Digital City:
How to Transform a City into an Urban Ecosystem

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Abstract

As complexity of our political, social and economic environment increases, cities begin to experience new pressures, which makes the transformation from a conventional city into a Digital Urban Ecosystem, or a Digital City for short, urgent. The paper provides a definition of Digital City and analyses problems experienced by urban conurbations caused by complexity of the Internet-based global economy. It outlines fundamentals of intelligent digital technology for converting a city into an adaptive, resilient and sustainable Digital City. The author advocates an evolutionary Digital Transformation methodology that ensures a minimum of disruptions to city services. The concurrent design of intelligent real-time schedulers for services and Digital City ontology, described in this paper, enables the transformation to be carried out by several design teams, each, if necessary, at a different geographical location.

Keywords: Smart City, Digital City, Complex Adaptive Systems, Urban Ecosystems, Selforganization, Coevolution.

Digital City

Digital City is a city, which is *adaptive, resilient* and *sustainable* and which offers to its citizens and visitors a high-quality pollution-free living, working and leisure.

For the purposes of our research, Digital City and Smart City are synonyms, two ways of describing the same concept. We prefer now to use “digital” instead of “smart” to distinguish our approach from those who use the term “smart” indiscriminately, just to look progressive and jump on the bandwagon.

The key point of using the term “digital” is that any man-made entity (administration, business, or city) to become adaptive, resilient and sustainable, must undergo Digital Transformation.

Natural and Digital Ecosystems

Natural ecosystems (forests, rivers, oceans, grasslands) are naturally adaptive to changes in their environments, resilient to catastrophic events, such as earthquakes or tsunamis, and sustainable for periods lasting, in some cases, millions of years.

We have developed now digital technology capable of transforming man-made systems into adaptive, resilient and sustainable “digital ecosystems”. This represents a major breakthrough in improving how we live and work.

Adaptability

Adaptive city means a city capable of (a) instantly detecting an internal or external disruptive event, (b) rapidly identifying which part of the city will be affected and (c) quickly rescheduling affected resources to eliminate or at least reduce, consequences of the disruption.

A good example is adaptive ambulance service – if a call is cancelled after an ambulance has already left the hospital to answer that call, an adaptive service would be capable of rapidly rescheduling ambulance and divert it to answer a different call.

Resilience

Resilient city means a city capable of (a) instantly detecting an electronic attack or fraud, (b) rapidly identifying which part of the city will be affected and (c) quickly rescheduling affected resources to eliminate or at least reduce, consequences of the identified attack or fraud.

Sustainability

Sustainable city means a city capable of coevolving with its environment (natural, political, social or economic).

For example, the increase in pollution from diesel vehicles, signalled by pollution sensors, is identified by the transportation service management system as critical and the system initiates the increases in taxes on the use of diesel vehicles in the city, which in turn accelerates the replacement of diesels by electric cars. The adaptive planning system rapidly picks up the trend and initiates installation of additional electric car charging points.

Why Digital City

The essence of the current problem with cities is that complexity of their political, social and economic environment has increased exponentially whilst their administration and technological infrastructure has remained rigid and therefore unable to operate effectively under new volatile, dynamic conditions (condition of complexity). As a consequence, citizens are frustrated, there is increase in health hazards from pollution, precious resources are wasted, and the natural environment is damaged.

Key problems that must be addressed are:

1. Wasteful and environment damaging services for citizens and visitors

2. Inadequate communication channels between citizens, visitors and city administration, which prevent citizens and visitors to convey their real requirements and expectations
3. Inadequate performance monitoring and lack of knowledge on how to effectively manage a city under conditions of complexity
4. Outdated strategic planning

Let's explore these problems further.

Consider an urban settlement such as a town, a city, a megacity or a city state. Typically, it provides a large variety of services, which may include education, healthcare, social services, roads and transport, food supply, water supply, drainage, waste disposal, rubbish collection, economic development, planning, protecting the public (from crime, fire, elements, etc.), libraries, environmental health, tourism, leisure and amenities, planning permissions, housing services, collection of council tax, local elections.

Every one of these services can be improved by using environment-friendly resources and by scheduling of these resources in real time.

Even greater improvements may be made by coordinating the delivery of services using advanced digital technology, making sure that services compete for available resources and share them when necessary. At present, every vital service is managed individually, and the coordination of services is almost non-existent. It is done, if at all, intermittently through a set of meetings.

Whilst this may have been quite adequate in the past, when city authorities worked under stable operating conditions, it is currently unacceptable. There is a considerable waste of resources, significant damage to the natural environment and increased health hazard from pollution, primarily due to the recent exponential increase in complexity of political, social and economic environment of the city, which increases the frequency of unpredictable disruptive events, such as, changes in policy (due to political instability), changes in demands for services (due to influx of immigrants, diversity of needs, excessive tourism), failures of overstretched resources and delays (caused by accidents, traffic jams, unexpected shopping sprees, festivities, tourist seasons, epidemics, terrorist attacks, etc.).

In addition, there is an increase in the awareness of citizens of environmental issues as well as of health hazards resulting in frustration and, frequently, in demonstrations and demands for improvements.

Important contributing factors are a rigid, departmentalised structure of the administration, preventing the effective coordination of services and the use of conventional Information Technology (IT) unable to cope with the new dynamics.

Our research identified that very few cities, if any, provide effective communication channels for the *interaction* of citizens and visitors with city authorities. As a result, city councils are rarely well informed about requirements and expectations of those for whom cities exist and tend to rule rather than facilitate.

It seems, no city administration knows how to effectively organise living, working and leisure of its citizens and visitors under conditions of unpredictable changes in their political, social and economic environment. It is an imperative to spread the knowledge of *managing complexity* as wide as possible.

Technology for Digital City

The basic premise of Complexity Science is that only complex adaptive systems can operate effectively within a complex environment. Rigid structures of deterministic systems tend to crumble when placed under conditions of complexity – the phenomenon which can be currently observed in many decaying urban complexes around the world. In contrast, complex structures easily adapt to changes, are resilient to attacks and coevolve with their environments, which makes them sustainable.

We have developed technology for transforming a conventional city into a Complex Adaptive Urban System, which we shall call here Urban Ecosystem.

Adaptability, resilience and sustainability can be designed into a Digital City by using intelligent real-time schedulers to allocate service resources to demands. We shall call services scheduled by intelligent real-time schedulers Digital Services

Intelligent real-time schedulers are capable of cooperating (or competing) with each other, ensuring that Digital Services are interacting with a view to maximising the agreed values of the Digital City.

The architecture of a Digital Service is depicted in Fig. 1 below. The service consists of

1. Real World of human and physical resources and demands that delivers the service to citizens and visitors
2. Digital World of digital Agents engaged in real-time scheduling of Real-World resources
3. Knowledgebase containing knowledge how to run the service
4. Interfaces between the two worlds, primarily concerned with the transmission of
    a. information about disruptive events from the Real to Digital World and
    b. instruction how to reschedule human and physical resources, from Digital to Real Word

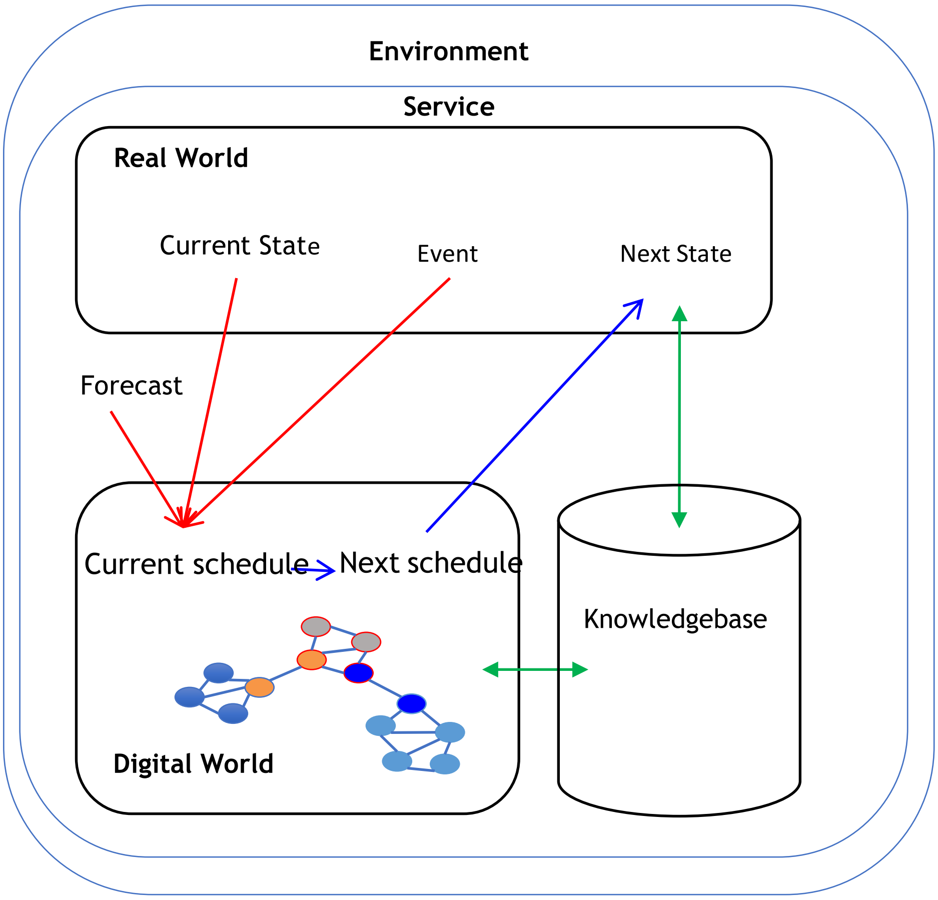

Fig. 1. Architecture of a Digital City service scheduled by an intelligent real-time scheduler

The process of transformation of a City into a Digital City could be done with a minimum of disruptions by following a methodology outlined below.

Transformation of a City into a Digital City

Let us consider a typical urban settlement governed by the council and managed by the town administration responsible for services to citizens. And let's assume that the Council has decided to substantially improve each service to citizens and at the same time reduce the costs of service provision.

Requirements Specification

The conventional wisdom is to approach the problem top-down by attempting to perform requirements specification for the whole city before starting the work on transformation.

Such approach would be unacceptable under current dynamics of the political, social, economic and technological urban environment. Requirements would be obsolete before completion.

In contrast, an evolutionary transformation method would enable a seamless transformation.

Evolutionary Digital Transformation Method

Under conditions of frequently changing requirements, it is advisable to adopt an evolutionary method, as follows:

1. Consider all services with a view to identifying the one whose improvement will bring the highest value to the city
2. Complete a requirements specification for the improvement of the selected service
3. Design and implement an adaptive real-time scheduler for the selected service only
4. Evaluate and update the solution demonstrating the achieved increase in the city value
5. Select the next service and repeat steps 2,3,4, ensuring that the newly added service cooperates, and if necessary, competes for resources with the previously improved services
6. As the number of improved services increases, continuously monitor and, if necessary, adjust the overall Digital City design

In theory, the evolutionary improvement of services should never stop. In practice, contractual arrangements between clients and urban ecosystem designers cannot be indefinite and will have to be limited to the improvement of one or more services at a time.

A wise client would ensure that they have priority access to a skilled team for continuously maintaining and improving the new urban ecosystem. And that would represent an extension of the urban ecosystem with additional self-maintenance and self-improvement services.

Concurrent Transformation Mode

In addition to approaching the transformation in an evolutionary manner, the work on (1) requirements specifications, (2) the design, and (3) the commissioning of improved services should be done *concurrently*, timing the work in such a way that

- Whenever the design of the improvement of a service is completed, the requirements specification for the improvement of the next service is ready for design
- Whenever the commissioning of the improved service is completed, the design for the improvement of the next service is ready for commissioning

The concurrent design is especially convenient if the design is conducted by cooperating teams located at several different geographical locations.

Illustrative Example

Let's assume that the critical service selected for the improvement is the ambulance service.

Designing Ontology

The transformation begins with outlining ontology for the ambulance service, which involves:

- Selecting Object Classes (Ambulance Vehicle, Ambulance Crew, Crew Member, Ambulance Equipment, Route, Road, Hospital, Patient, Relative)
- Identifying Relations (Crew belongs to Vehicle, Equipment belongs to Crew, Vehicle follows Route)
- Defining Properties of Object Classes (for Crew Member: id, qualifications, availability)

It is prudent at this stage to write scripts for agents, which should be also stored in ontology and ready for agents to pick them up when given a task to perform.

All policies, rules and regulations guiding the delivery of services should be also stored in ontology.

In addition to ontology, the knowledge base also contains all data on Object Instances, which are normally stored in client databases.

Designing Digital World

Digital World is a place where agents negotiate among themselves how to allocate resources to demands. The process is rapid and, in principle, not repeatable. The conditions, under which negotiations between agents are conducted, often change during the negotiations. In this respect, Digital World is like Heraclitus' river.

To design the Digital World means to design the whole digital infrastructure that supports the exchange of meaningful messages among, potentially, hundreds of thousands of agents. The choice of coding technology is vital and recent advances in Python and Microservices brought considerable gains in the transformation speed.

In the Ambulance Service Virtual World, the matching of crew members to crews, crews to ambulance vehicles, ambulance vehicles to hospitals, roads to routs, patients to hospitals, etc. is done by exchange of messages between relevant agents.

To achieve adaptability, the matching of demands to resources is done by agent communication rather than by computation. If, for example, a road to selected hospital is blocked by excessive traffic, Road Agent of the blocked road will immediately let affected Agents know of a problem and trigger a wave of renegotiations between affected Agents to determine a new route to the hospital. If a new route is too long, agents may try to negotiate a switch to a different hospital.

The key advantage of this type of rescheduling is that parts of the Ambulance Service Ecosystem not affected by the road closure, continue functioning as though no disruption occurred.

What is described here is just a minute part of the design process, hopefully sufficient to demonstrate how our new technology offers a considerable advantage over conventional batch-mode optimizers. Many more design details may be found in [1].

Designing Interfaces between Real and Digital Worlds

Information on disruptive events occurring in the Real World must be transmitted to the Digital World and all scheduling decisions, made by agents in the Digital World, have to be conveyed to the Real World.

Initially, the exchange of information is likely to be implemented by messaging between digital Agents and human operators (e.g., drivers), using their smart phones or specially designed handheld communication devices. However, the preferred method is to exchange information directly between digital Agents and physical resources of the Real World (e.g., vehicles, robots, conveyors), using The Internet of Things technology.

Extending the Initial Design

Scheduling of ambulance vehicles is easily extended to cover, for example, the scheduling of hospital staff and facilities that are required by patients brought in by ambulance vehicles. We just need an additional swarm of agents to do this job. And then, of course, we can add more swarms of agents to schedule other hospital resources such as operating theatres, etc. The design should advance step by step, each step proven in practice before the next one is commissioned.

Conclusion

The transformation from a conventional to a digital city is urgent because of the huge gap between the increased complexity of the political, social and economic environment of modern cities and old rigid administration and technological infrastructure unable to operate effectively under the condition of complexity.

In our paper we have proved that it requires re-thinking of the key elements and the general concept of the Smart City. Based on this we have provided an updated definition of the Smart City as complex adaptive smart system because only complex adaptive systems can operate effectively within a complex environment.

We have proposed and described an evolutionary transformation methodology that ensures a minimum of disruptions to city services, enables a seamless transformation and can be carried out by several teams in parallel. The developed methodology is now being implemented by the authors in the project aimed to develop Smart City - the digital ecosystem of services that allows to achieve synergic effects between various subsystems (transportation, ecology, energetics, urban design).

Complex Adaptive Systems

A system, or a situation, is said to be ***complex*** if it is *open* (exchanges information with its environment), consists of many *diverse*, partially *autonomous* and richly *connected* components, called ***Agents***, and if it has *no central control*. Behaviour of complex systems is uncertain without being random. The global behaviour *emerges* from the interaction of constituent agents. The autonomy of agents is limited by constraints imposed on them by the system to which they belong.

The word “complex” derives meaning from the word ***plex*** (interwoven or interconnected) and should not be confused with words like “complicated” (as a jet engine), “cumbersome” (as bureaucracy), “unwieldy” (as an aged empire), “chaotic” (as a disorderly administration) or “difficult to understand” (as a verbose document).

Since the key feature of a complex system is that it is ***Adaptive,*** it is customary to call complex systems ***Complex Adaptive Systems***. Complexity is discussed in detail in [39].

Using ***Uncertainty*** as a criterion, we can divide all systems into 3 classes:

- ***Deterministic***, whose behaviour is predictable (uncertainty = 0). Examples include man-made systems such as cars, aircraft, bridges and clocks, as well as closed models of physical system such as pendulums and planetary movement.
- ***Complex***, whose behaviour emerges from the interaction of agents, it is not predictable in detail and yet follows discernible patterns (1 > uncertainty > 0). Examples include natural ecology, social, political and economic systems, businesses and markets.
- ***Random***, whose behaviour is completely unpredictable (uncertainty = 1). A good example is movement of molecules.

RANDOM	COMPLEX	DETERMINISTIC
Uncertainty = 1	1 > uncertainty > 0	Uncertainty = 0
Full autonomy of agents	Partial autonomy of agents	Agents have no autonomy
Disorganised	Selforganising	Organised
Unpredictable behaviour	Emergent behaviour	Predictable behaviour

Table 2. Classification of systems

The key features than differentiate complex systems from deterministic are as follows: (1) Connectivity, (2) Autonomy, (3) Emergence, (4) Nonlinearity, (5) Nonequilibrium, (6) Selforganisation, and (7) Coevolution.

Connectivity of an agent denotes the number of other agents to which the agent is connected. Complexity of a system increases with connectivity. The highest known connectivity is associated with neurons in the human brain, which is of the order of 1,000. Connection strength is also an important in assessing the level of complexity. Complexity is higher when connections between agents are weaker and can be easily disconnected and new ones established. The right side of the human brain has weaker connections between neurons than the left side, which explains why it is responsible for creativity – the ability to discard old and create new, more effective patterns of behaviour.

Autonomy of agents denotes the degree of freedom of agent behaviour. Complexity of a system increases with autonomy of agents. For example, old-fashioned large families with strict rules of behaviour and hierarchical structure are less complex than modern arrangements where individuals are subjected to few constraints. Nevertheless, in complex systems agents always have restricted freedom of behaviour. In the extreme, when agents are given full autonomy, the system behaviour becomes random.

Emergence - Complex systems have properties that cannot be found in constituent agents. They emerge from the interaction of agents. For example, human intelligence and creativity are emergent properties of the brain, they emerge from the interaction of neurons.

Nonlinearity - Links among agents are nonlinear and include amplification, self-acceleration and auto-catalytic property. As a result, small, insignificant disturbances my cause extreme events, phenomenon known as ***Butterfly Effect***. More importantly, the accumulation of small disturbances over time may cause a ***Drift into Failure***.

Nonequilibrium - The operation of complex systems is typically affected by frequent disruptive events. If complexity level is high, disruptive events occur with high frequency and the system has no time to return into equilibrium before the next disruption.

Selforganisation - When disrupted by a disruptive event (arrival of an unexpected demand, failure, delay, fraud, electronic attack or similar), the system rapidly identifies affected parts and reschedules constituent resources to eliminate, or at least, reduce the effect of the disruption before the next disruptive event occurs. Selforganisation is an extremely useful property of complex system, making them ***Adaptive*** to changes in their environment and ***Resilient*** to attacks/fraud. Selforganisation may also lead to ***Self-improvement***, when agents, by trial-and-error selforganise to improve system performance.

Coevolution - Complex systems coevolve with their environment, they are affected by changes in the environment and, in turn, affect the environment.

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