some purpose, ways of improving the efficiency, equity, sustainability and quality of life in cities. In *FuturICT*, we will research smart cities not simply in terms of their instrumentation which is the domain of both large and small ICT companies who are providing the detailed hardware and software to provide what some have called the operating system for the smart city, but in terms of the way this instrumentation is opening up dramatically different forms of social organisation.

We will focus directly on ways in which this infrastructure can be integrated, how the data that are being collected can be mined, how services delivered by traditional means can be organised and delivered much more efficiently using these new technologies, all part of the idea of the Planetary Nervous System that is central to our proposal. This is our first goal but in parallel and embedded within this, we are interested in standing back from the nuts and bolts of the smart city, and devising much more effective models and simulations that will address problems of efficiency, equity and quality of life, set within a new context where a much wider group of citizens can engage in the science of smart cities through new ways of participating in the future design of their cities and neighbourhoods. These embrace our ideas of Living Earth

Simulators and the Participatory Platforms that are key to the *FuturICT* approach. In short, the smart city will be the boost to new forms of policy analysis and planning in the information age, and the greatest impacts of new technologies will be on the way we organise ourselves in cities and the way we plan this organisation. The main goal of *FuturICT* is to provide intelligence functions that will make this possible in the most effective and equitable ways.

The concept of the smart city emerged during the last decade as a fusion of ideas about how information and communications technologies might improve the functioning of cities, enhancing their efficiency, improving their competitiveness, and providing new ways in which problems of poverty, social deprivation, and poor environment might be addressed [26]. The essence of the idea revolves around the need to coordinate and integrate technologies that have hitherto been developed separately from one another but have clear synergies in their operation and need to be coupled so that many new opportunities which will improve the quality of life can be realized. The term smart city in fact has many faces [40]. Intelligent cities, virtual cities, digital cities, information cities are all perspectives on the idea that ICT is central to the operation of the future city [1]. Our research will embrace this challenge in the belief that coupling, coordination and integration are required so that future and emerging technologies can best be exploited in the interests of the community at large. An essential strand in our approach is to use ICT to engage the community through diverse instruments and initiatives that build upon online engagement in solving the key problems of cities, using the kinds of computer-based tools, techniques, methods and organisational structures that we will research here. To focus our research, we define seven goals.

1.1 Goals of research

A New Understanding of Urban Problems. Cities are complex systems par excellence, more than the sum of their parts and developed through a multitude of individual and collective decisions from the bottom up to the top down. The complexity sciences are integral to their understanding which is a moving target in that cities themselves are becoming more complex through the very technologies that we are using to understand them. We will not only fashion a programme for Europe to grow our understanding as a prelude to action and decision, but embed this as part of a wider international effort.

Effective and Feasible Ways to Coordinate Urban Technologies. Rapid advances in building information technologies into the very fabric of the city while at the same time using these technologies to integrate and add value to the provision of urban services provide the mandate for the sustained development of new methods. This will involve integrating data, software and organisational forms that best improve the efficiency and competitiveness of the environment in which cities operate.

Models and Methods for Using Urban Data across Spatial and Temporal Scales. Much data which is being generated in real time in cities needs to be merged with more traditional cross sectional sources but built on simulations that link real time, more routine problems to longer term strategic planning and action. Multilevel integrated modelling is thus key to this effort.

Developing New Technologies for Communication and Dissemination. New sources of urban data, the articulation of urban problems, plans and policies, and all the apparatus used in engaging the community in developing smart cities require new forms of online participation making use of the latest ICT in terms of distributed computation and state of the art human computer interaction (HCI).

New Forms of Urban Governance and Organisation. New ways of re-engineering cities to make them smart, responsive, competitive and equitable will require new forms of governance for an online world. Issues of privacy and access are key to this vision.

Defining Critical Problems Relating to Cities, Transport, and Energy. FuturICT is focussed on defining critical problems that emerge rapidly and unexpectedly in human society, some of which reveal critical infrastructures. The analysis of such problems and their identification is crucial to the sustainability and resilience of smart cities. Models and simulations associated with rapid changes in cities from housing market bubbles to regeneration to ethnic segregation will be explored using new approaches. The idea that cities are far-from-equilibrium, dominated by fast and slow dynamics in short and long cycles is central to our approach.

Risk, Uncertainty and Hazard in the Smart City. A much more informed understanding of risks in urban society is required which involves new data, new technologies, and new collective approaches to decision-making. Our notion of cities as strongly coupled systems that generate unexpected and surprising dynamics needs to be understood and the introduction of new technologies into cities is changing the nature of this dynamics, not necessarily for the better. Our quest in one sense is to develop technologies that will outsmart the smart city, anticipating this dynamics. Future and emerging technologies will be key to developing such approaches.

1.2 Research opportunities

We stand at a threshold in beginning to make sense of new information and communication technologies that will be deeply interwoven with conventional material technologies within the next decade. Already 22 percent of all people in the UK have smart phones in which they are able to access online services and this is growing at around 38 percent each year. At this rate, there will be total penetration by smart phones of the market (see `http://en.wikipedia.org/wiki/Smartphone/`) for mobile devices by 2015. Other estimates suggest that by 2015, there will be more than 2 billion smart phone users globally which suggests that access to online services will be the dominant mode of accessing information by the end of the *FuturICT* project in 2022.

The opportunities for the development of smart cities using mobile and other platforms at every spatial scale and over very different time spans will be enormous but the real challenge is to put in place new technologies that will integrate individualised and local technologies that are fast proliferating. For there to be real synergy, the idea of the smart city with all its economic and social benefits will only become a reality if such coordination is specifically addressed. This will involve a blend of sciences and arts which *FuturICT* is extremely well placed to initiate. It will involve a clear synthesis of hardware, software, database, and organisational technologies that are able to relate to the key problems of society and will require entirely new methods and models for synthesising diverse data and ideas that are currently not being addressed. This in turn implies a massive paradigm shift in how we address social and economic problems using ICT. The smart city will be at the forefront of this revolution.

1.3 Research challenges

The major intellectual challenge that we and the rest of society face, is embracing the idea that as we develop new digital technologies, we use those same technologies to study the processes of their application, implementation and impact on society.

We shape our tools and thereafter our tools shape us said Marshall McLuhan in 1964 his seminal book [32], and this is the challenge that we need to resolve in developing truly smart cities that will benefit the quality of life of all our citizens. In this, it is likely that participation in formulating policies might be very different from the past when futures were dictated by the elite, primarily because of its access to information. Already it is clear that a citizenry which is informed through the power of the net is beginning to make a difference as new forms of data and advice are being implemented using crowd-sourcing. New forms of preference elicitation are being generated using mobile and other applications, while the economy is essentially moving online with the disappearance of material tokens (cash). These are profound changes that we need to mobilize using the equally powerful science that *FuturICT* will unleash.

To this end, we can identify five key scientific challenges that relate to the seven goals outlined above.

To Relate the Infrastructure of Smart Cities to their Operational Functioning and Planning Through Management, Control and Optimisation. ICT is being fast embedded into the very fabric of the city in terms of its materials and infrastructure while wireless solutions are proliferating in ways that are hard to understand. At the same time, developments in computation and data to inform the planning of such cities are using these same technologies. There needs to be a major effort at showing how such developments can be integrated so that cities can become truly smart in the way their planners and citizenry can use such technologies to improve the quality of life. This style of multimodality constitutes a real challenge.

To Explore the Notion of the City as a Laboratory for Innovation. ICT is being developed to increase the efficiency of energy systems, the delivery of services ranging from utilities to retailing in cities, and to improve communications and transportation. The prospect of building models of cities functioning in real time from routinely sensed data is now a clear prospect and smart cities should evolve intelligence functions in the form of laboratories – that enable their monitoring and design. The competitive edge that a city offers is crucial to such intelligence.

To Provide Portfolios of Urban Simulation which Inform Future Designs. As the real time city and its sensing gets closer to providing information about longer term changes, there will be a new immediacy in the construction of urban simulation models Aggregate models will be replaced with disaggregate and our project will explore many different kinds of models building on and extending the sciences of complexity. We consider it important to build many different models of the same situation in the belief that a pluralistic approach is central to improved understanding of this complexity.

To Develop Technologies that Ensure Equity, Fairness and Realise a Better Quality of City Life. Efficiency must be balanced with equity. New technologies have a tendency to polarise and divide at many levels and we need to explore how new forms of regulation at the level of urban and transport planning, and economic and community development can be improved using future and emerging technologies. The smart city of course offers the prospect of ending the digital divide but it will also open up different divides and our challenge is to anticipate and plan for these.

To Develop Technologies that Ensure Widespread Participation. New ICT is essentially network-based and enables extensive interactions across many domains and scales. Part of the process of coordination and integration using state of the art data systems and distributed computing must involve ways in which the citizenry is able to participate and to blend their personal knowledge with that of experts who are developing these technologies. Privacy concerns as well as security are key to this challenge.

To Ensure and Enhance Mobility for Urban Populations. New ICT is able to improve mobility on many levels thereby increasing spatial and aspatial accessibilities to jobs, leisure, social opportunities and so on, thereby enabling the citizenry to increase their levels of life satisfaction.

2 The state of the art

2.1 Key themes

2.1.1 Explanation: The science of smart cities

Our proposal is predicated on a robust and consistent definition of the smart city. The term smart is peculiarly American in that it is widely used in everyday speech to refer to ideas and people that provide clever insights but it has been adopted more recently in city planning through the cliche smart growth. Rather than letting the market dictate the way cities grow and sprawl, smart growth is a movement that implies we can achieve greater efficiencies through coordinating the forces that lead to laissez faire growth: transportation, land speculation, conservation, and economic development. We adopt here the definition that is coined by Caragliu, Del Bo, and Nijkamp (2009) [12] which is summarised in Wikipedia: a smart city is a synthesis of hard infrastructure (or physical capital) with the availability and quality of knowledge communication and social infrastructure. The latter form of capital is decisive for urban competitiveness. (`http://en.wikipedia.org/wiki/Smart_city`). Digital cities tend to focus on the hard infrastructure whereas intelligent cities on the way such infrastructure is used [3–5]. Earlier conceptions included the idea of the wired city [13] which originally came from James Martins conception of the wired society.

To this nexus, we add the notion that smart cities are also instruments for improving competitiveness in such a way that community and quality of life are enhanced. Cities that are smart only with respect to their economy are not smart at all if they disregard the social conditions of their citizenry. In fact the term smart city has become shorthand for the way companies that are developing global ICT from infrastructure such as networks to software as services large companies such as IBM, CISCO, Microsoft, Oracle, SAP are beginning to generalise their products as they see markets in cities representing the next wave of product development in the globally distributed world that now exists. In the sequel, we will sketch the main themes that are developing around the smart city idea from hardware through to services and from data through to simulation and thence prediction, participation, and design.

Many of the worlds most successful ICT companies are extending their focus in software to area-wide applications that involve developing online service delivery systems for cities and they are badging their products as part of the move to make cities smart. For example, IBM are in the vanguard of these services and although the focus is still from the perspective of routine services involving utilities and traffic in the first instance, very much in the tradition of urban operations research, their remit is expanding to deal with more strategic functions and intelligence. This is for directing and guiding the city as well as improving its long term quality of life. IBM under its Smart Planet initiatives has key centres working on Smart Cities as their site (`http://www.ibm.com/smarterplanet/us/en/smarter_cities/overview/index.html`) shows. Their business development division has produced a useful summary from which we take Fig. 1 that illustrates the range of services that this particular

Today...	What if a city could...	Already, cities are...
City services • Service delivery in silos with one size fits all	• Tailor services to the needs of individual citizens	• Using technology to integrate the information systems of different service delivery agencies to enable better services for citizens
Citizens • Cities have difficulty using all the information at their disposal • Citizens face limited access to information about their healthcare, education and housing needs.	• Reduce crime and react faster to public safety threats, by analyzing information in realtime? • Use better connections and advanced analytics to interpret vast amounts of data collected to improve health outcomes?	• Putting in place a new public safety system in Chicago, allowing realtime video surveillance and faster more effective response to emergencies • Giving doctors in Copenhagen instant access to patients' health records, achieving the highest satisfaction and lowest error rates in the world.[38]
Transport • Transporting people and goods is dogged by congestion, wasted hours and wasted fuel.	• Eliminate congestion and generate sustainable new revenues, while integrating all transport modes with each other and the wider economy?	• Bringing in a dynamically priced congestion charge for cars to enter Stockholm, reducing inner-city traffic by 25 percent and emissions by 14 percent, while boosting inner-city retail by 6 percent and generating new revenue streams.[39]
Communication • Many cities have yet to provide connectivity for citizens • "Going online" typically means at slow speeds and at a fixed location.	• Connect up all businesses, citizens and systems with universal affordable high-speed connectivity?	• Merging medical, business, residential and government data systems into a so-called ubiquitous city in Songdo, Korea, giving citizens and business a range of new services, from automated recycling to universal smartcards for paying bills and accessing medical records.
Water • Half of all water generated is wasted, while water quality is uncertain.	• Analyze entire water ecosystems, from rivers and reservoirs to the pumps and pipes in our homes? • Give individuals and businesses timely insight into their own water use, raising awareness, locating inefficiencies and decreasing unnecessary demand?	• Monitoring, managing and forecasting water-based challenges, in Galway, Ireland, through an advanced sensor network and realtime data analysis, giving all stakeholders – from scientists to commercial fishing – up-to-date information.
Business • Businesses must deal with unnecessary administrative burdens in some areas, while regulation lags behind in others.	• Impose the highest standards on business activities, while improving business efficiency?	• Boosting public sector productivity, while simplifying processes for business in Dubai through a Single Window System that simplifies and integrates delivery and procedures across a range of almost 100 public services.[40]
Energy • Insecure and unsustainable energy sources.	• Allow consumers to send price signals – and energy – back to the market, smoothing consumption and lowering usage?	• Giving households access to live energy prices and adjust their use accordingly, as in a Seattle-based trial, reducing stress on the grid by up to 15 percent and energy bills by 10 percent on average.[41]

Source: IBM Center for Economic Development analysis.

Fig. 1. IBMs typology of urban issues for the smart city, now and in the future.

company sees as part of their Smart City initiative [43]. This is not dissimilar to the sorts of problems and policies that have been defined for cities in more traditional terms over the last 50 or more years but where the focus of the solutions is now on ICT. In fact what *FuturICT* will offer is a much deeper and considered inquiry into the development of smart cities, linking these technologies to social questions, co-evolving these new technologies along with initiatives of the many other ICT companies who have similar missions to that of IBM.

2.1.2 Representation: Measuring and mining urban data

Traffic flows were the first data to be automatically sensed in cities but databases of various spatial data go back centuries. Indeed digital computing emerged as much from a concern over collecting census data as it did from a concern for scientific computation. Herman Hollerith introduced punched card technology for the 1890 US Census from which sprang the company that ultimately became IBM. Since the late 1990s, such data has been routinely collected and displayed using GIS (geographic information systems) technology, and the first visual systems to be widely available on the web were maps for navigation. This is the backcloth against which many different initiatives in collecting data from new varieties of digital access are being fashioned such as GPS in vehicles and on the person, from electronic messaging in the form of social media sites, from traces left through purchase of goods and related demand-supply situations, and from access to many kinds of web site. Satellite remote-sensing data is also now widely deployed, more local scale sensing from LIDAR is proliferating, and a variety of scanning technologies that range from the region to the person and to very fine scale tagging as in the focus associated with the internet of things, are becoming significant. One of the most extensive crowd-sourcing applications, next to Wikipedia, is Open Street Map built from a community of some 20000 active users who continually update the map using GPS. Indeed new models of scientific discovery are emerging from developments in rather focussed crowd-sourcing and these are applicable to how we might figure out good designs for efficient and equitable cities [33].

Within the next twenty years, most of the data that we will use to understand cities will come from digital sensors of our transactions and will be available in various forms, with temporal tags as well as geotags in many instances. To interpret such data, we need to exploit and extend a variety of data mining techniques through which the visualisation of correlations and patterns in such data will be essential. The open data movement is gaining momentum (e.g. `http://data.gov.uk/`) and we see *FuturICT* as sharply focussed on how we might integrate such data using new forms of database design adapted to and distributed at the city-wide scale. Moreover we also see the idea of crowd-sourcing as key to many new data sets that will be useful to smart cities while noting that these types of interactive technologies can also be used to elicit preferences and to engage in social experimentation with respect to what we know and think about key urban problems. New applications which elicit quite subjective preferences concerning happiness and associating these with places are currently being developed (`http://www.mappiness.org.uk/`).

The basic ingredient for the new wave of city analytics that has emerged during the last decade is big data sets concerning human mobility, fostered by the widespread diffusion of wireless technologies, such as the satellite-enabled Global Positioning System (GPS) and mobile phone networks. These network infrastructures, as a by-product of their normal operations, allow for sensing and collecting massive repositories of spatio-temporal data, such as the call detail records from mobile phones and the GPS tracks from navigation devices, which represent society-wide proxies for human mobile activities. These big mobility data provide a powerful social microscope, which may help us understand human mobility, and discover the hidden patterns and models that characterize the trajectories humans follow during their daily activity [8,21]. In such research, privacy is always considered but is rarely in danger for the data is anonymised through several levels of scrutiny and confidentiality.

The direction of this research has recently attracted scientists from diverse disciplines, being not only a major intellectual challenge, but also given its importance in domains such as urban planning, sustainable mobility, transportation engineering, public health, and economic forecasting. The European FET project GeoPKDD (Geographic Privacy-aware Knowledge Discovery and Delivery, `www.geopkdd.eu`, 2005–2009) is a precursor in mining human mobility data, which has developed various analytical and mining methods for spatio-temporal data. This and other projects, in Europe and internationally, have shown how to support the complex knowledge discovery process from the raw data of individual trajectories up to high-level collective mobility knowledge, capable of supporting the decisions of mobility and transportation managers, thus revealing the striking analytical power of big mobility data. Analysts reason about these high-level concepts, such as systematic versus occasional movement behaviour, purpose of a trip, and home-work commuting patterns. Accordingly, the mainstream analytical tools of transportation engineering, such as origin/destination matrices, are based on semantically rich data collected by means of field surveys and interviews. It is therefore not obvious that big, yet raw, mobility data can be used to overcome the limits of surveys, namely their high cost, infrequent periodicity, quick obsolescence, incompleteness, and inaccuracy.

On the other hand, automatically sensed mobility data are ground truthed: real mobile activities are directly and continuously sampled as they occur in real time, but clearly they do not have any semantic annotation or context. Much research has begun to show that the semantic deficiency of big mobility data can be bridged by their size and precision [23]. Large-scale experiments have shown how it is possible to find answers to many challenging analytical questions about mobility behaviour, such as: What are the most popular itineraries followed by individual travel and what is the spatio-temporal distribution of such travel? How do people behave when approaching a key attractor, such as a big station or airport? How do people reach and leave the site of an extraordinary event, such as an important football match? How can we predict areas of dense traffic in the near future? How can we characterize traffic jams and congestion? More than just examples, these questions are paradigmatic representatives of the analysts need to disentangle the huge diversity of individual locations and tracks to discover the subgroups of travel characterised by common behaviour and purpose [22]. It is no surprise, therefore, that finding answers to these questions is still beyond the limits of the current generation of available systems. In *FuturICT* we will push back these limits.

Explanations of why traffic significantly varies from one day to another even if demand profiles are similar is extremely weak and we consider that new ICT will provide us with dramatically new data sets that will inform this problem. It is not also clear how one could predict spatiotemporally the development and propagation of congestion with small errors. The severity of these effects is even stronger in case of non-recurrent events (e.g. accidents, road constructions), which can affect the resilience and productivity of transportation systems. How all of the above are related to the network topology and how small or large perturbations in demand profile and network characteristics affect choices of people (in terms of route, departure time and mode) is one of the challenges we need to address.

For long periods choices of people in transportation networks are based on equilibrium conditions with small variations. New data can help us understand whether or not the real urban traffic can be considered an equilibrium system with respect to a cost function, how people really make choices and how these choices affect the development and spreading of congestion in the networks. The large number of trajectories and disaggregated traffic data from cities of different sizes and in different locations globally will provide a unique way to identify the macroscopic observables and control parameters that affect individual decisions and integrate them in agent-based models. Current day-to-day traffic assignment models are not suitable for modelling the traffic evolution under strong changes of network topology (e.g. a heavy disruption or a new mode of transport such as that occurring in many cities in developing countries because such models assume that drivers build on their experiences from past days. But when significant network changes occur, lack of observation measurements do not allow for the realistic modelling of pattern evolution and identification of equilibrium or non-equilibrium. Our research programme in smart cities will attempt to address all these challenges.

The concept of reality mining [14] which concerns highly pervasive sensing of complex social systems using ubiquity of mobile phones is a key determinant of how citizens interacting with each other in cities are becoming smarter. Reality mining depends on software to log location, communication activity, as well as usage of other services and applications. The analysis of derived datasets helps extracting eigenbehaviours to identify structure in everyday routine activities [15]. This data have enormous potential to gain new insights into urban dynamic processes at high temporal and spatial resolution at the scale of cities, given enough effort is put into resolving privacy concerns. Recent studies of datasets of mobile phone usage and geo-referenced online social networks and micro-blogging platforms have identified promising directions for this work. The main areas of interest are mobility patterns, spatial aspects in social network structure, group behaviour identification and data-driven characterization of city functioning.

From data mining and network analysis, we are able to create an urban mobility atlas, i.e., a comprehensive catalogue of the mobility behaviours in a city, an atlas that can be browsed (by the hours of the day, the days of the week, geographic area, meteorological conditions, and so on) in order to explore the pulse of a city in varying circumstances, while also observing emerging deviations from normal [7]. To fully realise the idea of an urban mobility atlas for the smart city, there is the need to integrate increasingly richer sources of mobility data, including the data from public transportation, road sensors, surveys and official statistics, social media and participatory sensing, into coherently integrated databases, as well as connecting mobility with socio-economic networks. This integration will be extremely relevant to understanding how public energy saving transportation systems could satisfy the demand for individual mobility.

2.1.3 Connection: The idea of coupling networks

The social fabric of a city is the result of many intertwined, multi-faceted networks of relations between persons, institutions, places, and more: beyond mobility, we need to take into account social and economic networks. We believe that the key insight for understanding the city is in understanding the structure of these coupled networks, and how this structure evolves. One important example of coupling/connecting the different facets of urban life is between mobility, consumer exchange involving retailing, and social networks. Despite the recent explosion of research in social networks pushed by big data, the bulk of work has focused on the social space only, leaving important questions involving to what extent individual mobility patterns shape and impact social networks, barely explored to date, but there is some preliminary work on transport behaviour and its psychology [42]. Indeed, social links are often driven by spatial proximity, from job- and family-imposed programs to joint involvement in various social activities. These shared social foci and face-to-face interactions, represented as overlap in individuals trajectories, are expected to have significant impacts on the structure of social networks, from the maintenance of long-lasting friendships to the formation of new links.

Our knowledge of the interplay between individual mobility and social networks is limited, partly due to the difficulty in collecting large-scale data that simultaneously record dynamical traces of individual movements and social interactions. This situation is changing rapidly, however, thanks to the pervasive use of mobile phones. Indeed, the records of mobile communications collected by telecommunications carriers provide extensive proxies of individual trajectories and social relationships, by keeping track of each phone call between any two parties and the localisation in space and time of the party that initiates the call. The high penetration of mobile phones implies that such data captures a large fraction of the population of an entire country. The availability of these massive CDRs (Call Detail Records) has made possible, for instance, the empirical validation in a large-scale setting of traditional social network hypotheses such as Granovetter's strength of weak ties [25], and the development of a first generation of realistic models of human mobility and their predictability [24].

Indeed, despite the heterogeneity of spatial resolution (the uneven reception area of mobile phone towers) and sampling rates (the timing of calls), the large volume of

CDR data allows us to reconstruct many salient aspects of individual daily routines, such as the most frequently visited cells, and the time and periodicity of such stays. Therefore, these data help us scrutinize the spatial patterns together with social structure and the intensity of social interactions. Recent studies [2] show empirical evidence that these three facets, co-location, network proximity and tie strength, are correlated with each other: the higher the likelihood that two persons co-locate (i.e. are observed in the same location/cell), the higher the chance that they are strongly connected in the social network, and that they have intense direct interactions [31]. The emergence of such surprising three-fold correlation hints that it is conceivable to explain (and predict) how new social ties will form as a function of mobile behaviour, and vice versa. In perspective, by coupling the social and mobility networks with further information, it may be possible to edge towards exploring the evolutionary dynamics of the urban social sphere, predict the spreading of sentiments, opinions and diseases, and thus to understand in real time the evolving borders of the community structure of a city.

To make sense of this great proliferation of data, we need to establish standards for integration of this data, for ensuring that quality standards are met, for assessing the accuracy and error in such data, and for providing ways of filling in missing data using models of the very systems that this data pertains to. Much of this data is networked and we consider that coupling such networks of data bases will be key to making sense of this material. New methods of coupling in terms of hardware and software will be needed and this will be central to the sort of collective intelligence functions that we see the smart city developing. Currently control centres in cities tend to exist only for the most routine and constrained systems such as traffic but to realise the vision of the smart city such networked-based coupling will be essential. This is an enormous challenge.

2.1.4 Coordination: The need for joined-up planning

Urban planning was first institutionalised in the late 19th century in several western industrialised nations and since then, it has diffused as a function of government in most countries worldwide. Its functions are exercised at national, regional, metropolitan, city, district and neighbourhood levels with rural, environmental and transport planning representing more specialised foci. However, planning is much wider in its import than these institutional frames for it is exercised as a function of many businesses and community groups, indeed across every activity that has a distinct interest in the city. In short, when we call for joined-up planning, we mean integration across the board, selectively and sensitively of course, but integration that enables system-wide effects to be tracked, understood and built into the very responses and designs that characterise the operations and functions of the city. This relates very strongly to the previous theme involving connection, networks and data integration. The sort of intelligence functions that we envisage for the smart city would be woven into the fabric of existing city institutions whose mandate is producing a better quality of life for its citizenry.

We envisage that the smart city would focus on the usual components that make the city function as a competitive entity as well as a social organism. The idea of ICT penetrating wherever it can improve performance and generate a better quality of life is central to this quest [18]. In this project, we will focus on ICT in buildings and the built environment, urban design, transport planning, local planning, metropolitan planning, regional planning, and upwards to the European level where, for example, the ESPON (European Spatial Planning Observation Network) project is already mobilising resources to examine smart city ideas across Europe through traditional urban and regional planning instruments.

2.1.5 Participation: Citizen science

Public participation is a long-standing tradition in institutionalised planning but the emergence of the digital world has turned the activity on its head. The ability for all citizens to communicate with one another and with agencies and groups that represent them, has provided a new sense of urgency and possibility to the idea that smart cities are based on smart communities whose citizens can play an active part in their operation and design. There are many such initiatives at the present time and we will focus on ways in which citizens can first access information about what is happening in their communities and cities but also explore ways in which a wide range of different groups can become actively involved in the design and planning process, both remotely and in face-to-face situations using data, models and scenarios all informed by contemporary ICT [27].

Current forms of participation are responding to new ICT but still remain inert and somewhat passive. New media and the web are increasing the liquidity of this type of interaction as both data and plans are being shared [16]. Participation is becoming more bottom-up than top-down, more in the spirit of the way complex systems actually evolve. In *FuturICT*, we envisage that we would pioneer a number of demonstrators as to how an informed citizenry might engage with experts from many domains in generating scenarios for improving the quality of urban life and urban performance, in ways that hitherto have not been possible. This will require a huge mobilisation of resources which draw on many aspects of the *FuturICT* proposals and imply serious progress in data, model, and policy integration. Already key data sources are being opened up such as mapping data, crime and policing, house price data, health data and so on and this will provide the momentum for the various demonstrators that we will initiate.

In our vision, participation and self-organisation are the cornerstones to building a global knowledge resource that, by design, will represent a public good, accessible to every citizen, institution or business. On the one hand, people should be fully aware of the kind of public knowledge infrastructure they are contributing to, and of the potential benefits they will be able to get from it. On the other, people should be in full control of their contributed data/profiles: how their data are being acquired, managed, analysed and used, when and for how long. Only a public system capable of delivering high-quality information within a trusted framework has the potential for raising a high degree of participation, and only large, democratic participation can ensure the creation of reliable, timely and trustworthy information about collective phenomena. This view is at the basis of a citizens science, where sentiment and opinion mining from trusted information can detect shifts in collective mood in a timely manner, detect the weak signal of important changes, and detect the structure and evolution of social communities.

2.2 Understanding smart cities

2.2.1 Sensing and measuring

In the past, cities have been understood and planned across several levels. Currently there is real momentum in sensing urban change from the ground up, so-to-speak, using new sensing technologies that depend on hand-held and remote devices through to assembling transactional data from online transactions processing which measure how individuals and groups expend energy, use information, and interact with respect to money. Network technologies make possible extensive data collection and coordination of such data in terms of the data itself and in terms of how that data is stored and made accessible. New forms of data base organisation and mining offer the prospect for adding value to the data in terms of massive data integration. The list of components and sectors in the city is almost too long to catalogue but the key sectors which currently are being heavily networked involve: transport systems of all modes in terms of operation, coordination, timetabling, utilities networks which are being enabled using smart metering, local weather, pollution levels and waste disposal, land and planning applications, building technologies in terms of energy and materials, health information systems in terms of access to facilities by patients the list is endless. The point is that we urgently need a map of this terrain so that we can connect up these diverse activities.

There is a strong evidence of spatial patterns in social structures. Distance decay in spatial interaction processes is a well-known phenomenon, and many recent studies on mobile phone data sets have confirmed distance decay relationships: the likelihood that two individuals are connected decreases with distance between them [30]. Generally, social structures of communities detected from phone data analysis show strong spatial regularity in regional [20] and city scale levels [45], revealing finer patterns concerned with cultural and socio-economic heterogeneity of cities. More work is required to extend these findings to reveal temporal dynamics as the potential for optimising urban transportation systems through exploiting social structure is enormous. Spatial interaction also manifests itself in strong spatial consistency in the function of the city, both defined by infrastructure and underlying urban planning, so as in terms of the ways people tend to use cities [38] and the temporal evolution of these patterns. The eigenplaces approach does not ascribe any semantics to these regimes but it is possible to provide an interpretation by examining changes over space and time, taking into account land use and services distribution in the city. The analysis of content-rich data from micro-blogging adds novel dimensions to these studies. Content analysis allows semantically-rich analysis of land use [41], temporal variability of current-moment interests within cities and related travel behaviours [37], and inter-city comparisons which reveal common dependencies in human mobility across countries and continents [34]. Notwithstanding these developments, integrating diverse real time data from different sources is problematic not only from a computational perspective but also in terms of building integrated models.

Linking GPS, satellite remote-sensing, online interactive data systems focussed on crowd-sourcing, all with the automation of standard secondary sources of data, and then meshing this with more unconventional data elicited from social media provides a very rich nexus of possibilities in terms of providing new and open sources of data essential to a better understanding of how smart cities will function.

2.2.2 Movement and networks

Travel is the minimum price we pay to participate in out-of-home activities as individuals. Networks are the infrastructure we provide collectively to reduce these costs. Increasing urbanisation in conjunction with the growing depth of networks in terms of technologies (water, travel, energy, communication) put an emphasis on our ability to grow these networks in a way which strikes a compromise between their current and future costs, reliability and resilience. The ever-growing density and volume of information about the state of the networks as built artefacts and about the state of the networks in terms of user experience provides an enormous opportunity to improve both their planning and operation. This growing complexity should be approached with local solutions and local rules (grammars) to reduce the planning costs for all participants, especially in parts of the world where the planning system does not have the strength to impose or bribe large scale and long range solutions. These grammars will have to be defined at both large and small spatial scales to address both the local and regional/national scale of the demands of society. These grammars will be the focus of the research work planned.

2.2.3 Travel behaviour

The density and timeliness of information flows allow travellers to respond immediately with an ever more complete picture of the situation in mind, if they are confident enough in the accuracy of the information and in their ability to judge the impact of the information used on the response of all other travellers. The difficulty for the traveller is to learn how much he or she can trust her judgement in a particular style of situation and related to this, how much weight should she give to the particular source (radio station A, government advice B, friend C, the last minutes of travel flow/movement observed). It is also part of the learning process to learn when the effort of changing the route or mode is not worth the effort where maintaining the existing plan is the least-effort choice.

This empowerment of the traveller is a challenge for any advice system where it aims for self-consistency. The self-consistency of any advice system in a group of advice systems is an unexplored problem, especially for a mixture of public and private systems with different assumed objective functions for the travellers. The *FuturICT* project will address this issue through both mathematical and simulation-based work, both to gain understanding of the interactions between the travellers and different advice systems, as much as to guide the systems to the best achievable system configuration given the number and types of players involved. The development of multimodal trip planners and advice systems are in their infancy and we expect *FuturICT* to spur the development of such applications.

2.2.4 Land use and transport

The increasing richness in social terms of the telecommunication experience raises the question of whether or not cities are still needed in their central function as places, which enable innovation and scale through the enforced concentration of many actors: suppliers and buyers; designers and engineers; businessmen and retailers; scientists and craftsmen. The increasing physical range of travellers (and logistic-chains) reduce the importance of any one place, while not discounting the symbol importance of certain locations for different actors groups and milieu. The net of networks, both social and physical, needs to be explored using a wealth of traces which our computing and telecommunication systems can now generate. The assessment of their structure and impact needs to cover the whole range of impacts from the economic to the environmental; both in steady state and in crisis, and both with regards to the possibilities of governmental control and its ability for emergent social control.

2.2.5 Urban markets and exchange

Cities are essentially sets of markets where individuals and groups come together to exchange. This is their traditional rationale to overcome the friction of distance which enables people to compete for scarce resources in the highly favourable conditions generated by agglomerations of labour with quite specialised tasks and skills. It is well known that ICT changes the effects of distance (and cost) quite radically and it would be surprising if this were not critical to the structure of cities and the way they function. So far markets in cities have worked in traditional ways but with globalisation, network economies, and the substitution and complementation of information for energy and materials, the local economy is moving increasingly online and this is influencing locational decisions in ways that we are largely unaware of. It is clear for example that bookshops and some other retail outlets are changing in terms of their presence and location as much of this activity moves to the net but in the case of housing markets, labour markets, economic development, the demand and supply of transport facilities and access to education and health care, the impact of ICT on markets is complex and largely unexplained. Moreover the development of many new systems for the movement of goods and freight is likely to revolutionise the logistic industry and new systems are emerging from the impact of ICT on transport.

We need to understand these markets in the network economy much more clearly and part of our proposal will be to initiate new approaches to such understanding, linked strongly to other projects in *FuturICT* that involve the simulation of financial markets and behaviours [11]. Moreover, new networks and markets are emerging such as the market for energy [17] and this is yet another example where the city is increasing in complexity as human behaviour is enriched by access to new ways of deciding how to utilise spatial resources.

2.2.6 Firms and organisations

The current modelling approaches used in urban planning have a very reduced understanding of firms and their spatial behaviour. Based on the possibilities of tracing choices over time and space on the web, it will be necessary to develop agent-representations of the firms by size, type and sector. These agents will be crucial in the new models of land use, transport and the economy. Without them, agent-based modelling of urban markets would be incomplete and potentially misleading. Traditionally aggregate economic forecasting models based on input-output analysis have dominated this area hitherto but there is an urgent need for new models which reflect stronger behavioural rules that are clearly relevant to such decision-making.

2.2.7 Communities and networks

Traditionally there has been a strong focus in cities on questions of community which 50 years ago were largely based on replacing worn out infrastructure in the form of housing built during the 19th century. The public sector was dominant in these activities in many western industrialised cities but from then on, the role of this sector has declined. The focus has also shifted from problems manifested in the built environment to problems of social deprivation and the lack of economic opportunities. Policies involving welfare and social conditions combined with positive attempts to steer labour markets have begun to replace more infrastructure-based instruments. ICT is making obvious inroads into the delivery of information about these issues to the affected populations while at the same time providing interactive advice concerning how such opportunities can be realised. Smart technologies are central to this as they are to related services such as health and education. There is however still a massive effort required to enable such services to connect to one another and to gain real value through such connectivity.

The role of ICT in terms of collecting and modelling new ideas about community through much deeper analysis of social networks is an obvious extension to our analytical capabilities in dealing with questions of community. *FuturICT* will explore

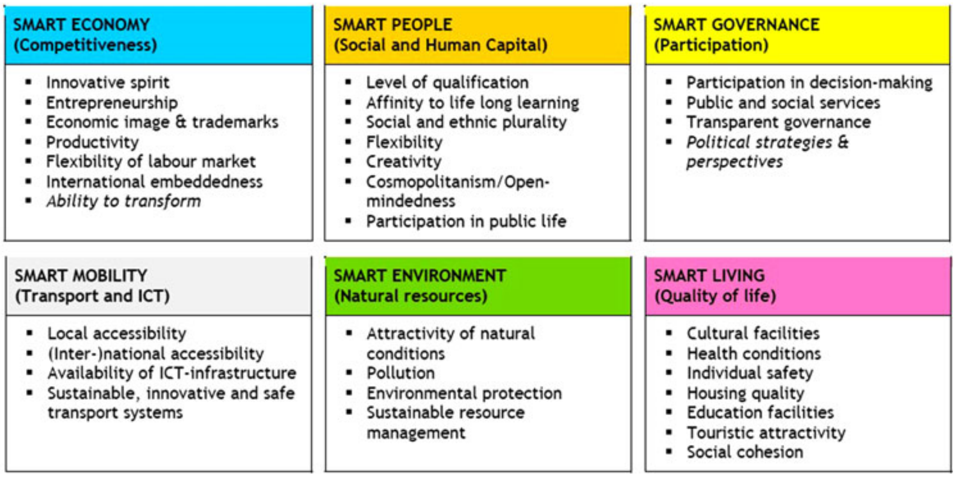


Fig. 2. A typology of smart city functions.

the way community networks can be generated using new social media and related connectivities that can be mined from mobile device data bases and web sites, and explore how these can be linked to data on housing and labour markets. Moreover, in planning smarter communities, there is a design dimension to social networks, which needs to be factored into new ways in which we can generate plans, involving the community itself in the analysis of its own data.

2.3 Planning smart cities

2.3.1 The need for coordination and coupling

Coordination, communication, coupling and integration are different perspectives in developing the smart city which we see as a programme of connecting up infrastructures and services so that the city can function more effectively. This will require new forms of database, new methods of mining and pattern analysis, new software for integrating diverse and hitherto unconnected components and sectors in urban functioning, and new forms of organisation and governance, which will enable such connectivity to become effective and fair. The smart city balances efficiency against equity with a focus on improving the ability of its citizenry to innovate through a balance of cooperation with competition. There are strong links here to uniform markets for generating greater liquidity and mobility in the use and provision of urban services and these goals lie behind the mission statements produced by governments and businesses for the smart city. There are many examples of how various sectors might connect up presented in these papers and mission statements. Here we show one of these as an exemplar: this is reproduced below in Fig. 2 from two sources: from `www.networks-etp.eu` [18] and from `www.smart-cities.eu` [19].

2.3.2 New data systems and integration

In our quest to master the complexity of the knowledge discovery process for the smart city, we need to build an entirely new holistic system for integrated data acquisition, querying and mining. The entire analytical process able to create the knowledge services should be expressible within systems which support the following:

- The acquisition of data from multiple distributed sources, including services for participatory sensing and online communities
- The management of data streams
- The integration of heterogeneous data into a coherent database
- Data transformations and preparations
- Definition of new observables to extract relevant information
- Methods for distributed data mining and network analytics
- The management of extracted models and patterns and the seamless composition of patterns, models and data with further analyses and mining
- Tools for evaluating the quality of the extracted models and patterns
- Visual analytics for the exploration of behavioural patterns and models
- Simulation and prediction methods built on top of the mined patterns and models
- Incremental and distributed mining strategies needed to overcome the scalability issues that emerge when dealing with big data.

Although preliminary, partial examples of this line of research already exist, in specific domains, such as mobility, which is fast becoming an exemplar for encompassing all the domains of data, patterns and models for the smart city, a continuing research challenge for *FuturICT*.

2.3.3 Governance in smart cities

We have already argued that a much stronger intelligence function is required for coordinating the many different components that comprise the smart city. These will depend on some sort of structure that brings together traditional functions of government and business. Business has the expertise in providing hardware, software and data solutions enabling cities to be smarter while government is engaging users of services, community and citizen interests whose traditional focus in on the quality of life of their communities. Such governance reaches out to higher level NGOs whose function is to set the community in a wider context extending to extra territorial agencies such as the EU and of course national governments.

There can be no one agency responsible for all of this but just as cities are increasingly being seen as constellations of active agencies and groups, so their overall governance and coordination can be constituted in the same way, from the bottom up as well as the top down. Again, the idea of governance that extends in this way to the many functions that we envisage and will be coordinated in the smart city, is a relatively new prospect and is part of the wider debate about decentralisation of governance in the information age [28]. It relates strongly to privacy, security as well as economic performance, social inclusivity and a host of issues that are being changed by new ICT. We envisage that this theme will be part of our programme of research related to new organisational infrastructure for smart cities that are built around new developments in ICT. We consider that the traditional role of planning which now includes regeneration, traffic, economic development, and housing, will involve questions of the operation of utilities, the access of citizens to services, health, education, indeed any functions which have a spatial effect on the city in terms of location and movement.

2.3.4 New methods for design and planning

Over the last 50 years, various simulation models operating at different spatial scales and over different temporal intervals have been developed for understanding how cities function. Most of these models have been focussed on understanding as a prelude to their use to inform the planning and design process. These models have been focussed largely on simulating the location of physical activities, albeit through an economic and demographic lens which enables material transport and the location of land uses to be predicted using computer models of various sorts. Some extensions of such models into optimisation have been made as in urban operations research but generally such models are used in a somewhat intuitive dialogue with policy makers in the context of what are now called planning support systems [16].

The emergence of the smart city poses enormous challenges for these styles of modelling for many reasons. First, the city itself is being transformed from a place dominated by physical actions to one in which such action is complemented by extensive use of information technologies. Second, many routine functions in cities are being replaced by computer control and various forms of automation are increasingly being blended with human actions. Third, the provision of data from these new electronic functions in the city offers the prospect of a world in which the implications of how the city is functioning is continuously available and such immediacy is compressing time scales in such a way that longer term planning itself faces the prospect of becoming continuous as data is updated in real time. We also face the prospect of developing intelligence and planning functions at the same time as the very object that we are concerned with the city is changing its nature due to similar if not the same functions being used in its operation. This kind of space-time convergence in cities implies a level of complexity that only the new and powerful science of the kind that we will pioneer in *FuturICT* can address.

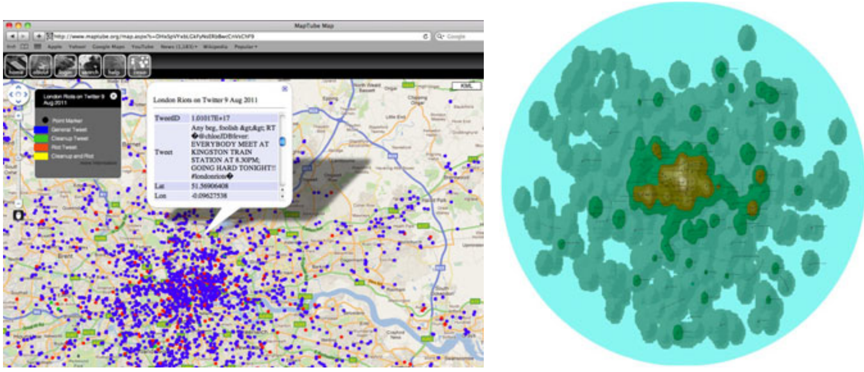
Much of our focus on smart cities will be in evolving new models of the city in its various sectors that pertain to new kinds of data and movements and actions that are largely operated over digital networks while at the same time, relating these to traditional movements and locational activity. Very clear conceptions of how these models might be used to inform planning at different scales and very different time periods are critical to this focus. We envisage that quite new forms of integrated and coordinated decision support systems will be forthcoming from this research.

2.3.5 Participation and online communications

We have already implied that new forms of participation in developing the smart city need to be generated from new forms of ICT. To date, web-based participation is largely passive and only quite recently have Web 2.0 technologies which presume true interactivity come on stream. In fact for purposes of participation in designing the city, there is an enormous overhead of time and interest required and therefore processes have to be devised which enable interested citizens to make an impact in terms of their participation. The HCI issues in such developments are crucial as are issues of privacy and confidentiality. Online communication comes in many forms and in terms of mobilising the wider citizenry, then we can define at least four key modes of interactivity: first, portals and other access points to useful information about any aspect of routine living and working in cities, second ways in which citizens can interact with software that enables them to learn more about the city by engaging with other users online and actually creatively manipulating information, third citizens engaging with crowd-sourced systems in which they are responding to queries and uploading information, and fourth, fully fledged decision support systems which enable citizens to engage in actual design and planning itself in term of the future city.

2.4 A sample of contemporary exemplars

There are hundreds of examples now that pertain to how ICT is being embedded into cities yielding new data for understanding key urban problems, enabling better urban



(a) (b)

Fig. 3. Mapping Twitter feeds: (a) the London riots, Summer 2011, and (b) a map of Twitter feeds over 24 hours in Paris.

functioning and generating new solutions that improve urban performance and the quality of urban life. We will identify seven and simply outline their salient points to give some sense of how ICT is being successfully used and how it might be used in the short and medium term future.

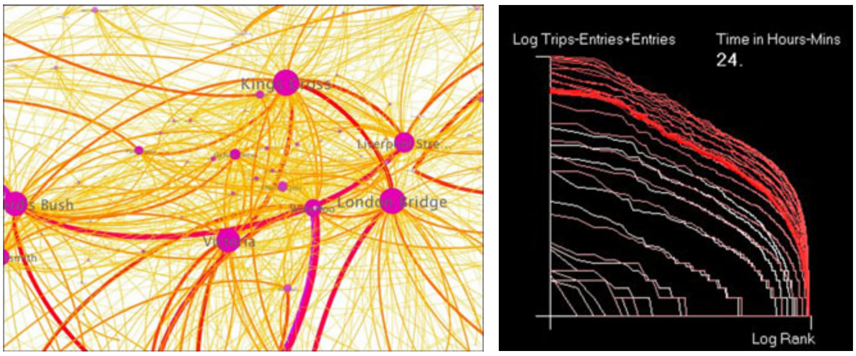
2.4.1 Real time sensing: Crowd-sourcing and mapping social media

The most high profile social media currently is short text messaging in which any kind of information can be transmitted in less than 140 characters to anyone signed up to particular network systems, the best example being Twitter. Any smart device or computer that is able to access the Twitter domain can enable a geo-coding facility that locates where the message is sent from and there is considerable research into how social networks as well as spatial networks might be fashioned from such data. Geo-locating the sources of such messages is in fact the main application to date. We are only just beginning to see the potential of such media and the extraction of content is a major issue. However it is likely that there will be considerable advances in content to extract useful information and this might be linked to new schemes for mobility management; even if this is not the case with Twitter data, the point is that similar data will come on stream that is likely to be more focussed as this kind of technology becomes widespread. Below are maps of Twitter feeds showing the London riots of August 7–9, 2011 in Fig. 3(a) and a map of Twitter densities in Paris produced during 24 hours in June 21, 2010 in Fig. 3(b).

The largest data at present of a more professional usage is produced by crowd-sourcing and this is Open Street Map which is produced by armies of volunteers recording positional information using GPS like technologies which deployed in the field. We will not show this here but it has high accuracy in many areas of the world and it can be used as a base-map for other social media data as in the map above of Twitter feeds. The map above is Google Maps but OSM is an obvious alternative.

2.4.2 Multiple networks: The london oyster card data

Movement on public transport in large cities is increasingly made by passengers using cards that are loaded with cash to facilitate more than one journey. In London, all buses, overland (heavy rail), and underground (tube) can be used with an integrated



(a) (b)

Fig. 4. Daily flows (a) and volumes (b) between and at hubs on the London rail network from qyster card data.

card and there is a detailed data base of almost one billion events corresponding to entries, exits, transfers, and refunds over a 6 month date ranging from November 2010 June 2011 which we have been mining and visualising. So far we have examined data on the overground and tube systems and we are intent on examining patterns in the flows between hubs as in Fig. 4(a) and volumes at hubs as in Fig. 4(b).

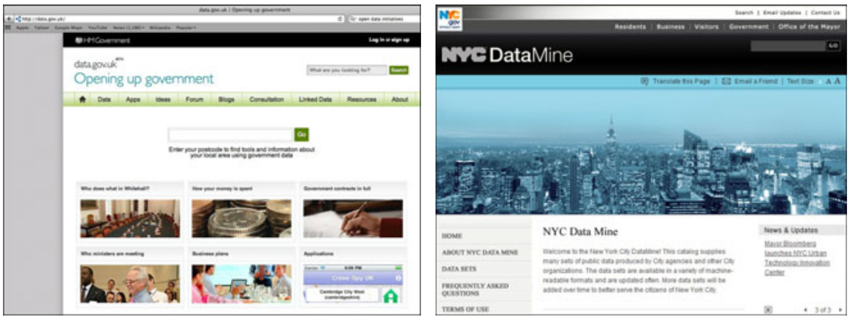
Algorithms are being developed for constructing multimodal trips associated with this data that will require various assumptions about movement between modes due to the fact that it is only on rail that the card is used for swiping in and out, thus giving origins and destinations. The map on the left in 4(a) shows flows between various hubs while that on the right in 4(b) is a series of rank size plots of the total traffic volumes of all nodes in the network at every 20 minute interval over the 24 hour day. Already as part of such projects multimodal trip advisors are being created.

2.4.3 New urban data systems: Open data

A number of national governments have developed initiatives in opening up public data to a wide audience of interested publics and professionals. So far, following the lead of the US, many other countries such as the UK and many city governments have taken up the challenge and are making public data available in many different formats. This is also part of the transparency agenda in contemporary government, which is founded on accountability but it also relates to questions of confidentiality and privacy. The EU is also heavily involved in these issues with respect to PSI directives (`http://ec.europa.eu/information_society/`). The portal for the UK is shown below left in Fig. 5(a) and the New York City equivalent right in Fig. 5(b). In terms of smart cities, we envisage that many such portals will emerge in the next decade.

2.4.4 New models of movement and location: MATSim and simulacra

The range of interactions between the different agents in the transport and land use system requires agent-based approaches to capture their impacts: travellers, network operators, transport service providers (taxi, car pooling, car sharing, bus, trains, etc.) information system providers, activity providers (retailers, bar operators, restaurant chains, cinema owners, etc.), developers and property owners, policy makers in competing jurisdictions and others. Open-source agent-based micro-simulation such as



(a) (b)

Fig. 5. Portals for open data: (a) the UK and (b) New York city.

(a) (b)

Fig. 6. Land use transport models: an ABM for Tel-Aviv at different scales (a) and an aggregative model for the London metropolitan region (b).

MATSim has an excellent track record for computational speed and the size of the problems it can address. It will be the basis for a richer version of the model which will enable the inclusion of these different agent classes in both equilibrium and non-equilibrium (path oriented) versions. We show a typical application for Tel Aviv (in Fig. 6(a) where the model is being used to simulate traffic at different spatial scales where interaction with activities at these scales is modelled. (See `www.matsim.org` for software download, tutorials, papers and result animations). Simulation using aggregative models of a more traditional kind are illustrated in Fig. 6(b) for the London region. *FuturICT* will also improve the speed and quality of these models in terms of computational infrastructure being developed and of course the range of issues that such modelling systems are able to address.

2.4.5 Risk analysis of development paths

Brute force risk assessment of a system as complex as a metropolitan area is beyond the current computing abilities of even the highest speed clusters: the number and types of agents are too large and the time to enable such computation too long. The aim has to be to develop intelligent systems to (a) capture the range and correlation structure of the many driving factors of urban development and (b) search mechanisms which are able to identify the range and form of the joint distribution of the central outcomes in terms of quality of life, urban success, resilience and robustness. And of course extreme events such as terrorist attacks, natural disasters, criminality and so on.

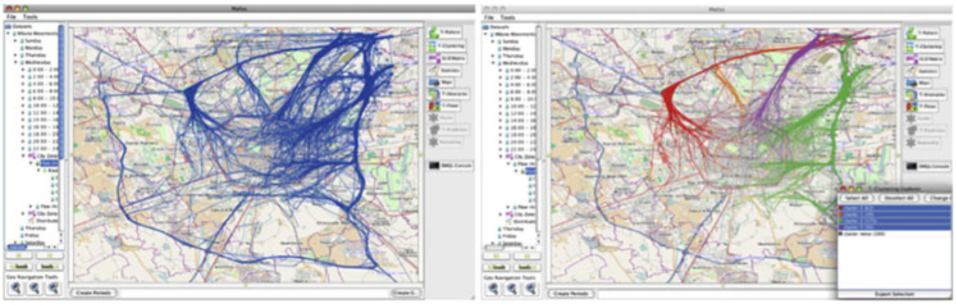


Fig. 7. GPS tracks in metro Milan (a) city centre to the North East and (b) clusters of like trajectories.

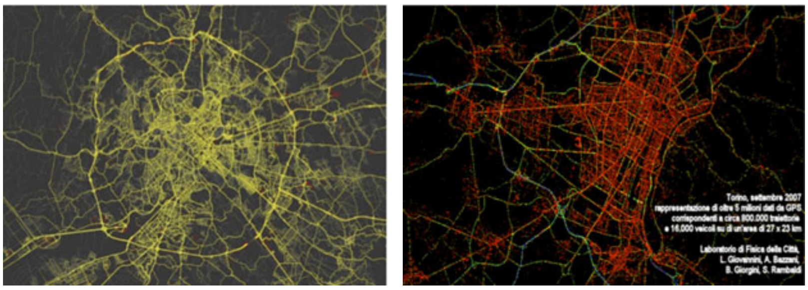
2.4.6 New models and systems for mobility behaviour discovery: M-Atlas

The M-Atlas system was conceived as a framework to master the complexity of the mobility knowledge discovery process. M-Atlas is an integrated querying and mining system, centred onto the concept of a trajectory, i.e., a sequence of time-stamped locations, sampled from the itinerary of a moving object. Trajectories pertaining to human travel or movement can be reconstructed from data sensed in various contexts, including GPS tracks from vehicular or hand-held navigation devices, call detail records from mobile phone (GSM) carriers and providers, time-stamped location records from online services or social networks, such as Flickr, Foursquare, Google Latitude, and so on. M-Atlas supports the complex knowledge discovery process from raw data of individual trajectories up to high-level collective mobility knowledge, by means of methods for:

- Trajectory reconstruction from the raw location data
- Trajectory database management and querying
- Trajectory mining: pattern extraction, clustering and prediction/classification
- Trajectory visual analytics and model presentation/exploration.

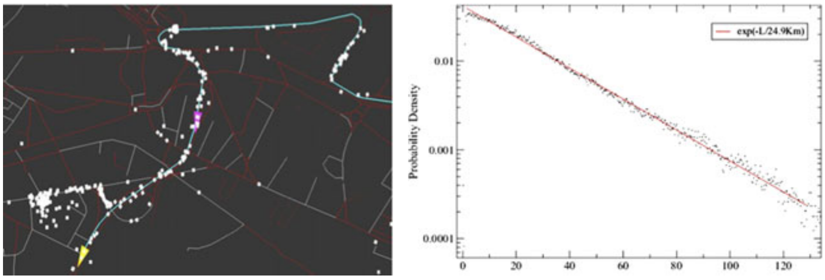
As an example, Figs. 7(a) and (b) above show a possible analysis performed on dataset of GPS tracks from approximately 20,000 private cars sensed over a period of one week in the metropolitan area of Milan, Italy. In the example, the trajectory clustering method reveals typical profiles of commuting behaviour from two selected areas in the city. In the left-hand Fig. 7(a), the M-Atlas visual interface shows the data selected as input for the clustering algorithm, namely the trajectories from the city centre to the North-East suburbs. Figure 7(b) to the right shows the clusters obtained, where the trajectories in the same cluster are visualized by M-Atlas with the same colour. Once the most popular commuting profiles and routes have been identified, the analyst can zoom on the different clusters, studying, e.g., the hourly distribution of travels, etc.

Example projects that are being pursued by various stakeholders using M-Atlas as enabling technology include the characterisation of tourist profiles in Paris, France, on the basis of GSM roaming call detail records, the simulation of a participatory car pooling and car sharing service in Tuscany, and the preparation (based on integrated GPS, GSM, sensors, participatory mobility data) of a detailed mobility atlas for the urban area of coastal Tuscany, as a tool of policy definition for the public administrations at urban and regional scale. We will begin with this M-Atlas as a map of the smart city and then extend it to other kinds of Atlas that relate to the integrated databases that we will progress.



(a) (b)

Fig. 8. (a) GPS volumes in Rome and (b) velocities (red to blue) in Turin.



(a) (b)

Fig. 9. Trajectory reconstruction (a) and statistical behaviour mobility (b).

2.4.7 New tools for the governance of mobility demand

GPS technologies allow us to record individual mobility data across an entire urban network. In Italy, a sample of 3 percent of the whole vehicle population is monitored for insurance purposes, providing information on single trajectories with a spatial scale of 2 km and a time scale 30 seconds [9]. Moreover, one datum is always recorded when the vehicle engine starts or stops. Each datum includes position, speed, motion direction, GPS quality. In Fig. 8, we show the data georeferencing for whole metropolitan area of Rome (40000 vehicles) along the entire month of May 2010 in Fig. 8(a) and the metropolitan area of Turin (16000 vehicles) during the month of September 2007 in Fig. 8(b). The colour scale (from red to blue) gives information on the travelling velocity thus illustrating the structure of the network.

Despite the relatively poor spatial resolution of such GPS data, it is possible to perform a real time reconstruction of the individual trajectory dynamics on the road network. This result is achieved by applying specific algorithms that select the paths consistent with experimental observations, the individual habits of travellers and different road usage. In the Fig. 9(a) we show an example of trajectory reconstruction where we also plot the historical data to point out the relevance of habit behaviours of individuals. Moreover the data analysis suggests the existence of general individual behaviours related to the use of urban space-time. In Fig. 9(b) we show the spatial distribution of the daily individual mobility derived from GPS private car data: the straight line in a logarithmic scale implies an exponential decay with the length that reminds us of the statistical Boltzmanns distribution. The results shed lights on the average traffic properties in a city, but future microscopic data will allow us to study the evolution of transient states from a microscopic (individual) point of view [10].

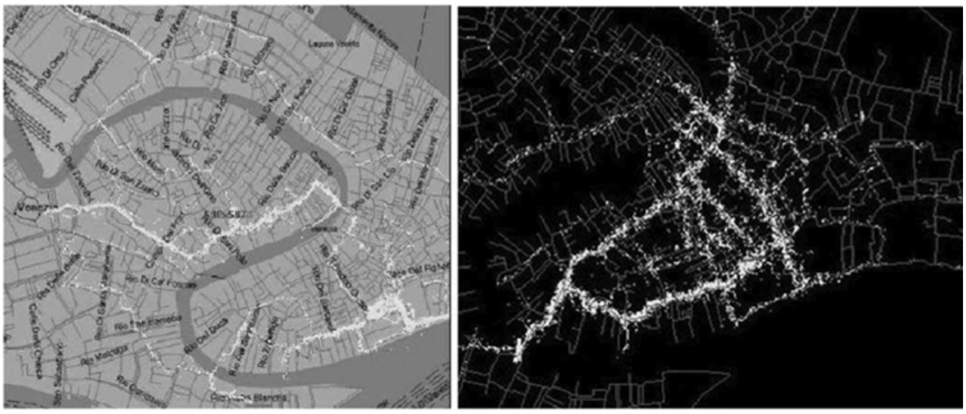


Fig. 10. (left) and (right) Reconstruction of movement dynamics of pedestrian movements at different scales in the Venice carnival 2007.

This also opens new research opportunities that use microscopic mobility data as a paradigm to study the human decision mechanisms and the information based interactions. These macroscopic laws will be the starting point of a new generation of microscopic models based on individual mobility demand, and will enable us to perform a real-time reconstruction of the traffic state across the whole urban network (nowcasting), to integrate the private mobility with the public mobility realizing low-energy sustainable transportation policies, and to predict future scenarios simulating emerging crisis events. This activity enters in a road-map toward a safe-city within the *FuturICT* project. Our aim is to generate an entire research dimension with respect to the role of failsafe mechanisms which pertain to crises that are generated by problems of mobility.

Moreover in order to understand human mobility behaviour, one takes in account the cognitive issues which originate the intentional dynamics of travellers. ICT technologies allow us to investigate the crowd dynamics using a microscopic approach. For example, Figs. 10 (a) and (b) shows pedestrian flow reconstruction via GPS measures at the Venice Carnival 2007.

Using this input data base, we can model and simulate the pedestrian mobility on the network and furthermore crowding in key places and nearby critical bottlenecks. Figure 11(a) shows a snapshot of a pedestrian flows simulation nearby Punta della Dogana (left) and of similar flows in 3D form as a snapshot of the crowding mobility in San Marco square Fig. 11(b). Extreme events will be certainly more and more frequent in the big future cities and their impact on citizenry safety and security is a key problem.

These data base types and modelling functions are fundamental in an ICT framework to project and to build up e-governance tools, and to connect individual information with the cooperative participation for fluid, safe and low-energy mobility.

2.5 Scenarios for the smart city

As we have noted there are many smart city initiatives as the term has become extremely popular for initiatives associated with the development of ICT and competition, with cities, particularly large cities, at the forefront of these proposals. We need to position ourselves on this spectrum of opportunities because there are several

(a) (b)

Fig. 11. Pedestrian movement dynamics in 2D (a) and 3D (b).

elements of the smart city movement that we will strongly relate to but others that will be more peripheral. We can identify at least seven types of initiative:

The development of new cities badging themselves as smart. These are proliferating in rapidly growing countries. Masdar outside of Abu Dhabi is being developed by GE as the worlds first carbon neutral city, Paredes in Portugal is where Microsoft are wiring an energy efficient city, Dongtan in the Yangtze Delta is being developed by Arup as a smart green eco-town, and Songdo in South Korea is where Cisco are building a town wired at all levels.

The development of older cities regenerating themselves as smart. In much more bottom-up fashion, which include many cities who are embedding new ICT as a matter of course. Examples of best practice are to be found in world cities where spontaneous developments of new technologies are emerging in places such as Silicon Alley (New York City), Silicon Roundabout (London) and Akihabara (Tokyo).

The development of science parks, tech cities, and technopoles focused on high technologies. Silicon Valley and Route 128 are the classic examples but the science park idea is still highly resonant with respect to local economic development where high tech production merges with its consumption in making such areas smart.

The development of urban services using contemporary ICT. In the form of networked data base, cloud computing and fixed and mobile networks, a force which is more central to our concerns here in coordinating diverse interests and sectors which will make the city smart in its design and planning.

The use of ICT to develop new urban intelligence functions. These are new conceptions of the way the city functions and utilise the complexity sciences in fashioning powerful new forms of simulation model and optimisation methods that generate city structures and forms that improve efficiency, equity and the quality of life.

The development of online and mobile forms of participation. In which the citizenry is massively engaged in working towards improving the city alongside planners and designers from government and business. Decentralised notions of governance and community action are central to these new forms of participations which use extensive ICT.

3 Our innovative approach

3.1 The essential tensions

The crucible for technological innovation is the cultural context in which it takes place. Technology is a social construction as much as it is a material or ethereal one, and its application is intrinsically social. There is an increasing consensus that cities represent the crucible for technological innovations and that larger cities with a highly educated workforce represent the best places where progress can be made with their invention and application. Globalisation complicates this picture but one of the reasons why so many companies and governments are embracing the idea of the smart city is that there is now a widespread view that to remain competitive and be ahead of the game, cities must mobilize ICT to become ever smarter in the pursuit of their competitive advantage. Alfred Marshall said it over 100 years ago but agglomeration economies, which come with cities growing ever bigger in terms of their populations and knowledge base lie at the core of the smart city. ICT holds the key to a better world and it will be most clearly demonstrated in large cities.

There are a number of innovations that our work on the smart city will establish. First and foremost, *FuturICT* is a programme that is founded on the application of complexity theory to human problems and as such, it is immediately apparent that the very subject of its focus in this project human systems are in and of themselves becoming ever more complex. This in turn is because of the invention of new modes of human functioning using ICT. This project is firmly at the forefront of understanding complex social systems using the very tools that are fashioning those social systems in the first place. As we noted earlier, McLuhans [32] notion that the tools that we shape then shape us is key. The science itself changes the very science that we are using. Cities, which adopt ICT in diverse forms, change the very nature of the adoption process by using that same ICT. The nexus is complex and we ignore this interwoven complexity at our peril. The problems that we deal with characterize all cities and are what many years ago [39] called wicked. When one tackled wicked problems, they became worse not better due to the unforeseen consequence and unanticipated effects which were ignored because the systems in question were treated in too immediate and simplistic terms. The great innovation of our program in smart cities as an exemplar of *FuturICT* is that we approach these issues in full knowledge of these dilemmas. We are particularly energised by concerns for privacy and confidentiality and the risks involved in the generation of new routinised individual based data that is emerging from all these initiatives.

3.2 The key themes

It might also seem at first sight that a programme related to smart cities would be strongly focused on hardware and networks but our focus will be much more on questions of organisation that imply software development and management of large scale computer resources, networks and data. As we have been at pains to point out throughout this paper, our focus is on integration of data, models, and users through ICT. This collective set of issues in ICT we might refer to as orgware, an old term dating back to the 1980s but one which symbolizes the constellation of issues that surround the use and development of new varieties of computation.

Developing and coupling databases which in turn are being forged using new kinds of media for collecting data through sensing, mining online transactions, and the automated recording of behaviour in the environment and communication, is one of the key foci in our project [46]. These kinds of coupling and the organisation that is developed will be part of new governance structures for the smart city new intelligence functions that utilize much wider participation in decision-making as well as real time construction and use of a variety of simulations and optimisations relevant to decision support. The research focus that we outline below pulls all these themes together in distinct projects, that inevitably will overlap with one another and with other projects in other domains of *FuturICT*.

One of our major themes will be the development of new forms of simulation model that embrace the new forms of complexity being developed in smart cities. An innovative aspect of our project is the development of a new class of simulation models for various activities in cities that will evolve as the city structures themselves evolve and become smarter. In other words, the models will simulate the city dynamics as self-organizing evolution processes, that mimic the Darwinian biological evolution in a balance between innovation and selection mechanisms. An example will suffice. Fifty years ago, cities were conceived in a manner that had barely changed for a thousand years: as a core dominated by the workplace and the movement of individuals to work and exchange goods (shop and receive services) in the car. This model was predicated on the basis that the city is a stable unchanging structure. Since then ICT and globalisation has dramatically shifted this model. Physically cities may not look very different from the material flows that inspired this past conception but in terms of their social networks and economic transactions, the old model simply cannot address current conceptions of a networked society. The world is now one that is as much dominated by flows of information that do not leave physical traces in the manner of the old. Our challenge is to build models that grapple with these changes and that have the potential to embrace very different conceptions of how the city might function. The rudiments of these types of models are already there in structures such as MATSim and Simulacra, in many of the agent-based models built for sectors of the city, and in new approaches to transportation modelling [35]. We intend to exploit these conceptions strongly within *FuturICT*.

Just as this then changes our conception of the way we might build models that respond to a changing and evolving system, our last theme relates to how the process of planning and decision might change to embrace the ability to sense the city in real time. Spatial scales and time scales are being collapsed by the emergence of real time data from the bottom up. Data sets are being created that show immediately the functioning of the real time city but also imply how long term changes in the city can be detected. In short, if all the data that we collected were in real time, at any instant, we could aggregate the data to deal with change in the city at any scale and over any time period. This prospect is a long way off and will never be reached (for once we reach it we will find more and different data that need to be collected) but what it does promise is an ability to have a real time view of change at different spatial scales and over different time scales. This will change both the models that we are able to build and the way in which these technologies can inform the planning and decision process with simulations and decision support being telescoped across space and time. This is crucial to the kind of citizen science that we will develop to provide a powerful participatory context to the future development of the smart city.

3.3 Our proposed projects

As we have noted, we cannot tackle all dimensions of ICT and the smart city and in fact, we will work with business interests such as IBM and Cisco to relate what they are doing to our wider quest. Therefore we will organize our research directions into seven distinct but overlapping areas that we show in aggregate form by the block diagram that is reproduced in Fig. 12 below. We define these areas as follows.

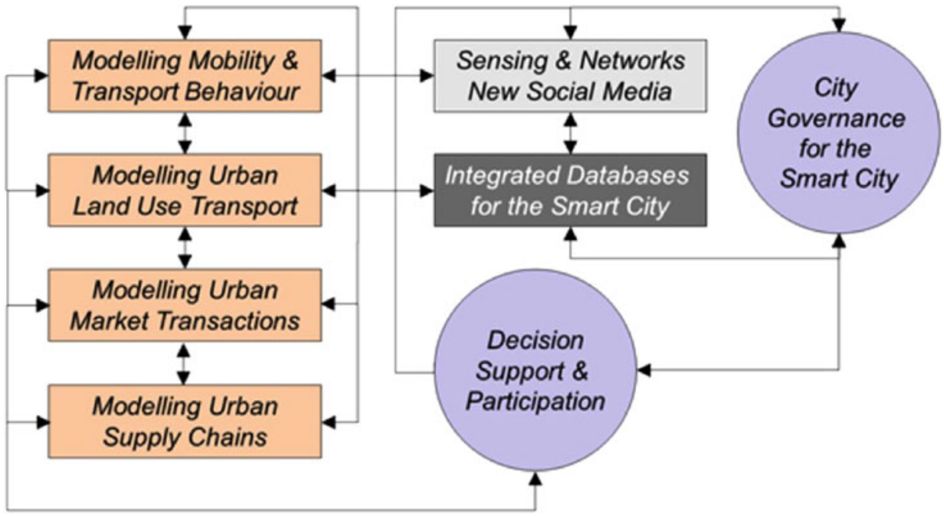


Fig. 12. The structure of *FuturICT*s smart cities programme.

3.3.1 Integrated databases for the smart city

We will select a series of databases that are being developed for different sectors of the city all of which rely on digital sources captured but not necessarily available in real time. We will consider how these data-bases can be enriched by adding data from more conventional sources such as recurrent cross-sectional censuses. We will explore error in such data, focus on standards of integration and provide an array of data mining and pattern recognition techniques, many based on machine learning to extract useful data for assessing the way the city is working. We will also enable these data bases to provide more aggregate possibilities useful for longer term decision support and we will focus on how new more unconventional and experimental sources of data through social media might also enrich these data sets. For example we envisage that we might link conventional online traffic data to utilities data such as water and electricity lines monitoring and location, and to social network data from STM (Synchronous Transport Module) network sources [17]. To this we will fuse population census data and consider how electronic data on land prices and residential transactions might be linked. There is nothing equivalent to this kind of integration available anywhere although there are attempts beginning in the GIS community.

In terms of transportation data, then we will collate available data streams from different European countries and this will require their translation into a common terminology and where necessary adjustments to make them comparable. The necessary contracts with their providers will have to be negotiated to make their collection smooth and reliable (APIs instead of web-bots). Examples are traffic counts, flight movements, container movements, shipping rates, TCP/IP traffic, tourism flows, mobile phone use, FAA 10 percent ticket sample, commercial air ticket data base, EUROSTAT statistics, National Population Census data, health warnings and so on which will constitute a particular focus of our database integration for Smart Cities. We will also derive key leading indicators using the best techniques to summarize the various data streams, while accounting for both their temporal and spatial nature. The publication of the key indicators and of our forecasts for them will be at least quarterly and we will extend this notion to other city data sets that we are intent on coupling together. The comprehensiveness of the indicators and the underlying data streams will be continuously improved.

3.3.2 Sensing, networking and the impact of new social media

We do not consider that we will develop our own sensors for we are more concerned about mining available data and adding value to its interpretation. Data from the usual social media sites have already been explored in great depth but largely in terms of its immediacy. We see the smart cities dimension of this task as involving how we might interpret the content of such media to very specific issues pertaining to the way cities work and the way citizens interact with their planning. In *FuturICT* there is a strong focus on networks and in this area, we will exploit and link to other network science initiatives and begin to explore how new online real time data sets can be mined so that various network and flows can be extracted from this data and used to provide a deeper understanding of how communities, markets, government and businesses relate to one another. We see this area as extracting social and economic data on which we have little information and understanding so far. Community detection in a liquid world is one obvious outcome from such research.

In terms of starting to extract social networks from travel data, two data streams are missing to understand the dynamics of transport movements: on the one hand, we are lacking the observations and the understanding of the social network geography of the Europeans and how their movements and their resources, and infectious diseases are channelled through them; on the other hand, there is no easy point-of-access to costs of long-distance travel, as all operators use price discrimination to maintain their margins. We will redress these issues in the programme. For example, first, we propose to establish a set of social network surveys in 10–12 European countries/regions, which cover the range of the current economic development and history of migration. In this initial survey the samples of 750 persons will be drawn in selected regions (NUTS 2-level) to be economical in the face-to-face survey administration. The expectation is that further research groups will join the initial effort over the years. The project will make some support for these teams available (data archiving; staff support; data analysis). Second, the long distance travel market (air, rail, ferries, gasoline prices) is characterised by strong price discrimination and the time of booking, season, service levels/class and origin/destination pair. We will set up an automated web-based observatory which will sample the prices systematically across the continent for European and Intercontinental journeys for a range of booking conditions (time to departure, class, length of stay) employing a number of servers simulating different customers by location. The dataset is enriched with suitable data on booking levels, school holidays, legal holidays, tourism flows, etc. The data set will be archived continuously and made available in regular intervals as a counterpart to the official 10 percent FAA ticket sample available for the US airline market.

3.3.3 Modelling network performance, mobility and transport behaviour

We will explore a broad range of theoretical developments to better understand traffic and transportation network performance, from the development of new theories to explain traffic breakdown, car following, and traffic kinetics, to the development of new route choice mechanisms, cooperative game behaviour under network uncertainty, and dynamic models for travel activity generation.

- large scale integrated travel behaviour and logistics simulation models with open-time horizons and explicit learning mechanisms at the agent-levels as tools for policy analysis
- simplified representations of the travel demand and logistics systems for integrated models across the infrastructure systems (energy, communications, water, long-haul-logistics)

- improved network and schedule design optimisation for resilient operation
- fast network design optimisation for basic built infrastructures (roads, railways, canals, pipelines)
- data fusion and data aggregation processes to allow continuous system performance
- new performance metrics for different users that combine efficiency reliability and equity.

We will also build the tools for crisis preparation in personal transport. The possible crises are manifold: e.g. a volcano eruption disrupting air travel across Europe; major population movements after a major chemical accident; shutdown of the railway services during a developing epidemic. The authorities and firms need models describing the current situation and its underlying interactions and dependencies reliably with theoretically sound models. These tools will be the basis for detailed models of disease spreading.

3.3.4 Modelling urban land use and transport

Several groups in *FuturICT* are working with land use transportation models of different kinds ranging from conventional social physics-urban economic style models to cellular automata models of urban development and agent-based models of spatial behaviour which extend to new directions in transportation modelling. We plan to use and extend the agent-based micro-simulation MATSim which provides a basis for extensive model implementation that links travel behaviour, land use, mobility issues and social networks. We want to extend it towards a multi-day timeframe to match the choices of long-distance travel. We have to speed up the already fast model implementation to enable a simulation of the 108 agents in a network of 107 to 108 links/services and 107 destinations in reasonable time. We will draw on the tools available for the GNU-public license framework at `www.matsim.org`.

To support the tool we will model the impacts of the social network geographies of Europeans: based on the new data collected, the project will model the interactions between the frequencies of contacts across all modes and the political, economic and transport performance across Europe and where appropriate the world. We will also extend these models to build tools for crisis preparation in logistics: The market for logistics services is more complex than the market for passenger transport due to lengths of the supply chains and the larger number of decision takers and actors involved. Based on on-going work to expand MATSim with the suitable data structures and models, we need to increase the computational speed to match the new scale of the implementation. We will implement the tools for Europe so that related projects in the *FuturICT* and elsewhere can explore scenarios of interest to them. We will consolidate the necessary data, choice models, generate the agent population, establish the networks, calibration and validation data for the first implementation and then the necessary biannual updates and five-years major updates. The contacts with the users and their experiences and results will be integrated on an on-going basis: the living model will continuously adapt and learn.

Other classes of more aggregate land use transportation models (such as the Simulacra suite of models (`www.simulacra.blogs.casa.ucl.ac.uk`) will be extended and linked to more disaggregate physical models. These simulate aggregate dynamics of development and we envisage that models of this kind can be linked to models of the MATSim variety. This style of model will be used to demonstrate how new planning and decision support systems can be fashioned for planning the smart city, and our focus will be on developing a wide portfolio of modelling tools that users and participants of various kinds can use in their dialogues.

3.3.5 Modelling urban transactional activities in labour, housing and transportation markets

We plan a new focus on modelling the market transactions that determine the way land, property and labour is developed, purchased, allocated and rewarded in the urban environment. We know little or nothing about how urban systems respond to macro-financial crisis (which will be explored elsewhere in *FuturICT*), and the booms and busts that plague national and international economies certainly play out at the city level. Indeed it might be argued that the origins of these crises in one sense lie at the heart of how cities function, or dysfunction. We will develop a series of housing market models built using agent-based technologies, synthesising various databases which relate to financial transactions in these markets, ways in which these markets clear and/or jam, how access to more global capital dictates the spatial behaviours of these markets, and how potential purchases and developers are affected by access to resources. And we will progress the design of smart cities with different kinds of transportation systems that both optimise efficiency and equity in mobility and access to opportunities.

In similar ways, we will explore how local labour markets behave with respect to the supply of businesses, the role of government, environmental quality, and the extent to which such labour relates to innovation. Migration is a key component linking housing to labour markets, and we will examine the impact of aging, the role of statutory instruments and regulations, and the role of capital provision from financial services in determining how such markets work. We envisage that the models that we will build will be closely linked to the transport and urban land use models that are being developed elsewhere but in the spirit of understanding that requires multiple models being used in parallel to explore complex systems such as cities, we envisage a fair degree of parallel and also counter modelling.

3.3.6 Decision support as urban intelligence: Real time modelling and participation in policy making

Templates and structures for decision support systems that involve the wide portfolio of models and tools that this project will focus on planning smart cities for the future, are in their infancy. Most attempts at building intelligence functions for city governments have in the past been top down and have been concerned with professional usage. We are suggesting that cities are so complex, that this kind of intelligence function is only one of many that needs to be coordinated in planning the city. Our work on integrating data bases and models will support the development of integrated intelligence but new ways of visualising data and urban problems, new ways of using tools which inform and predict the impacts of future scenarios, and new ways in which citizens might provide useful and focused advice all need to be refashioned into integrated systems that operate continuously and robustly. We will develop these environments for several different but related types of planning problem, at different scales and over different time scales, resolving issues of modelling that are multi-scale and multi-temporal following rudimentary ideas of integrated modelling of which there are a number of simple applications so far.

3.3.7 City governance structures for the smart city

What is required not only for cities but for government and governance at every level are new frameworks that take account of the extensive access to information that contemporary citizenship now makes possible. This is much wider than our project here and it clearly relates to issues of participation in the sixth project (3.3.6) above. This and the previous project are syntheses as Fig. 12 above shows pulling together much of the modelling capabilities that we intend which in turn are built on the integrated data systems that we foresee will be developed. Standards for data and model development, appropriate interfaces, security of who is able or not to access the material online, questions of confidentiality, IPR, privacy and so on will all feature under this area of the project. Just as the city is changing due to ICT and so are our models of its functioning, these kinds of institutions must also embody a degree of flexibility that is quite different from existing organisations that are tasked to deal with the future of our cities. In this, ICT will be central but so will issues of responsibility, openness, transparency, access to public data and the regulations that extra national government agencies may impose on what and how and where and why citizens are able to influence the governance of their cities.

3.4 Demonstrators

To date, we have not detailed exactly how we might demonstrate our research but it will be highly applied, developed and focused on real, live applications to cities that are manifestly planning to be smart and those that are becoming smart in a less self conscious manner. We intend to select a series of places and sectors that we consider typical of these types: for example, new planned smart cities, large cities that are clearly becoming smart such as our own London, Turin, Paris, Rome, Zurich and Tel-Aviv, for example, cities that have particular problems of economic decline whose future might be assured by explicit development of a smart city ethos, cities that have specific ethnic problems and high rates of migration, aging cities and so on. Our portfolio of tools for decision support will be developed on the basis of these demonstrators and we will ensure that these are linked to key initiatives on the smart city being developed by the worlds major ICT companies.

4 Expected paradigm shifts

Thomas Kuhn [29] who introduced the term paradigm in 1962, defined them as universally recognized scientific achievements that, for a time, provide model problems and solutions for a community of researchers, in short, a world view that dominates science for a period of time during which that world view is extended. A paradigm shift occurs when this world view becomes eroded, when anomalies and inconsistencies mount up to such an extent that researchers can no longer work within the framework. The history of science has shown that the turbulence that sets in can lead to a paradigm shift that takes place over a very short period of time, years or decades rather than centuries. The development of modern computation could be seen as generating such a shift but in one sense, this is more because the very systems that we are focused on here have also been evolving just as our knowledge of how to understand them is evolving. This sea change we have alluded to previously is thus more than a paradigm shift for it may represent a once-for-all transition from a world based in energy and materials to one based on information. Nevertheless, it is quite clear from what we are suggesting that many of our traditional approaches to cities are no longer relevant, the planning systems that we currently work with are not fit-for-purpose, and thus the shifts that we will initiate here are paradigm changes of a kind that are unprecedented. In the more modest context of smart cities, we will present some of these here.

The first major shift which is the most obvious is the development of information infrastructure that underpins the city through distributed computing and networks available to everyone with devices that can access such infrastructure, Whether or not they can access this ICT depends on questions of governance and security but the fact that such infrastructure is now available, requires coordination so that services can be delivered most effectively. As an obvious spin-off from such service delivery, the data that is routinely collected is now being used to make cities smarter over different spatial and temporal scales. This is an unprecedented time for in the past, such data has not been available routinely and the fact that it can now be, yields opportunities for solving human problems that we have never had before. At the same time, cities will never be entirely automated and in this transition period, and maybe forever, we need to grapple with existing non-automated, non-digital technologies and enable these to merge and co-exist in an integrated fashion with the digital.

We are also realising that for the first time that we stand at a threshold in devising a new science of human behaviour and in our own domain, this will be a science of spatial behaviour. Routine data sensed in real time is yielding big data that will require new tools for their usage and analysis, and new methods of data mining that are applicable to individual observations are required. This will move the field of data analysis and statistical method forward in great leaps, if we can fashion new ways of dealing with millions of observations. Our traditional statistics aim to extract macroscopic average information using modest population numbers in the thousands, not the millions or the billions even, and these no longer work very well in this new world. We need new statistical methods to handle these data that are also able to recover generic information on the microscopic dynamics (usually not known for social systems) in a top-down approach. Visualisation is all important in this context and visualisation in the spatial domain leads the way. In developing new models of human behaviours, we need a focus on questions of location and mobility and in this sense the role of social media and web access is crucial [44].

These developments also impress upon us a new view of the spectrum from the local to the global, from bottom up to top down. Complexity theory stresses the evolution and development of systems from the bottom up but it is clear that systems reflect a mix of interventions across all scales notwithstanding these are all predicated by individual actions. In terms of localism, in cities this new science is finding its way down to the urban design, neighbourhood and building scales merging with models of how buildings function. It is here that behaviour hits physicality and in this domain of smart cities, we have opportunities to see how behaviour is conditioned by physical issues just as these same physical issues can be moulded by human behaviour. This is a paradigm shift in that it has not been possible to explore these issues hitherto.

5 The proposed research strategy

5.1 Relevant disciplines and fields

We have outlined seven key areas on which our research will be focused in Sect. 3.3 above and here we will set this in context with respect to the strategy we will adopt. Cities represent a focus for many different disciplines. Indeed in the human and social sciences, everything we study takes place in cities but our focus here is on cities as spatial systems, with our concern being directed at their spatial and physical organisation. Most of our proposals in understanding the smart city and how to make it smarter revolve around spatial issues and although we are conscious that non-spatial and a-spatial issues are relevant, these issues represent the boundary between what we will research and those of other groups within *FuturICT*.

The complexity sciences represent our focus in *FuturICT* but these sciences are linked to many different disciplines and professional fields that have the city as their concern. In particular, urban planning and transport planning are distinct areas that are central to this research while computer science is key to the development of large databases, networks, data mining and human computer interaction. Cities can only be studied in an interdisciplinary context and our perspective involves developing a social physics of cities that is consistent with treating their structure and evolution as complex systems [6,36]. In this sense, our quest involves ideas drawn from the mathematical physical and natural sciences but set within a social context that blends the qualitative with the quantitative.

5.2 Key references and patents

We intend to work with several companies who are building the smart city with respect to its hardware and software infrastructure. It is unlikely that we will develop hardware in any form but there are several areas where we might plan innovative software and database solutions to problems that involve coupling databases together and mining them in real time to extract patterns used to steer and control the way the city functions. These deliverables will be subject to IPR and we consider that some of these products might be patentable. However, much of the software we develop will be in the public domain, available under Creative Commons licenses which city governments and any agency or group acting in a non-profit context will be able to access in a transparent fashion. It is unlikely that we would be in a position to support such developments but arrangements with our partners, such as the developers of MATSim and such like software would be negotiated so that these kinds of software would be widely supported. Some of these systems are already open access.

5.3 Demonstrator outcomes

We provide a number of demonstrators as we indicated above in Sect. 3.4. These will be focused on a) specific problems types, b) specific model types and c) specific cities. In particular we envisage producing demonstrators which will present how the following problems can be articulated:

- Housing booms and busts in large cities, linked to financial crises
- Impacts of changes in energy on urban transportation systems and mobility
- The fracturing of transport networks due to short term problems related to urban conflict, weather and one-off events
- The efficiencies produced by synthesising different urban data sets
- The impact of climate change on cities in Europe, particularly sea level rise and rising temperatures on population location
- The participation of citizens in the development of plans for smart cities of the future focussing on mobility, housing, better design and aesthetics (the city beautiful) and access to opportunities
- The impact of immigration phenomena in a global world.

These are just a sample of possible issues that our science can be used to inform. We will match these against different styles of model and different city contexts developing some of these to the point where individual cities will be able to translate our applications to real contexts, particularly as we envisage that many of the these applications will be developed *in situ*.

5.4 Ethical issues

Because our projects deal with developing new data systems from the ground up, systems that involve sensing individual behaviours and merging these with secondary data sets constructed at an equivalent level, there are major privacy concerns. As we merge different data sets from different sources to produce integrated and coupled systems, there are clear issues of copyright and IPR which will have to be addressed. Much of our work on integrated databases will tackle these issues.

In terms of our focus on involving a large array of groups and citizens in planning the smart city of the future, we will need to take account of what information is accessible to whom and this becomes crucial when such information is available at a fine spatial scale where individuals can be identified. We will draw on an extensive knowledge base about how confidentiality can be assured in the construction of such data systems and their use and access. We will engage with the open data agenda being pursued by national and city government and NGOs and ensure that our research is entirely consistent with these developments.

6 Expected impacts

We will list these as a series of bullet points, which to an extent have been elaborated already in the previous presentation. These apply to all three sections on science, technology and society.

6.1 Impacts on science

We will tackle the essential conundrums of social evolution through the lens of the city. This will involve developing strategies and methodologies that deal with evolving systems that are becoming more complex due to technological innovation and increasing prosperity while at the same time, analysing these issues and anticipating them using the same technologies that are increasing that complexity. This also means the development of a statistical mechanics of cognitive systems.

We will progress the science and art of urban simulation which we believe is strongly rooted in robust theory of how the city functions in space and time as an economic entity and social artefact. This will involve embedding our models in new theories of the contemporary city which are grounded in the new economic geography, urban economics, agent-based conceptions of social and economic systems and new approaches to mobility and communications.

We will develop new methods of integrating spatial and related databases and continue to progress developments in data mining of very large data sets of the orders of terabytes. These will require new developments in neural nets, machine learning and evolutionary computation.

6.2 Impacts on technology and competitiveness

We will generate new ideas about enabling cities to realise their potential by getting smarter. Smart cities are incubators for ever smarter ideas and we will demonstrate this model on several exemplar cities with whom we will develop our science *in situ*.

Smart cities are competitive cities and we will identify ways in which cities that stand on a spectrum of the smartness scale can respond to new initiatives and increase their competitive advantage. We believe that smart cities and systems of smart cities need to embody this sense of competition in an interactive evolutionary context so that no city falls too far behind or progresses too far ahead.

We will develop new web-based interactive contexts that will enable a wider range of citizen activist and groups in the understanding and design of the city and community in which they have an interest and stake.

6.3 Impacts on society

Smart cities are equitable cities. We will develop infrastructures that are accessible to a wider range of interests and groups with differing levels of expertise and activism so that all are involved. Our focus on efficiency balanced against equity is central to this vision.

The web based interactive systems which we consider to be basic to the kind of citizen science that we assume should be normal in the smart city will enable fairness to be progressed and balanced against competition.

We believe that many of the methods that we will develop will be based on notions about how groups compete and cooperate and we consider that the sort of infrastructure, expertise and data that will characterise the smart city will enable equity to be easily established and such cities to improve the quality of urban life.

A more detailed research plan will follow but as yet our quest is simply to define the context, state the key problems and imply some sense of what solutions in terms of our research might focus on. We consider that this paper represents a basis for further discussion to argue the point that new technologies have both disruptive and synergetic effects, particularly on forms of social organisation that are required for future forms of governance and community action as well as business. A sense of what this research promises is available from the many contributions arrayed on the *FuturICT* web site: (`http://www.futurict.eu/`).

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