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Towards High Impact Smart Cities: a Universal Architecture Based on Connected Intelligence Spaces

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Abstract

Smart cities constitute a new urban paradigm and a hegemonic phenomenon in contemporary city development. The concept envisages a data-enhanced future and efficiency gains made possible by automation and innovation in city activities and utilities. However, the way smart cities are created brings about two weaknesses. First, there is strong compartmentation of solutions and systems, which are developing in vertical markets for energy, transport, governance, safety, etc., silos with little interoperability and sharing of resources. Second, there is a low impact, some increase in efficiency, some reduction in costs, time gained, some decrease in CO_2 emissions. There is an important knowledge gap about developing cross-sector, high-impact smart city systems. This paper deals with these challenges and investigates a different direction in smart city design and efficiency. We focus on 'Connected Intelligence Spaces' created in smart city ecosystems, which (a) have physical, social, and digital dimensions; (b) work as systems of innovation enabling synergies between human, machine, and collective intelligence; and (c) improve efficiency and performance by innovating rather than optimizing city routines. The research hypothesis we assess is about a universal architecture of high impact smart city projects, due to underlying connected intelligence spaces and cyber-physical-social systems of innovation. We assess this hypothesis with empirical evidence from case studies related to smart city projects dealing with safety (Vision-Zero), transportation (MaaS), and energy (positive energy districts). We highlight the main elements of operation and how high efficiency is achieved across these verticals. We identify commonalities, common innovation functions, and associations between functions, allowing us to define a common architecture enabling innovation and high performance across smart city ecosystems.

Keywords Intelligent cities · Smart cities · Connected intelligence · Innovation systems · Innovation routines · Digital platforms · Performance

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Introduction: Problem Definition and Knowledge Gaps

Problem Definition

The twenty-first century is an era of connectivity enabled by the Internet, of sharing resources over collaborative platforms, of collecting data and using artificial intelligence to reveal insights hidden in data, and of automating almost everything. Using connectivity, digital platforms, and data, smart cities have emerged as a way to address more effectively complex contemporary challenges of growth, sustainability, and governance and provide more intelligent systems for decision-making and innovation (Komninos & Kakderi, 2019). Smart cities are formed at the intersection of digital technologies, disruptive innovation, and urban environments (Deloitte, 2015) and constitute a rising urban paradigm, “a hegemonic phenomenon in the contemporary metropolis” (Rodrigues & Costa, 2020). The concept envisages a data-enhanced city future and efficiency gains made possible by automation of services and utilities (Batty, 2018).

Streitz (2017) outlined the landscape of smart city spaces resulting from connectivity: the Internet of Everything (IoE), a term coined by Cisco for people, processes, data, and things connected into an overall network that uses machine-to-machine communication (M2M), machine-to-people (M2P), and people-to-people (P2P) interactions; hubs connecting many urban objects, in the form of public spaces, streets, parking lots, marketplaces, shopping malls; commuting spaces working as ‘transient spaces’; smart cities and ecosystems; self-aware cities that know themselves and communicate this knowledge to citizens; hybrid cities that combine real and virtual worlds through augmented reality solutions which generate overlays and multiple representations of the environment; and cooperative cities supported by computer-enabled cooperative work.

The development of these spaces, which drive the formation of smart cities, take place per city ecosystem (or vertical market), and advance by sector-focused projects and e-services, data collection, and analytics (Appio et al., 2019; Faber et al., 2018; Zygiaris, 2013). This segmented development is attributed to the diversity of city ecosystems, market complexity, the features of each ecosystem, and other specificities and has been addressed as a public sector ‘complexity paradox’, the more complex policy issues are, the more compartmentalized policy-making becomes (Mazzucato, 2019).

However, this development path brings about two weaknesses. First, there is *strong compartmentation* of digital solutions and smart systems across vertical markets for energy, transport, waste management, water management, governance, safety in the public space, and others. An estimation of the smart city market in 2020 by Frost and Sullivan (2019) reveals a total market value of 1.5 trillion, segmented into smart governance and education (20.93%), smart energy (16.65%), smart security (14.11%), smart water and waste management (13.75%), smart transportation (9.09%), smart healthcare (15.26%), and smart building (10.21%). These systems are developed in silos with low interoperability and solutions rollout between them. Most solutions available on the market do not share infrastructure between them, nor generated data, even though they could benefit from such exchanges (Weber & Zarko, 2019). Vertical markets prevail. Compartmentation is an obstacle to smart city replication as different solutions have to be designed for every ecosystem of a city, which increases costs, effort, management, and maintenance complexity. It hampers synergies, but also the scaling up of solutions and economies of scale through adoption across city ecosystems.

Second, there is *low effectiveness of smart city solutions,* which leads to small or marginal increases in performance and feeds disappointment and mistrust about the efficiency and added value of smart city systems. For instance, the most ambitious target in Amsterdam Smart City was to reduce CO_2 emissions by 40% from the 1990 baseline by 2015 (Amsterdam Smart City, n.a.). The City of Ghent implemented a multimodal traffic management system based on Variable-Message-Sign for travel information, traffic light management, and parking guidance, which increased the speed of public transport by 5%, and the park and ride by 10%. In Aalborg, the implementation of an adaptive traffic signal control system led to an 8.5% decrease in travel time. But in Bologna, the combination of Intelligent Transport Systems with traffic regulations led to a much greater reduction of absolute traffic by 23–32%, and a much higher reduction of particle emissions by 47% (Egeler & Dell, 2013). In the field of sustainable development, widespread concern has been expressed on the inefficiency of the global response to urban sustainability challenges, which is not yet sufficiently transformative. The general vision is that grand challenges should be addressed more quickly, and smart city developments are evidently not contributing enough (United Nations, 2019). Referring to smart city impact, R. Bell wrote recently "Sorry Smart Cities – You Completely Missed the Point: We get a 5% increase in efficiency, a 10% reduction in costs, a 30% drop in time wasted looking for a parking spot. Wow. We do also sometimes save lives thanks to more efficient policing, firefighting and emergency response. So, aside from saving those lives, what difference have smart cities made to their citizens?"(Bell, 2020).

Aim of the Paper, Contribution, and Limitations

These two weaknesses can be disastrous for the smart city as a holistic model of urban development and planning. They are due to bad design of smart environments, lack of cross-sector platforms, low integration between the physical, institutional, and digital dimensions of smart cities. It is a fact that in many cases smart city projects are reduced to digitalization, creation of e-services, and digital infrastructures poorly connected to the institutional and physical environment of cities. In such cases, the 'city' dimension is lost, together with the novelties and externalities it brings. These weaknesses indicate also the need for more flexible smart systems and more complex architectures connecting the urban, innovation, and digital components of smart cities.

Behind the 'silos' and 'effectiveness' weaknesses are deeper knowledge gaps about more universal and high-impact smart city systems and spaces. We still know very little:

- How to create generic solutions and architectures of smart environments that overcome compartmentation and silos and can be used across city ecosystems, e.g., variations of the same smart system to be used in transport, energy and waste, and other utilities.
- How to integrate different forms of intelligence that are present in smart cities, such as human intelligence based on the skills of the city's population, collective intelligence and rule-based decision-making in communities and institutions, and machine intelligence embedded in the digital space of cities.
- How do city activities change when performed in smart environments where innovation prevails on optimization and how the performance of activities in smart city spaces and ecosystems scales up.

In this context, the paper aims to investigate a different path for smart city design and development, based on lessons learned from high impact smart city projects and ecosystems. Cities, and large cities, in particular, comprise hundreds of business, business, and living ecosystems, each of which is composed of different actors, activities, functions, and infrastructures. The digital transformation of cities is structured by ecosystems (Abella et al., 2015; Komninos & Tsarchopoulos, 2013; Vermesan & Friess, 2013). It evolves per city ecosystem (known also as vertical market) defined by activities, areas, and infrastructure networks. This granularity is a source of effectiveness, as solutions come nearer to the challenges and features of each ecosystem. Nevertheless, it is also a source of complexity as demands high efforts in designing and coordinating strategies and digital solutions specific for each ecosystem. It is neither functional nor effective to deploy 'one hundred intelligent spaces' for 'one hundred city ecosystems' that usually compose a city. Developing a common ontology and a prototype smart ecosystem to be used across city domains and verticals would allow overcoming the fragmentation of smart city solutions and create a digital platform to be used across different city ecosystems. This can greatly simplify the design of smart systems suitable for different city ecosystems and vertical city markets, offer advantages of interoperability, efficiency, cost, and complexity reduction, as well as management simplification.

Given this aim, the paper presents our research as follows. We first outline the theoretical framework to address the problem stated, including a short reference to pillars of related literature, the research hypothesis we will assess, and the theoretical framework relevant to hypothesis verification. After that, we provide empirical evidence from case studies on high impact smart city projects dealing with safety, transportation, and energy. We highlight their main elements of operation and how high efficiency is achieved across smart city verticals. In the discussion, we reflect on the lessons learned from the case studies, describe what is verified for the hypothesis assessed, and identify commonalities, innovation functions, and associations between functions, allowing to define a common architecture for innovation and performance scale-up across smart city ecosystems.

Finally, in the conclusions, we return to our main argument that high efficient smart city ecosystems replace rather than optimize existing city routines by deploying Connected Intelligence Spaces. However, this initial verification of the hypothesis assessed is based on the few cases we have examined. It needs further investigation with a larger sample of smart city projects and ecosystems. We conclude the paper by highlighting three directions for further research.

Literature and Theoretical Background

Two Strands of Related Literature

A rich literature has been developed around the design, development, and impact of smart cities. It contains, among others, two strands that are very relevant to the problems stated on smart city diversity and efficiency. Related to efficiency and impact is the literature on innovation-led urban and regional development and territorial systems of innovation. Related to the diversity of smart cities and smart city solutions relevant is the literature on the digital transformation of cities, IoT urban infrastructures, digital services for cities, and data-based governance of cities. There are bridges between these two theoretical strands that allow understanding of how smart cities evolve and work as localized cyber-physical-social systems of innovation.

Innovation is the key concept in understanding efficiency and performance scale-up. In the 1980s, the Schumpeter's legacy and both the 'Mark I' model of innovation based on creativity, and the 'Mark II' model of innovation as a process in the R&D department of large companies, were challenged (Cantwell, 1989). Griliches (1979, 1984) developed an input-output model linking patented innovations (output) with new technological knowledge generated by R&D in industries and universities (input). Jaffe (1986, 1989) showed that the innovative performance of firms depends not only on their own R&D investments, but it is also strongly affected by the R&D spending of other firms and universities. The evolutionary metaphor proposed by Nelson and Winters (1982) introduced a more robust relationship between intra-company *organizational routines* and the modification of routines by an external *selection environment.* Consequently, systemic thinking of innovation was formed emphasizing *National Innovation Systems*, which connected innovation with networks and interactions among companies, universities, and government (Edquist & Lundvall, 1993; Freeman, 1987; Metcalfe, 1995; Nelson & Rosenberg, 1993; Patel & Pavitt, 1994). The triple helix and later the quadruple helix models (Carayannis & Campbell, 2010) stand on these interactions. In the 1990s the systemic approach on innovation and the 'Learning Region' paradigm (Cooke & Morgan, 1999; Landabaso et al., 1999; Simme, 2004) were adopted by the European Commission (Landabaso, 1997). Regional Innovation Strategies were introduced, a prequel of the current research and innovation strategies for smart specialization (RIS3). In this theoretical strand, innovation is shaped by a multi-governance system of regional, national and EU policies and institutions. More recently, the literature on evolutionary economic geography points out at the context of cognitive conditions, and diversification and generation of new economic activities are described as a path-dependent process based on knowledge and technological proximities (Boschma & Frenken, 2011; Xiao et al., 2018).

In early 2000, the spread of ICTs, the Internet and the world-wide-web, the creation of online networks, virtual communities, e-services and digital spaces, enriched innovation supply chains and systems (Jaruzelski et al., 2013; Yoo et al., 2010). With the spread of digital networks and various smart environments, innovation systems evolved and currently have physical, institutional, and digital dimensions. Key innovation processes such as R&D, innovation funding, technology dissemination, technology learning, new product development, marketing, and promotion are strongly shaped by digital networks, virtual environments, and e-services. Moreover, hundreds of e-services enriched the landscape of service innovation, creating a new domain of digital innovation.

In parallel, the smart city literature revealed a new dimension in the knowledge and innovation-led development of cities. Mora et al. (2017) highlighted various facets of the process towards the digital transformation of cities and city smartness; numerous publications discussed the digital components and architectures of smart cities and the origins of spatial intelligence (Deakin, 2011; Ishida & Isbister, 2000; Komninos & Panori, 2019; Mitchell, 2007); the relation between smart cities, business processes and innovation (Belissent, 2010; Caragliu & Del Bo, 2019; Zygiaris, 2017); the working of smart cities as innovation ecosystems (Gil-Garcia et al., 2016; Komninos, 2008; Schaffers et al., 2011; Zygiaris, 2013); the development of smart Quintuple Helix Innovation Systems (Carayannis & Campbell, 2019; Leydesdorff & Deakin, 2011). The digital transformation of cities brought new forms of connectivity, e-services, data analytics, which pushed forward the creation of knowledge and innovation.

Intelligent territories, smart ecosystems, smart cities, and regions are born out of the convergence between urban systems, innovation systems, and digital systems. Smart places (cities, districts, neighborhoods, ecosystems) depend on the way digitalization evolves and systems of innovation are enhanced, becoming more open, global, participatory, and agile. In smart cities, cyber-physical systems of innovation are created, the innovation nodes acquire digital companions, collaboration is deployed over digital spaces, actors can use complex methods guided by software, and get insights from data and analytics (Panori et al., 2020). The convergence of innovation and digital systems in cities and regions brought also new actors, users, and citizens and new forms of innovation, such as user-driven innovation, innovation crowdsourcing, open innovation, innovation driven by demand, free innovation (Von Hippel, 2006, 2016).

Research Hypothesis

Among the variety of spaces created in smart cities, which Streitz (2017) vigorously described, some spaces stand out due to their effectiveness and can shed light on the above-mentioned weaknesses and knowledge gaps. An example is the space created by '*Vision-Zero*' projects to eliminate all traffic fatalities and severe injuries in cities. It is a physical, institutional, and digital space characterized by data collection, fatalities analytics, reporting and witnessing by users, education and learning safe driving, intersection re-design for visibility and safety, law enforcement, digital services and automated alert, and other real-time services. Another is the space created in '*Positive Energy Districts*', a cyber-physical-social space that combines smart technologies, building technologies, and spatial, regulatory, financial, legal, social, and economic interventions towards annual net-zero energy import and net-zero CO_2 emissions. These spaces differ radically from usual smart city use cases, such as 'Connected Public Transport', 'Traffic Monitoring and Management', 'Water Level and Flood Monitoring', 'Connected Streetlights', which optimize (minimize or maximize) existing routines through automation of city infrastructures (IoT Analytics, 2020). On the contrary, in spaces created by Vision-Zero or Positive Energy Districts, a change of rules and routines that command city activities takes place. Existing routines are replaced by more efficient ones, and we observe innovation and change of routines than optimization of existing routines.

'Vision Zero' projects and 'Positive Energy Districts' create spaces (or ecosystems) of connected intelligence that introduce innovations to behaviors and the decision-making by interactions between human, collective, and machine intelligence. Connected Intelligence Spaces (CIS) are localized cyber-physical-social spaces; they cultivate networks between humans, smart systems, institutions and communities; and enhance learning, optimization and innovation (Komninos, 2020). CISs have three main characteristics: (a) physical, social, and digital dimensions; (b) work as systems of innovation enabling synergies between human, machine, and collective intelligence; and (c) improve efficiency and performance by replacing rather than optimizing city routines. CISs created by effective smart city projects can be found in various smart city ecosystems, city districts, digitally assisted clusters, poles and groups of activities, and in other smart city spaces.

The research hypothesis we propose to assess is about the universal structure (a common set of components and organization across city ecosystems) of Connected Intelligence Spaces, due to their operation as cyber-physical-social systems of innovation. We assume that we can identify common processes and innovation functions in CISs, regardless the city ecosystem they belong. These common innovation functions allow defining a universal CIS architecture working as a cyber-physical-social system of innovation. Specific features of CISs to be assessed include (a) the ecosystem or community base of CISs and (b) the digital or cyber-physical platform as the connector of human, collective, and machine intelligence in the ecosystems created (Komninos, 2018, 2020).

This hypothesis addresses both the compartmentation and low effectiveness of smart city systems. The verification would enable to transform the smart city's silos and vertical markets in a more homogeneous landscape based on universal CISs; develop a generic CIS ontology based on common innovation functions to be used in any smart city ecosystem; and document that behavioral changes in CISs can lead to more efficient routines and higher performance. But these are further steps of research. In the first place, we have to investigate commonalities across smart city ecosystems created by high effective smart city projects.

The significance of this hypothesis is at leveling the smart city landscape. If verified, any smart city system could be designed as Connected Intelligence Space modifying routines, sustaining innovation, and performance scale-up. A verification would pave the way towards next-generation smart cities based on innovation rather than automation of activities, entailing higher efficiency and performance. This quest has been raised at the start of the smart city movement with the seminal paper of Hollands (2008) "Will the real smart city please stand up? Intelligent, progressive or entrepreneurial?". Instead of optimizing existing routines, as happens mostly in smart cities, a new route would open toward innovation and modification of urban routines by more efficient ones.

There are smart city projects that suggest this is feasible, such as the *Vision Zero* to eliminate all traffic fatalities and severe injuries, while increasing safe, healthy, equitable mobility for all; the *City-zen Virtual Power Plant* in Amsterdam Smart City, experimenting with renewable energy solutions, heating and cooling networks, energy planning, thermal renovation of housing, smart grids, energy sharing; *Energy Cells GR*, the RegioStars Award 2019 in the category of Digital Transformation; and smart city projects related to *Sharing Platforms* and the growth of sharing culture and economy in cities. These projects open an alternative path to the algorithmic logic for automation and optimization that guide smart city solutions, which is not enough for delivering the full potential of current advances in science and technology for cities (Komninos et al., 2019b). They show that efficiency in smart city systems relies on complex environments (physical, social, and digital) in which systems integration empowers users and human communities.

Theoretical Framework of Reference

From the theoretical journey we summary referred to in the related literature, we would point out three concepts that are particularly relevant to the theoretical framework that guides this research.

First, innovation is about the *modification of routines* that command activities of production, consumption, and exchange. Routines are bottom-level sets of rules inside the firm, the public organization, or the household, and rules for doing things in production, R&D, marketing, management; routines are also behavioral patterns at the consumption side and the use of urban space and infrastructures. Routines can be also understood as skills higher to the sum of individual skills of an organization (Boschma & Frenken, 2006; Nelson & Winters, 1982). At the territorial level, routines include usage and consumption behaviors related to buildings, urban infrastructure, mobility, recreation, and other urban activities.

Second, *routines evolve along with an external environment* or institutional system that selects the fittest routines and guides the replacement of existing by new more efficient ones. Currently, this environment for innovation and routine modification is cyber-physical-social, integrating human, physical, institutional, and digital elements, platform-enabled (Jacobides et al., 2018), deploying global networks and Internet services. Smart and intelligent cities are such cyber-physical-social environments for innovation and behavior change, enabling digitalization, optimization, and innovation (Komninos, 2006; Malone et al., 2009; Picon, 2015; Tansley & Tolle, 2009; Weinstock & Gharleghi, 2013).

Third, innovation is documented by the combined outcome of *routines modification and performance scale-up* (Greve, 2008; López-Nicolás & Meroño-Cerdán, 2011) and the positive relationship between innovation and increase of performance (Salim & Sulaiman, 2011). While innovation, as routine modification, is mainly qualitative, performance metrics provide the needed quantitative dimension to innovation. But the innovation–performance relationship is also context-specific, dependent on the cognitive and cultural environment in which it takes place (Rosenbusch et al., 2011; Zollo et al., 2002).

Focusing on the modification of routines, we can explore the bridges between urban systems, innovation systems, and digital systems. Activities performed in smart/intelligent cities are subject to digitalization, optimization, and innovation. These three scales of digital transformation are defined at the interface between digital systems and innovation systems:

- Digitization: characterizes activities performed in digital space (e.g., Internet transactions) but routines that govern these activities (and their underlying rules) remain unchanged, as performed in the physical or social space of cities.
- Optimization: characterizes activities performed in digital space but routines that govern these activities are optimized to the best configuration by automation and AI.
- Innovation: characterizes activities performed in digital space but routines that govern these activities are replaced by more fit ones, defined within a cyber-physical system of innovation.

In principle, performance scales up with optimization and innovation, as the underlying routines become more productive or efficient. Digitization alone is not enough for higher performance; on the contrary, if alone can reduce performance by limiting the communication width. There is evidence that the low performance of many smart city projects is due to solutions that introduce marginal or low-level innovations to city activities (Komninos, et al. 2015). The low impact can be attributed to smart city projects which promote digitalization only rather than combined digitalization-innovation.

Methodology

To a large extent, research on the hypothesis stated is beyond the current smart city state-of-the-art and transfers the focus from smart technologies to innovation system building and city routine modification. Most importantly, it conveys in the field of smart cities a central concept of systems of innovation, namely *innovation as learning or cognitive process and smart cities as learning-based innovation environments*. This requires an interdisciplinary approach combining research in urban planning, territorial systems of innovation, and design/development of smart systems, digital applications, and e-services.

To verify the hypothesis of Connected Intelligence Spaces as cyber-physical-social systems of innovation operating across city ecosystems, we should (a) search for common components and innovation functions in radically different smart city projects and ecosystems and (b) search for a common architecture based on those common functions, which allow for creating a generic system of innovation. At the next steps of research, we will develop the prototype of an IoT platform operationalizing the innovation functions and universal architecture identified, and document by experiments the modification of routines and scale-up of city activities when performed in Connected Intelligence Spaces.

We will base the assessment of the hypothesis on case studies by looking into three large-scale smart city projects that (a) correspond to very different city ecosystems and vertical markets; (b) have radically different goals related to safety, mobility, and decarbonization; and (c) create Connected Intelligence Spaces combining physical, institutional, and digital elements. In these cases, we will examine the components that enable a radical change of safety, mobility, and energy usage routines, and assess whether common innovation functions operate across the cyber-physical-social systems created.

Figure 1 illustrates the scope of this survey about components and common innovation functions across city silos and vertical markets. While the city ecosystems, their material base, activities, and objectives in the three cases differ enormously, we search for a more holistic underlying system based on common innovation processes and functions that sustain the radical change of routines commanding respective activities. In the case studies, we will assess the degree of difference and similarity of innovation functions across the ecosystems for safety, mobility, and decarbonization.

Innovation Functions Across Smart City Ecosystems: Three Case Studies

Vision Zero: Promoting Public Safety

Vision Zero (VZ) is a strategy to eliminate all severe traffic injuries in cities, while increasing safe, healthy, equitable urban mobility. Introduced in Sweden in 1997 (Whitelegg & Gary Haq, 2006), it has gradually been adopted by cities in Europe, in the Netherlands, and the UK (Blackpool, Brighton, Hove, Edinburgh) and since 2014 by many US cities (San Diego, San Francisco, Los Angeles, New York, Boston, Austin, Fort Lauderdale, and other). The US Vision Zero Network was founded in San Francisco and currently counts 43 VZ cities across the many US states.

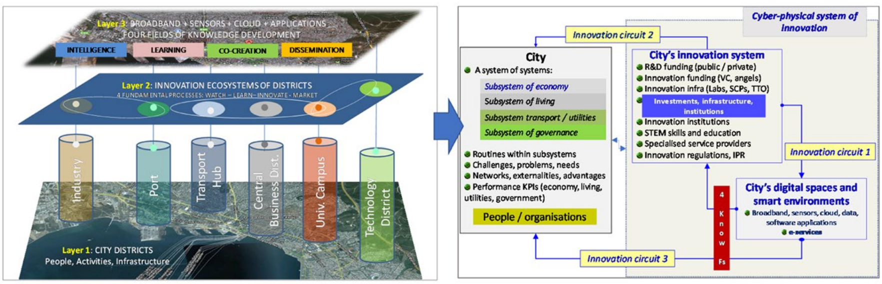

Fig. 1 From smart city silos to innovation functions across city ecosystems

Vision Zero differs from traditional thinking on road safety: it focuses on fatalities and serious injuries instead of accidents; it takes into account human behavior and acknowledges the limits of human capabilities; it accepts shared responsibility for all traffic system components instead of individual responsibility in case of an accident; it designs a forgiving road system in which crashes do not necessarily lead to death; and it recognizes vehicle speed as the crucial factor for safe road mobility (Belin et al., 2012; Stimpson et al., 2014). Following these principles, the VZ is implemented by an action plan comprising actions on the physical space of cities, mobility rules, institutional change, and digital technology. These actions create a Connected Intelligence Space in which drivers and pedestrians make the best decisions to avoid severe and fatal traffic accidents. But how this intelligent space is constructed? The experiences from cities that implemented VS strategies (e.g., City of New York (2014); City and County of San Francisco (2015); City of Chicago (2016) reveal some fundamental building blocks, which are deployed in parallel with complementarity and interactions.

Mapping urban mobility and the geography of motor accidents is the starting point. The causes and the geography of fatal traffic accidents and serious injuries are specific to each city. They depend on the geometry and features of city roads, the drivers' and pedestrians' culture, risk awareness, safety measures, which differ from one city to the other. Fatal and serious accidents occur in a small percentage of streets, on a high-injury network, which is necessary to identify, raise awareness, and focus there the preventing measures. For instance, more than 70% of severe traffic injuries in San Francisco happen in 12% of streets, and almost half of the high-injury network is located in disadvantaged communities. Mapping is part of a data-focused approach to gather, analyze, and share data, and understand traffic safety issues. It includes information collection, identification of high-injury network and areas of risk, analytics on fatalities, and major injuries per areas and social groups.

Engineering solutions under the principles of VZ include city streets redesign, especially the re-design of intersections, street resurfacing, street-related physical improvements and maintenance, disabled access enhancements, bicycle upgrades, arterial slow zones, guidance with signs and labels on how to behave. The aim is to improve visibility and safety and help drivers and pedestrians to adopt better behavior on the streets. Engineering interventions use the High Injury Network to identify gaps and design and implement actions for safety related to vulnerable road users, child and senior injuries, school location, housing for seniors and people with disabilities, and other user communities of concern. Hundred re-design solutions are in this field: designate movement lanes and clarify who belongs where on the street through better markings; add crosswalks; remove visual barriers from intersections; widen the parking lane; add bike paths and lanes; new left-turn lanes; eliminate unsafe turn movements; install speed bumps; add signals to avoid confusion for all users; improve visibility in high-crash intersections (Perez, 2020).

Rules, regulations, and law enforcement are important parts of the VZ action plan. Priority is given to speed control, driving while impaired, and failure to wear seatbelts. Also, on driving modes associated with following too closely, distracted driving, and identification of high-risk drivers for traffic-related offenses. Speed reduction is a key action in this field: if a vehicle hits a person at 30 km/h, an adult has a 95% chance of living, while at 60 km/h, the chance is only 10%. Law enforcement is necessary for minimizing violations leading to fatal injuries, which occur in the high-injury network and at intersections. In some cities, safety in areas close to schools is systemically assessed (The Office of Traffic Safety, 2016).

Digital technology is used in many ways and includes dashboards and interactive maps to report the progress of safety and mobility measures in San Francisco; digital speed-feedback equipment and use of automated photo enforcement as part of the speed-management in Edmonton; emergency response and advanced speed detection in New York, a technology that alerts passengers and drivers when they travel over the speed limit; pedestrian countdown signals, automated enforcement and deployment of speed cameras and red light cameras, as well as more advanced systems to predict weather trends and patterns and enhance education and enforcement in Edmonton (City & County of San Francisco, 2015; City of New York, 2014; The Office of Traffic Safety, 2016).

Improving awareness and guide behavior is a key objective of the above actions. Awareness is enhanced by data, such as publication of risks, crash and safety data regularly, major causes of collisions, fatalities, and injuries among all transportation users, traffic laws where the failure to follow them is identified. Introducing data-informed thinking is the challenge. Education is also part of awareness to develop a driving culture suitable for Vision Zero, educating road users to understand the underlying traffic-safety issues in the community, and educate on specific (e.g., large vehicle) driver training programs. Digital technologies enable also real-time awareness and adaptation of user behavior to conditions and risks as they occur.

The VZ action plan is based on participatory design. It is formed and implemented by multi-governance engagement of the City Hall, the Police, transportation authorities, taxi associations, and in some cities with the engagement of health organizations (City of New York, 2014). It is based on public dialogue, living labs for new ideas and solutions, social media opinion crowdsourcing, and advocacy for safer streets and partnership between citizens, government authorities, and the private sector. Evaluation analysis and monitoring is an integral part of the action plan to continuously analyze collision data, identify causes and high injury areas, and assess the effectiveness of engineering, enforcement, education and policy efforts, and give recommendations for refinement.

The VZ action plan creates a space with physical, institutional, and digital dimensions, which enable better decision-making regarding mobility. What happens is a change of routines that command mobility and a behavior change of drivers, cyclists, and pedestrians. A cyber-physical-social space is established that changes both the routines of mobility and the institutional environment in which these routines are defined. Once the VZ space is created, thought partnership in the community, the change of individual behavior routines is spontaneous. Drivers and pedestrians adopt new rules, skills, and behavior patterns to maximize individual benefit.

We may identify a series of innovation functions taking place in the VZ Connected Intelligence Space, which are responsible for the change of mobility routines and behavior. All functions take place on a cyber-physical-social space and rely on combinations of elements belonging to the physical, institutional, and digital space of cities. These are the following:

The Physical Space, Buildings, Objects, and Equipment of the public space of cities make the material basis of Vision-zero, which is re-designed and adapted to human behavior that minimizes fatalities and severe injuries.

Engagement is the starting point for partnership and collaboration of city stakeholders in defining VZ actions. As VZ demands change in the areas of responsibility of different stakeholders, their engagement, resources, experience and skills are a requirement for setting a safer mobility environment.

Ecosystem Building is the outcome of stakeholder and citizen collaboration and engagement, leading to coordination of material elements, rules, and digital means in setting up a system which accepts human error, which is protective and forgiving.

Awareness starts from identifying the high-risk network and continues with monitoring and reporting, better visibility of traffic and crossroads, identification of causes of accidents. It is both offline and online, awareness of mobility and weather conditions, alert in areas that need attention, real-time services and analytics, alert in case of an event, dispatch ambulance, and quick response for first aids.

Mobility Rules that improve safety are introduced by law and police enforcement, changing the institutional framework in which mobility and responsibilities are defined.

Guidance can be real-time by traffic signs in the physical space of cities or digital guidance by smart city applications and e-services.

Two-Sided Coordination and Learning how to advance security in mobility behavior is a concern of all mobility service suppliers and is addressed to all users, drivers, cyclists, and pedestrians. It is achieved by multi-channel communication, information dissemination, and learning.

The impact of Vision Zero is fully documented "In Sweden, the most famous example and originator of Vision Zero, traffic fatalities have dropped 30% since 1997. In Minnesota, Utah and Washington State, traffic fatalities have fallen steadily since the introduction of Vision Zero-style programs in the early 2000s; a 43% reduction in Minnesota, 48% reduction in Utah and a 40% decrease in Washington" (City of New York, 2014, p.9). In Norway, "a hypothetical program designed to implement Vision Zero for traffic fatalities was developed and its effects on the number of fatalities estimated. Implementing the whole program could reduce the number of traffic deaths in Norway from about 300 per year to about 90 per year" (Elvik, 1999). Any criticism of VZ is not focused on the impact to eliminate all deaths and serious injuries on the roads, but on the risk to a setting of erroneous social priorities, and undesirable social side-effects, such as imposing measures that seriously infringe on personal freedom. However, the credibility of this criticism is questionable as one person's freedom in mobility may lead to another person's death (Belin, 2012).

Mobility-as-a-Service: a New Model for Urban Mobility

Mobility-as-a-Service (MaaS) is the integration of multiple transportation services into a coordinated mobility service offered over online platforms: "It combines different transport modes to offer a tailored mobility package, similar to a monthly mobile phone contract and includes other complementary services, such as trip planning, reservation, and payments, through a single interface (Hietanen, cited in Jittrapirom et al., 2017). As a novel mobility model, MaaS covers shared mobility (ride-sharing, car-sharing), free-floating e-mobility, demand-responsive transportation, flexible transportation services, which represent alternative ways of mobility services combining the advantages of public transport (externalities, economies of scale) and the flexibility/availability of private motor vehicles. MaaS forms an all-embracing platform in which each of these mobility models can be put together (Matyas & Kamargianni, 2019).

A literature review by Butler et al. (2020) identified six major smart mobility innovations that shape the landscape of mobility in cities: (a) demand-responsive transportation; (b) shared mobility; (c) intelligent transport systems; (d) alternative fuel vehicles; (e) autonomous vehicles; and (f) mobility-as-a-service. Figure 2 shows how these are organized and complement each other. We can identify two strands in these smart mobility innovations related, on the one hand, to transport technologies, such as ITS, alternative fuels, and AI-based autonomous vehicles, and on the other hand, to transport re-organization with demand-responsive transportation and shared mobility. Thus, MaaS is an umbrella enabling different configurations of smart mobility modes, while shared mobility remains the basis of MaaS.

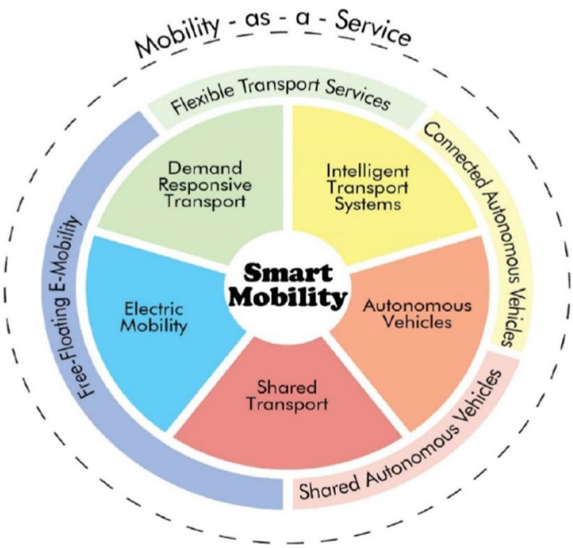

Fig. 2 MaaS integrating various types of smart mobility. *Credit:* Butler et al. (2020)

Shared mobility takes multiple forms: carsharing (car-rental scheme for those who need occasional use of a vehicle), corporate carsharing (allowing a company's employees to take and share a car when needed), peer-to-peer carsharing (car owners making their vehicles available for others to rent), bike sharing, scooter sharing, carpooling and ride-sharing (car owners inviting people who are making the same trip to share a vehicle). These schemes may incorporate the use of hybrid, clean and electric vehicle fleets. Under the umbrella of MaaS, different forms of shared mobility can be combined. Thus, compared with shared mobility, MaaS is associated with a more holistic organization of transportation services into the community. MaaS creates a Connected Intelligence Space in which different shared mobility choices and transport technologies are offered, and users have many options and tools to make the best choices regarding their mobility.

Looking at cities that have introduced shared mobility and MaaS, we find a wide range of cases. Most city authorities or private companies have developed low-end shared mobility, such as shared bicycles and shared scooters. These work under different business models, either for profit or non-profit. Ride-sharing based on smartphone applications is also very common and practiced in many EU and US cities, while companies like Uber and Lyft offer ride-sharing services all over the world. Car-sharing is less frequent. In cities where is available, it offers shorter-term use of cars compared with rental companies and quicker car pickup and return.

Even less frequent and more recent is MaaS in which a wide range of private and public transport modes is offered over a single platform. This is the case, for instance, of Smart Dublin, where in November 2019 the four Dublin local authorities decided to initiate MaaS around the city and integrate all transport options, both public and private onto one platform (Finnan, 2020). In the Netherlands, where seven pilots on MaaS started in the spring of 2020, each one focusing on a different aspect of mobility integration: in Zuidas the pilot focuses on commuting; in Groningen-Drentheon on public transport; in Twente on the integration of public, contracted and public transport; in Limburg on cross-border transport; in Eindhoven on CO_2 neutral travel; in Rotterdam-The Hague on multimodal accessibility; and in Utrecht on city neighborhoods (Bakker, 2020).

MaaS is available in a few cities worldwide, Helsinki and Turku (Finland), Antwerp (Belgium), Vienna (Austria), West Midlands (UK), Singapore, and Tokyo (Japan). In these cities, it is offered by Maas Global, a global MaaS operator via the Whim application (https://whimapp.com/). The application brings over the same digital space public transport, taxis, city bikes, cars, and scooters, under unified rending tariffs. Jittrapirom et al. (2017) report on different schemes of MaaS, such as Kätevä Seinäjoki (Seinäjoki, Finland), Mobility Broker (Aachen, Germany), Mobility Mixx (Netherlands), Open Mobility (Berlin, Germany), Radiuz Total Mobility (Netherlands), Reisbalans (Netherlands), Stadtwerke PlusCard (Münster, Germany), Stuttgart-Services (Stuttgart, Germany), Swiss-Pass Plus (Switzerland), Switch (Hamburg, Germany), Tripkey (Netherlands), Ylläs Around (Ylläs area, Finland).

With the deployment of MaaS, a fundamental change in the mobility routines takes place, as citizens use third party vehicles and green transport means instead of their fusil-fuel vehicles while maintaining a high level of flexibility in terms of timing and choice of destination. In MaaS, all components of a Connected Intelligence Space are present: (1)

communities of users, both service providers and customers, (2) institutional agreements and rules of operation for the use of vehicles, payments, dispute management, etc., and (3) digital platforms enabling communication, transactions, and interactions among users. Key functions into this space created by MaaS, which allow the radical change of mobility routines and move from *an ownership-based transport system* to an *access-based one*, are the following:

A Collection of Transportation Means including cars, buses, taxis, bikes, scooters makes the material basis of MaaS. Their spatial allocation, coordination and usage offer an alternative to the privately-owned mobility model.

Engagement Various mobility service providers and users have to collaborate and set up the community of MaaS. Here, the contribution of providers in the inventory of services is crucial. Shared mobility to be appealing has to provide services that cover a wide range of individual choices and access to employment, healthcare, and recreational city districts (Cheyne & Imran, 2016). On the other hand, users sharing data helps the system make better decisions, considering the transportation system as a whole rather than looking into particular providers and services (Gonzalez-Feliu et al., 2018).

Ecosystem Building The MaaS ecosystem gathers different groups of actors interacting over a digital platform. Besides transport service providers and users, other stakeholders engaged are local authorities, payment clearing, telecommunication, and data management companies. Engagement is the driver of ecosystem building that brings producers, consumers, and go-between actors into the same system.

Awareness Based on the reviewed literature by Butler et al. (2020), the added value of smart mobility is at improving accessibility by providing more transportation options—especially first and last-mile access to public transport- creating a system more responsive to user needs. This calls for high awareness (both on digital and physical spaces of the city) to inform users about available transportation means, linkages, and ways to move.

Benchmarking and Analytics MaaS is user-centric and offers transport solutions that are best from the customer's point of view. It is based on benchmarking of alternative multimodal trips and let the customer decide. Benchmarking and forecasting of travel options is an essential component of the system, even if all options are not always visible to users (Jittrapirom et al., 2017).

Operating Rules In the assessment of twelve MaaS schemes by Jittrapirom et al. (2017), pay-per-use is offered as a tariff option in seven cases, all schemes offer their platform through smartphone apps, and two schemes offer web-based solutions as alternatives. An important part of operating rules is related to coordination between mobility service providers.

Guidance Can be online through smartphone apps or offline based on city signs, traffic lights, demarcation of lanes, depot areas, parking, and other facilities. The vehicles may be equipped with semi-AV setting, in-vehicle technologies such as crash avoidance; warnings for lane departure, collision, and blind spots; navigation systems; parking assistance; and adaptive cruise control. All these technologies offer real-time guidance.

Two-Sided Coordination and Learning are achieved by the MaaS platform. Both shared mobility and MaaS stand on two sided-platforms, digital spaces that orchestrate providers and customers to share resources, have more mobility choices, and take advantage of externalities (Hinz et al., 2020; Rochet & Tirole, 2004). MaaS produce network effects as the utility of the system increases by the growing number of users who learn and adopt a shared mobility culture. The more shared transport is being used, the fewer private vehicles are on the roads and less air pollution produced.

The impact of shared mobility and MaaS is impressive. According to a survey conducted by the Transportation Sustainability Research Center at UC Berkeley in California, carsharing in North America eliminated approximately 28,000 vehicles only, but reduced up to 146 million driving miles, and greenhouse gas emissions by 10% (SCC Europe Staff, 2018). Shared mobility can also counter-balance some negative aspects of autonomous vehicles, as this technology by introducing a shift away from public transport is expected to increase traffic volume by 15–59% (Rojas-Rueda et al., 2020). But more importantly, MaaS provides a model for eliminating private vehicles from cities, leading to a radical change in the urban environment and cities we know.

Positive Energy Districts: Transition to Decarbonization

"Positive Energy Districts" and "Zero CO_2 Districts" form another type of complex smart city space that induce a radical change in energy production and consumption routines. "A Positive Energy District is seen as an urban neighborhood with annual net-zero energy import and net-zero CO_2 emissions working towards a surplus production of renewable energy, integrated into an urban and regional energy system." (Urban Europe, n.a.).

Zero CO_2 is a city district or neighborhood in which "all the energy that is consumed directly or indirectly will be replaced by renewable energy consumption/local energy production and all the emission that is created by the city's activities will be neutralized by offering carbon-free energy options on the market" (Merit et al., 2017). The Zero CO_2 District is a platform to extend zero energy buildings at the city scale. The district approach allows considering energy interactions between each building and the broader energy system. It produces environmental gains both from energy-efficient buildings and the use of renewable energy sources (RES) (Saheb et al., 2019). Besides the contribution to the-end-of-carbon, these city districts are places that stimulate environmental awareness, innovation, economic growth, and social progress (Sougkakis et al., 2020).

The making of a Zero CO_2 District follows a series of planning principles, such as (a) define zero energy goals in the district master, (b) accurately represent the energy system, the size and location of photovoltaic arrays, geothermal wells, and central utility plants, (c) identify complementary loads for heating and cooling within the district and coordinate energy recovery through building locations, density and the district thermal system, and (d) produce energy design guidelines, such as zero energy design guidelines for infrastructure and buildings (Polly et al., 2016). An important part of planning is about the smart grid. It requires increased use of ICT to improve the reliability, security, and efficiency of the electric grid through dynamic optimization of grid operations and renewable energy resources. Full communication is the backbone of a smart grid as a basis for the integration of distributed energy resources. At the lower end is smart metering, which allows remote metering, dynamic tariffs, power monitoring, and control.

A JRC survey on 24 energy communities in the EU documented the need for social innovations and actions to be introduced at the community side of such districts (Caramizaru & Uihlein, 2020). The survey aimed to provide an overview of activities, organizations, and implications of energy communities, which refer to collective energy actions that foster citizens' participation across the energy system. Two main findings were about (a) empowering users for social innovation and (b) taking an energy system approach. The objective of engaging citizens through collective energy actions is to reinforce the energy transition, citizens' participation, and control over decision-making in renewable energy. The social innovation potential resides in the ability to ensure that the benefits of decarbonization are shared by all in the community. The energy system approach provides flexibility and complementarity between decarbonization actions, customers benefit from lower energy prices, and access to private capital from renewables investments through citizen participation.

The cyber-physical-social space of Positive Energy Districts and Zero CO_2 Districts is a system that integrates renewable energy sources, smart metering, energy optimization, connectivity over the smart grid, passive energy systems in buildings, nature-based solutions, as well as energy sharing, community-based operating rules, participation, and governance. It is a low-carbon transition based on complex negotiations and trade-offs between multiple objectives and constraints (Geels et al., 2017). Key functions in the Connected Intelligence Space created are:

A Collection of Renewable Energy Production Means and Buildings including photovoltaic panels, wind turbines, small hydro, bio-energy, and other, connected over a local smart grid make the material base of a Positive Energy District.

Engagement The transition towards climate-neutral city districts cannot be achieved through technology alone. There is a need for a social transformation in which civil society and citizens play a crucial role in a prosumer culture. A Positive Energy District is a social innovation and relies on a community that can combine the individual and the public interest and 'commonify' decentralized renewables where people co-operate to regenerate a common solution (Geels et al., 2017). Local policies in favor of renewables, such as feed-in-tariffs, tax incentives and grants, document the engagement of public authorities in the community ownership schemes (Curtin et al., 2017).

Ecosystem Building is a critical part of the whole district transformation process. The review of projects such as *City-zen Virtual Power Plant* in Amsterdam Smart City shows that even a small number of prosumers is sufficient for building a system connecting renewable energy supply and demand with dynamic adjustment of energy production, storage, and use in the community. Local energy ecosystem building is an alternative model compared with renewable energy production by large wind farms and large energy producers.

Awareness Smart metering provides real-time awareness and analytics of the system and dynamic adjustment of energy supply, demand, and storage. Also, emission inventories are necessary for a comprehensive strategy for local emission reduction. Inventories measure air pollutants discharged into the atmosphere from various sources in the transport sector, the industrial and manufacturing sector, and domestic fuel use for heating, cooling, and cooking in houses.

Operating Rules The governance of energy communities and cooperatives is led by well-defined operating principles, responsibilities, obligations, and sharing of benefits. A sharing and community culture shape the governance model. A cooperative energy utility business model provides the details of governance, energy production, payments, balance. Participation in renewable ownership and decision-making can either be direct by the members of the partnership or indirect through a board of directors.

Two-Sided Coordination is provided by the smart grid of the district and the continuous flow of data between producers and between users and producers. Data flow enables the adaptation of RES production to local consumption, energy storage, and energy trade. Incentives and learning new consumption patterns can contribute to level the daily use of energy, and production better adjusted to energy consumption.

Nature-Based Solutions With the current knowledge, it is impossible to stop all CO_2 emissions from human activities. Thus, carbon neutrality means that the anthropogenic carbon dioxide emissions are net zero and some remaining emissions will be compensated by carbon dioxide uptake by nature-based solutions. Thus, the net input of carbon dioxide to the atmosphere due to human activities is zeroed (Only Zero Carbon, n.a.).

Discussion

In these three cases, we looked into smart city verticals related to safety, mobility, energy, and the environment. In each case, different physical elements are organized in the respective ecosystem: city elements, such as crossroads, traffic lanes, public space equipment, and city signs in the case of Vision Zero; private and public transportation means in the case of Mobility as a Service; and renewable energy production means, building retrofitting, and nature-based solutions in the case of Positive Energy Districts. While the activities, the material base, and the objectives of these smart city projects vary considerably, they produce cyber-physical-social spaces with a remarkable similarity in functions and working principles. Most important, the radical change of behavioral routines in the respective activities stand on common functions and principles rather than the different material base and activities of each ecosystem. A comparative report is given in Table 1.

In all cases, *ecosystem building* or *community building* and a prosumer culture is the driver for the modification of routines, a transformation organized through (a) engagement of stakeholders and users, (b) new organizational and operating rules, (c) awareness, measurement and user feed-back, (d) two-sided coordination of producers and users, (e) benchmarking, measurement, and assessment, (f) guidance on physical and digital space, and finally (g) learning new behavior and ways to act. These processes become functions by repetition, modifying routines in the respective smart city ecosystem.

The ecosystem created is a cyber-physical-social system of innovation that guides the change of existing routines with more efficient ones in terms of safety, mobility, and environmental footprint. The replacement rather than the optimization of existing routines is the levier of higher impact. This ecosystem, which the main building blocks are presented in Fig. 3, is more universal, less partitioned, including the same set of functions that create a Connected Intelligence Space. Depending on the specific objectives of each case, some functions become dominant while others fall back. Creating an innovation ecosystem with a small number of innovation functions is the mechanism for leveling differences between smart city ecosystems.

As depicted in Fig. 3, a standard set of nine common functions is organized in three blocks. Initially, the ecosystem block is set with the deployment of a digital or cyber-physical platform enabling the engagement of users and stakeholders and creating an ecosystem or community with a specific aim and mandate. Sub-processes on how engagement is achieved by motivation, collaboration, coordination, education can be part of the respective function. Then follow a block of interaction among human and digital agents, data generation, analytics, and insights based on data. Sub-processes of awareness, such as alert, event management, forecasting, real-time guidance, can be part of this function. Two-sided coordination between the producers of services and consumers is the central function in this block, producing rich datasets for informed decision-making. The third block is about behavior, performance, and impact. Within the Connected

Table 1 Commonalities in smart city projects entailing a modification of activity routines

	Vision zero	Mobility as a service	Positive energy districts
Different activities and material base of each ecosystem	Activities related to safety	Activities related to mobility	Activities related to energy and the environment
	Material base: A collection of physical elements, buildings, and public urban equipment	Material base: A collection of different transportation means, public and private	Material base: A collection of renewable energy means and building retrofitting
Common functions supporting the modification of routines per ecosystem	Ecosystem building/community building	Ecosystem building/community building	Ecosystem building/community building
	Engagement of stakeholders and users	Engagement of stakeholders and users	Engagement of stakeholders and users
	New organizational and operating rules	New organizational and operating rules	New organizational and operating rules
	Awareness, user feed-back, measurement	Awareness, alternative choices, smart metering	Awareness, smart metering, inventories
	Two-sided coordination of producers and users	Two-sided coordination of producers and users	Two-sided coordination of producers and users
	Learning, new behavior patterns	Learning, new behavior patterns	Learning, new behavior patterns
	Benchmarking and injuries analytics in different parts of the city	Benchmarking and forecasting travel options and transport	Benchmarking energy production and usage patterns and analytics
	Guidance on physical and digital space	Guidance on physical and digital space	Guidance through metering and awareness
Specific to ecosystem functions supporting the modification of routines per ecosystem	Redesign of physical space of cities and transport infrastructure		Redesign: Nature-based solutions

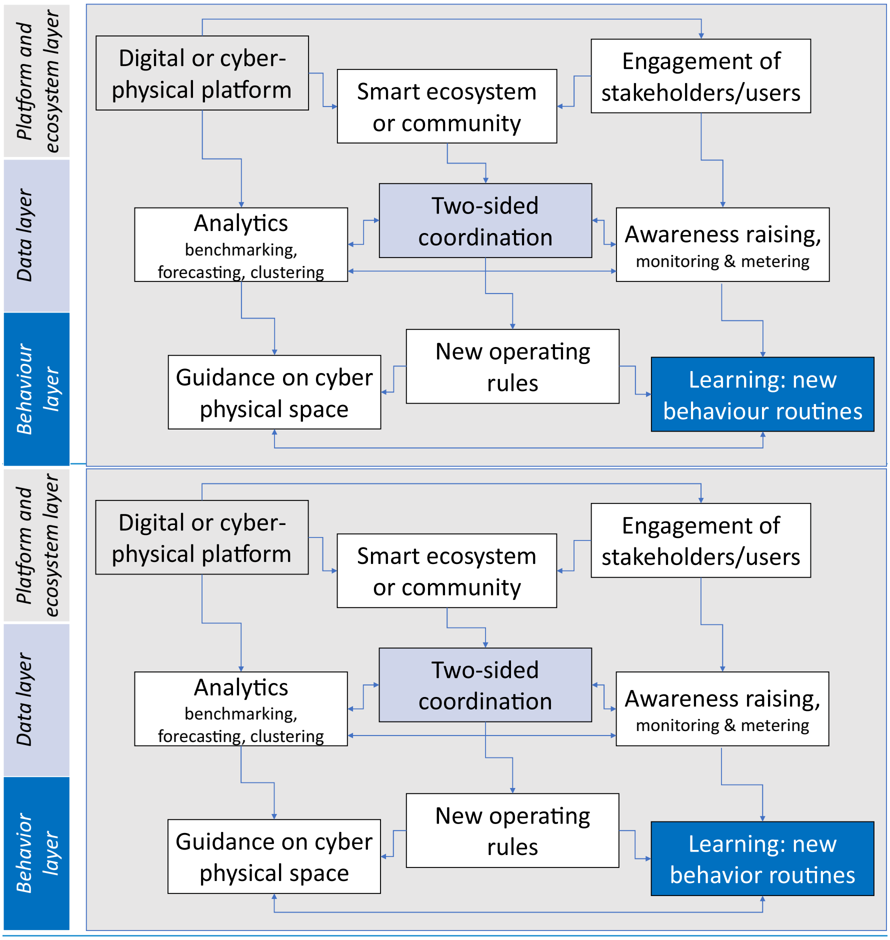

Fig. 3 Connected Intelligence Space. A universal architecture

Intelligence Space created by the three blocks, new operating rules for the community are defined, and direct guidance and learning contribute to replacing behavior routines with more effective ones. The digital or cyber-physical platform is the organizer of the entire CIS, supporting every component with communication, information processing and analysis, and online tools for guiding activities.

Conclusion and Further Research

In this paper, we examined high impact smart city projects and systems dealing with radically different objectives for safety, mobility, energy, and the environment. In all cases, the impact is documented and significant, eliminating fatal and severe traffic accidents, introducing a new shared mobility model, and turning to renewable energy with a very low environmental footprint. These smart city initiatives combine physical, social, and digital elements, and a platform-based ecosystem is created, driving the change of human behavior routines.

Analyzing how efficiency is achieved in these high impact smart city projects, we become aware of the importance of radical modification of behavior routines. High-efficient smart city ecosystems replace rather than optimize existing routines. A cyber-physical-social system of innovation is created, based on a set of common innovation functions, which are organized in a three-tier architecture. A remarkable similarity of innovation functions and associations between functions is observed across different smart city domains.

Based on this evidence, we can argue that a universal architecture of Connected Intelligence Spaces can drive innovation and higher efficiency in smart cities. A CIS combines user engagement, community building, platform-based coordination, and real-time digital services for best decision-making and rational behavior that maximizes utility (Bonanno, 2017). A digital or cyber-physical platform with its e-services, data processing, and analytics is the core of the CIS. The platform extends over and accommodates all functions of the CIS.

Thus, the paper offers a reflection on the legacy systems and foregrounding of the new smart district spaces created in cities. We propose a user-centric collaborative approach as opposed to the corporate approach of smart city development, which failed to achieve high-impact smart city solutions addressing the grand challenges of cities. The criticism of smart city solutions proposed by big IT and consulting companies is related to the helixes they engage, to fragmentation in vertical markets for energy, transport, government, etc., and mainly to the pursuit of digital transformation for optimization rather than digital transformation for innovation. Why does this happen is not evident and would need further research. Probably, companies developing smart city systems and solutions operate in preexisting fragmented markets; it is easier to optimize rather than innovate and replace a routine; implementation of technology solutions is less complex; it is transferable from one city to another, and less effort-consuming compared with institutional and planning-based solutions. Instead, what we propose is the design and development of smart cities by ecosystems, which evolve towards smart ecosystems through innovation rather than optimization of their routines. This can be done by developing Connected Intelligence Spaces, offering externalities, engagement, and awareness, which enable both digitalization and innovation of routine activities. The cases of public safety, smart mobility, and carbon positive districts, we analyzed, serve to demonstrate that Connected Intelligence Spaces follow a common architecture, which in turn facilitates implementation across the different ecosystems that make a city. Their higher added value is documented in addressing dire challenges, such as zero fatal accidents, new mobility models, or end of carbon.

However, given the limited number of cases we have examined, further research is needed on the structure, operation, and impact of Connected Intelligence Spaces in smart cities, in three directions.

First, a wider study of the smart city landscape to identify other cases of Connected Intelligent Spaces, cyber-physical entities and platform-based ecosystems that are deployed to make a city smart. The scope is to find common components, building blocks, and microservices into and across smart city verticals and ecosystems, and identify, through a representative sample of case studies, the components of Connected Intelligence Spaces responsible for the innovation of city routines.

Second, Connected Intelligent Spaces created by smart city initiatives are composed of a standard set of components and are structured by a common architecture. This standardization of functions allows building a generic ontology of CIS, based on a relatively small number of entities. We have to define classes, object properties, data properties, and relations between them, enabling a Connected Intelligence Space to work as innovation ecosystem. Moreover, this design has to be attempted and proved. A digital prototype has to be designed and the components to be developed in a way to accommodate all innovation functions of the CIS.

Third, we need experimentation with such CISs, their platform, functions, and architecture, to measure and document their impact. Working with experimental smart city ecosystems organized over common innovation functions is expected to reveal how routines are reorganized and how the deployment of human (based on skills), collective (based on the community), and machine intelligence (based on digital services/online tools and virtual assistants) modifies the routines of each ecosystem. Based on previous smart city impact studies, we can reasonably advance the hypothesis that the improvement in the performance of activities in smart city ecosystems organized over CIS will be greater than 40% of the baseline value and the scale-up will be super-linear rather than sublinear, as those concepts are defined by West and Bettencourt in the scaling of complex systems and cities (Bettencourt et al., 2007, 2010; West, 2017).

This line of research is expected to pave the way for generic, less compartmentalized in silos, smart city solutions that connect digital systems and innovation systems (Komninos, 2016). The integration of digital and innovation systems is the driver for higher efficiency. Standardization will allow better management of the smart city planning complexity (Komninos et al., 2019a, 2019b). Most important, this line of research is transferring the interest from stand-alone smart city applications and e-services, even most successful such as the Improve-my-City application (Tsampoulatidis et al., 2013), to larger-scale smart city projects aiming at the transformation of city ecosystems. Cities are composed of ecosystems and their transformation is the true object of smart city solutions. Below the level of the ecosystem, the city is lost, replaced by a sum of disintegrated activities.

Data Availability Data and material for the case studies comply with field standard.

Declarations

Conflicts of Interest The authors declare that they have no conflict of interest.

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