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The future of waste management in smart and sustainable cities: A review and concept paper

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ABSTRACT

The potential of smart cities in remediating environmental problems in general and waste management, in particular, is an important question that needs to be investigated in academic research. Built on an integrative review of the literature, this study offers insights into the potential of smart cities and connected communities in facilitating waste management efforts. Shortcomings of existing waste management practices are highlighted and a conceptual framework for a centralized waste management system is proposed, where three interconnected elements are discussed: (1) an infrastructure for proper collection of product lifecycle data to facilitate full visibility throughout the entire lifespan of a product, (2) a set of new business models relied on product lifecycle data to prevent waste generation, and (3) an intelligent sensor-based infrastructure for proper upstream waste separation and on-time collection. The proposed framework highlights the value of product lifecycle data in reducing waste and enhancing waste recovery and the need for connecting waste management practices to the whole product lifecycle. An example of the use of tracking and data sharing technologies for investigating the waste management issues has been discussed. Finally, the success factors for implementing the proposed framework and some thoughts on future research directions have been discussed.

Contents

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1. Introduction

In recent years, there has been some controversy over the role of technology in meeting sustainable development goals. While traditionally, based on IPAT formula ($I = PAT$), technology (T) along with Population (P) and the level of Affluence (A) are viewed as the main contributors to environmental Impacts (I) (Ehrlich and Ehrlich, 1997)., later on, the IPAT equation has been reshaped to emphasize that technology can influence environmental impacts in a positive way, $I = (PA)/T$ (York et al., 2003; Anderson, 1998).

The role of technology becomes ever more important, as we experience the fourth industrial revolution and new emerging infrastructure and capabilities offered by Cyber-Physical Systems (CPS), Blockchain technology, and the Internet of Things (IoT). CPS is a new class of engineered systems that offer coordination among physical and computational infrastructures and are the foundation of Industry 4.0, smart factories, and other smart systems such as smart buildings, security systems, data centers and medical systems (Khaitan and McCalley, 2015). If the networking functionalities offered by the internet are added to CPS, a new networking paradigm known as IoT is emerging where communications among all types of physical entities would be possible over the internet (Han et al., 2013). In addition, the capabilities offered by Blockchain technology for creating a decentralized public ledger facilitates information sharing among various users involved in a system and opens the door for new transparent business models.

IoT is expected to change the urban development and future cities, similar to other engineered systems. The impact of technology and innovation on urban development was highlighted under the term "smart city" (SC) coined in early 1990 (Gibson et al., 1992) and most recently under the term "City 2.0". Various definitions and dimensions have been provided for a smart city (Albino et al., 2015), among these definitions, the one offered in (Caragliu et al., 2011) is close to sustainable development, where it suggests that a city is smart when the aim of investing in cyber-infrastructure is to foster sustainable economic growth, better quality of life, and efficient management of natural resources.

There is a shared definition of what makes a smart city and what constitutes a sustainable one, where a smart city is not just about smart infrastructure but the extent at which such infrastructure assists in achieving sustainable development objectives. For instance, waste generation is a fast-growing problem of modern societies, particularly in growing urban regions. Around 1.7–1.9 billion metric tons of municipal solid waste is generated every year worldwide (Environment and Programme, 2010). If the city's population as a result of rural-urban migration is growing at the existing rate of 3–5 percent a year, then the waste generation will double every 10 years (UN-HABITAT, 2009). Although according to the environmental Kuznets curve (EKC) by increasing income per capita, the environmental degradation, and pollution decreases, the economy of scale and the population growth may offset the benefits of economic development. Further, there are controversial discussions on the accuracy of EKC. According to Stern (Stern, 2004), the statistical evidence behind EKC are not robust and the relation between environmental impacts and per capita income is not predictable. Waste generation is a concern for modern societies due to both the service cost of waste collection, and the environmental issues of landfills. The IoT seems a promising solution for handling waste collection and recovery operations in SCs (Zanella et al., 2014).

The number of studies that have discussed waste management practices in SCs is limited. The objective of this paper is to first review the existing studies on the topic and then introduce a data-driven model for waste management practices in SCs considering the circular economy concept.

Table 1 provides a list of previous review papers. As shown, the previous reviews were primarily focused on either smart and sustainable cities or waste management. The scope of every previous review provided is limited to the concept of SCs with one recent paper on ICT-enabled models for waste collection (Anagnostopoulos et al., 2017).

The current paper proposes a conceptual framework for waste management in SCs. The proposed framework consists of three main elements: (1) a Product Lifecycle Management (PLM) framework for collecting product lifecycle data and monitoring a product over its entire lifespan, (2) new business models compatible with circular economy and sharing economy concepts, and (3) intelligent infrastructure for proper separation, on-time collection, and

Table 1
Previous review papers and their scope.

Previous review papers	Scope
Cocchia (2014), Meijer and Bolívar (2016), Anthopoulos (2015), Arroub et al. (2016)	Smart and digital cities concepts
Kyriazopoulou (2015)	Technologies and architectures in SCs
Bibri and Krogstie (2017)	Smart sustainable cities
Talari et al. (2017)	SC and the concept of Internet of Things
Chauhan et al. (2016)	SC and big data challenges
Khajenasiri et al. (2017)	Energy control in buildings of SCs
Alibasic et al. (2016)	Cybersecurity for SCs
Shuai, Maillé, Pelov (2016)	Electric vehicles in SCs
Giusti (2009)	Waste management and human health
Zacho and Mosgaard (2016)	Waste prevention in waste management
Goulart Coelho et al. (2017)	Decision-making methods to support waste management
Beliën et al. (2012)	Solid waste collection
Sharholy et al. (2008)	Waste management in Indian cities
Anagnostopoulos et al. (2017)	ICT-enabled waste collection models

recovery of waste. The paper provides an example of electronic waste (e-waste) tracking effort to show the feasibility of applying sensor-based technologies in waste monitoring and management practices. Finally, several success factors for implementing the proposed framework have been discussed.

The remaining of this paper is organized as follows: Section 2 describes the research method. Section 3 discusses the role of technology, people and data in future SCs. Section 4 reviews the literature on waste management in SCs. Section 5 introduces a framework for collecting product lifecycle data towards proper waste recovery efforts. Section 6 provides an example of product monitoring through tracking technologies for the case of electronic waste. Section 7 discusses several factors for the successful implementation of the proposed framework and finally, Section 8 concludes the paper.

2. Research method

A four-step research method used in (Srivastava, 2007) has been adopted to collect and analyze the literature: defining unit of analysis, selecting the classification context, collecting publications, and evaluation of materials. The literature has been reviewed under three main topics, namely smart cities, sustainability, and waste management. The relevant studies have been searched through Engineering Village, Inspec, Compendex, Knovel, NTIS & GeoRef databases for the timeframe of 1997 to July 2017. Besides the point that these databases allowed the authors to find a wide range of publications, the capabilities offered by the search tool of these databases enabled the authors to refine the search based on vocabulary, document type, country, and publication year. Particularly, the resulting charts for publication year helped the authors to identify and locate any missing traditional and new publications related to keywords.

A single research paper or book has been considered as the unit of analysis. A set of keywords including waste management, smart cities, IoT enabled waste, sensor-based waste management, and RFID waste has been used to find relevant publications. These keywords have been applied with different combinations of AND/OR operators to assure the collection of a sufficient number of studies. The collected literature has been analyzed under two categories of problem context and methodology context in order to cover both studies that have discussed waste management in smart cities and studies that have developed methods to address such problems.

3. The role of data, technology, and people in smart and sustainable cities

To transform the urban environment into smart regions, many infrastructure and management-related factors are involved. In this section, we will discuss the role of three factors of technology, data, and people as highlighted by (Deloitte, 2015) with particular emphasis on the role of data and citizens, as they are among main driving forces of our proposed framework in Section 4. Later on in Section 4, we will discuss that new business models and policies are important too. Technology or infrastructure is only one element of this transformation, the collection of appropriate data toward defining smart solutions and changes that smart solutions bring into consumer behavior are two other cornerstones of SCs (Deloitte, 2015).

The collection of citizen-generated data is becoming more convenient as the number of smartphones and mobile devices users are increasing. The number of mobile devices sold in the global market in 2015 reached an all-time high of 1.4 billion units of which 70% were expected to purchase to replace older devices (Gartner, 2016). *Data* collected through smartphones is one of the main elements of smart communities. Data are often geo-referenced meaning that the data can be linked to a specific geographic location through a pair of coordinates. In addition, data are often time-specific meaning that data are relevant to a specific moment of time. The geo-referenced data not only are helpful for understanding the behavior of individual citizens but also for extracting trends and community features.

Data can be categorized under 1) private social data generated mainly by citizens, and 2) information about the public infrastructure collected by sensing technologies that are deployed for monitoring and management purposes. We are reaching the point when 'smart dust', the pervasive network of millimeter-size sensing and communication technologies are embedded in devices present in all daily activities (Warneke et al., 2001). In addition to data collection, new advancements in data processing systems such as edge and fog computing enable IoT users to localize their data processing needs and bring data processing close to data collection nodes. This improves the system latency, removes the need for centralized cloud servers, and reduces the computational costs as well as data privacy issues and energy consumption (Shi et al., 2016).

Several sources of data can be used to retrieve smart communities' data, ranging from the surveys conducted by the US Census Bureau to datasets collected by various governmental departments and private companies to apps and crowd-sensing where data acquisition is done by integrating readings from various devices and embedded sensors carried by citizens. As an example of datasets available through governmental agencies, SF OpenData publishes the data collected in the city of San Francisco under ten main categories of (1) economy and community, (2) city management and ethics, (3) transportation, (4) public safety, (5) health and social services, (6) geographic locations and boundaries, (7) energy and environment, (8) housing and buildings, (9) city infrastructure and (10) culture and recreation ("SF OpenData," 2017). Pan et al. (2013) grouped the main devices for collecting data into four categories: mobile devices, vehicles equipped with GPS devices, smart cards, and floating sensors.

Currently, data are collected essentially everywhere by different organizations, but what is missing is the communication between different sources and the lack of an integrated and connected data cloud that can be shared between different stakeholders (Lohr, 2014; Dasu and Johnson, 2003). Pan et al. (2013) have discussed that the data collected from SCs have been analyzed in the literature for the following purposes: (1) prediction of the patterns and models of citizens behavior, (2) tracing the citizen data at individual levels, (3) tracing the social relation and interactions among individual citizens, (4) connection between region characteristics and residents behavior of each region, (5) visualization of complex data and dynamics of city evolution, and (6) unwanted privacy issues and personal identity.

In addition to data, *citizens* made up another element of SCs as social machines. The sustainable cities may seek ways to use the capabilities of disruptive technologies toward making proper changes in human behavior, disruptive technologies that change consumer behavior toward pro-environmental behavior. Chourabi et al. (2011) categorized the critical factors of SC initiatives under eight categories of management, governance, policy, technology, people, infrastructure, economy, and natural environment.

The structure and dynamics of socio-technological communities formed in SCs contribute to sustainability results. Cities are made up of both citizens and infrastructures for food, water, energy, transportation, and other service activities. Therefore, they are considered as complex social-technological systems, where citizens as human agents operate various technological systems (Nam and

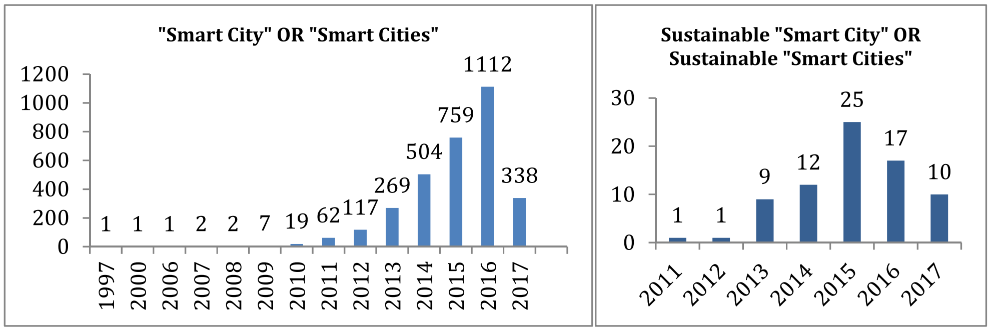


Fig. 1. The progress of smart and sustainable cities in the literature, the number of published work from 1997-July 2017 with the exact smart city-related terms in their titles derived from Engineering Village.

Pardo, 2011a). Sustainability requires critical insights into the way SCs are designed, the way citizens use technologies, as well as the ways technologies, are valued and should be altered in more sustainable ways.

The technological systems can be divided into two types depending on the type of decision makers: (1) systems that are built through decisions collectively made through public policy, and (2) systems that are built through individual decisions by citizens. The waste generation system is categorized under the second group, where the waste generation rate is influenced by decisions made by individuals. Arguably, most of the decisions made by individuals are mainly based on technical criteria such as cost rather than societal or ecological values (Miller et al., 2008). Therefore, waste management is becoming a complex urban problem. The role of citizen behavior is further discussed in Section 4.2.2. We should note that the relationship between citizens and technology is a two-way connection. While citizen decisions influence waste management system, the waste management infrastructure surrounding individual citizens also influence citizens behavior (Liboiron, 2014). Cities require innovative, cross-industry solutions to facilitate collection and disposal of solid waste. The solutions should be replicable, adaptable, and scalable (Patil et al. 2017).

Ahvenniemi et al. (2017) conducted a study to compare the extent in which the concept of SCs addresses the same concerns as the concept of sustainable cities. They compared the set of performance assessment systems used in both SCs and sustainable cities and concluded that the existing SCs frameworks do not sufficiently target the sustainability-related indicators, particularly environmental indicators such as energy, waste, and water management are underrepresented. Neirotti et al. (2014) reported a different conclusion about the energy domain and concluded that renewable energy and people mobility domains have received the most attention in many SC initiatives. The coverage of waste management domain is still *limited*. Surprisingly, even in the context of sustainability, the set of 29 indicators used by United Nations Cities Reports and adopted by various organizations only include energy and water consumed as main resources and does not include other types of resources such as solid and hazardous waste (Cote et al., 2006).

Fig. 1 shows the progress of the concept of the smart and sustainable city in the literature.

4. Review of IoT-enabled waste management practices

In this section, first, we briefly provide an overview of waste management practices and then discuss the major trends in waste management in SCs literature.

To the best of our knowledge about waste management literature, the studies on waste management have been focused on three main objectives of (1) waste characterization, (2) waste quantification, and (3) waste management practices.

Waste *characterization* studies mainly focus on sampling waste stream in different geographical regions with the aim of sorting and classifying waste stream into several fractions such as organic, paper, metal and plastic (Gomez et al., 2008; de Vega et al., 2008). Waste *quantification* studies on the other hand were mainly focused on estimating the amount of waste generation in a wide range of industries such as construction (Bossink and Brouwers, 1996), food (Parfitt et al., 2010), e-waste (Bigum et al., 2013), forestry waste (Castro et al., 2017), medical waste (Patwary et al., 2009), and ship scraping waste (Reddy et al., 2003). In addition to waste generated, estimations of waste recycled, incinerated, landfilled, and composted have been of interest in the literature.

The existing *management* practices include three main practices: prevention practices (e.g. product design), end-of-pipe strategies (e.g. recycling, waste separation, incineration, proper landfill), and environmental restoration practices (Dornfeld, 2013). *Prevention* practice studies have been mainly focused on analyzing strategies such as waste minimization (Ajayi et al., 2017), improving residents awareness (Clarke and Maantay, 2006), and waste legislation (Cooper, 2000). *End-of-pipe strategies* on the other hand aimed at recovering the value still embedded in the waste stream through practices such as proper and on-time collection (Wäger et al., 2011), recycling, waste repurposing (Wadhwa et al., 2015), waste separation methods both destination-separated collection and origin-separated collection (Sukholthaman and Sharp, 2016), reuse, recycling, and incineration or waste-to-energy (Syngellakis, 2014). Finally, *environmental restoration strategies*, also known as oops strategies have been focused on restoring the damaged environment after waste streams leak to the environment. It should be noted that among the above-mentioned three practices, prevention practices offer the highest effectiveness with the lowest cost, while environmental restoration is the most expensive practice with the lowest effectiveness (Dornfeld, 2013).

Although a lot of work has been done on the waste management topic, the concept of IoT-enabled waste management is quite new and the number of publications in this field is growing. The studies that have addressed IoT-enabled waste management systems can be classified into the following four categories:

- Development of data acquisition and sensor-based technologies (Glouche and Couderc, 2013; Catania and Ventura, 2014);
- Development of communication technologies and data transmission infrastructure (Medvedev et al., 2015; Chowdhury and Chowdhury, 2007; Longhi et al., 2012);

- Test the capabilities of IoT systems in field experiments (Hong et al., 2014; Gutierrez et al., 2015); and
- Truck routing and scheduling for waste collection operations (Anagnostopoulos et al., 2015; Ustundag and Cevi̇kcan, 2008; Chang et al., 1997).

Several studies have discussed the overall system architecture of IoT enabled waste management systems in which a number of bins are equipped with RFID tags for identification purpose, capacity sensors for waste level detection, actuators to lock the bin lids once they are filled, and wireless antennas to transmit sensor data to the network for waste collection operations (Longhi et al., 2012; Anagnostopoulos et al., 2015; Medvedev et al., 2015). Anagnostopoulos et al., 2015) have used the above-defined architecture integrated with a transportation system consisting of a number of low and high-capacity trucks equipped with GPS spatial technologies to describe the capabilities of IoT in both real-time monitoring of waste levels in trash bins as well as truck navigations for efficient waste collection.

Hannan et al. (Zhang et al., 2012) provided a review of ICT technologies in waste management applications and classified the technologies into four groups of spatial technologies (e.g. GIS, GPS), identification technologies (e.g. RFID, barcodes), data acquisition technologies (e.g. sensors, imaging) and data communication technologies (e.g. GSM, Wi-Fi, Bluetooth). The last three groups have received more attention in the waste management literature.

Before we start reviewing data identification, data acquisition, and data communication technologies, we will briefly discuss the way spatial technologies have been used for waste management. Reviewing the literature reveals that spatial technologies have been mainly used for the purpose of landfill site selection, path planning, and routing optimization problems. For example, Ghose et al. (2006) have developed a GIS-based routing model that define the optimal path for solid waste collection based on the population density, the types of road, and road network. Sumathi et al. (2008) have applied GIS-based data in a multi-criteria decision model to identify the optimal site for a landfill construction. Şener et al. (2010) also have used GIS data for landfill site selection. Leao (2001) have conducted a dynamic analysis in the GIS environment to quantify the demand of proper land for solid waste disposal over time.

One stream of literature has been focused on the development and application of identification and data acquisition technologies. The *identification* technologies are mainly RFID-based. To name a few studies, Glouche (2015) developed an RFID-based framework for waste identification in which digital information and QR codes attached to objects help users with correctly sorting and placing wastes in trash bins. Chowdhury and Chowdhury (Chowdhury and Chowdhury, 2007) showed how municipalities can use an RFID-based automatic waste weighting and identification system to identify stolen bins and communicate waste management information with individual households. Rada et al. (2013) also discussed the way that using an integrated Web-GIS system with RFID allows efficient waste separation in Italy. Al-Jabi and Diab (2017) also pointed out the application of an integrated RFID card, weight sensor, and ultrasonic sensor in monitoring the amount of waste that citizens drop in trash bins, and providing feedback reports to them. Abdoli (2009) however questioned the environmental implications of RFIDs and commented that while RFID tags facilitate the automatic identification of recyclable components in the solid waste stream, if used broadly, it may result in dissolving toxic and valuable materials in the established recycling processes.

The data acquisition technologies for detecting bin levels can be categorized under two groups of camera (or image-based) and sensor-based technologies such as weighing, ultrasonic, and light-emitting diode (LED) sensors (Elia et al., 2015). Reverter et al. (2003) designed a point-level capacitive sensor for improving solid waste collection. Vicentini et al. (2009) also designed a sensorized container that allows measurement of the actual weight and volume of the waste. They have tested the prototype of their design in the Pudong New Area, Shanghai. Medvedev et al. (2015) have extended the current sensor-based technologies by combining two types of technologies and adding surveillance cameras as an assistive technology that can provide further evidence to authorities in the case of an inefficient waste collection in inaccessible regions. Along similar lines, Hannan et al. (Rada et al., 2013) developed several image-processing algorithms to analyze the information received from a camera for waste bin level detection. Catania and Ventura (2014) discussed the application of the sensor-based smart-M3 platform, an open-source project, for real-time monitoring of waste bins with the aim of helping service providers avoid collecting semi-empty bins and helping consumers to locate closest bins to them and be aware of the fullness status of the nearest bins.

Another stream of literature has been focused on developing and employing *communication and data processing* infrastructure. To name a few studies, Lata and Singh (2016) developed a web interface to help authorities monitor trash bins with the data received through an embedded Linux board from a wireless sensor network. Toma and Popa (Shyam et al., 2017) discussed three types of IoT communication protocols available for machine-to-machine communication including Constrained Application Protocol (CoAP), MQ Telemetry Transport (MQTT), and Representational State Transfer (REST). Mahajan and Chitode have shown the application of ZigBee as a data transmission technology for bin monitoring in waste collection systems (Mahajan and Chitode, 2014).

The third stream of studies has shown the applications of enabling technologies in different domains and tested the capabilities in several pilot and field experiments. To name several studies, Zhang et al. described the use of RFID technology in enhancing construction waste logistics (Zhang et al., 2012). Tao and Xiang (2010) proposed a conceptual information platform model for waste cycle management in Wuhan city, China. Elia et al. (2015) discussed the information flow required to design a Pay-As-You-Throw (PAYT) strategy in solid waste management systems based on the existing bin level detection and data transmission technologies. Hong et al. (2014) designed a food waste management system in which battery-operated RFID-based garbage bins are connected through wireless communication to a server that informs administrators of the status of all bins for timely food pickup schedules in the Gangnam district, Seoul, Republic of Korea. Gutierrez et al. (2015) conducted a simulation experiment to test the efficiency and economic feasibility of such smart systems for waste collection in the city of Copenhagen, Denmark. They have used a GIS simulation environment along with graph optimization algorithms and available Open Data about the city. Shyam et al. (2017) conducted a simulation using Open Data from the city of Pune, India to estimate the cost to collect and dispose of wastes. On a separate note, Ho and So (2017) discussed the impact of media campaign emerging in smart cities on promoting the environmental friendly life among Guamanians.

Finally, the research has shifted from developing sensor-based technologies and data transmission infrastructure to support the use of such technologies. The main use of IoT-enabled technologies was for the purpose of waste collection and scheduling problems.

To clarify the nature of waste management practices in SCs, we should note that waste collection in SCs requires *dynamic* models rather than *static* planning approaches (Anagnostopoulos et al., 2015). The availability of capacity sensors and wireless communication infrastructure makes it possible for municipalities to monitor trash bins status and adjust collection scheduling and routing problems accordingly for each municipality region or even trash bin as a demand node (Lundin et al., 2017). Anagnostopoulos et al. (2015) analyzed several dynamics collection routes models for waste collection in SCs. They have proposed four different models including the dedicated trucks model, where a specific number of trucks are dedicated to waste collection activities from a number of high priority trash bins, the detour models in which trucks can deviate from their original routes to serve high priority region, the minimum distance model and the reassignment model, where the demand nodes will be reallocated when new information is coming to the system. Often, the objective of collection routes problems is to maximize on-time collection and minimize waste depletion cost. McLeod et al. (2014) developed a vehicle routing and scheduling method based on tabu search algorithms to show how remote sensing technology can facilitate more efficient charity collection scheduling in the UK.

On a side note, Schafer commented that data privacy and data security concerns may limit the capabilities of IoT-based waste management systems (Schafer, 2014) since it opens the venue for having municipalities access to individual household data.

The review of previous studies shows that studies about waste management in SCs so far have been primarily focused on making waste *monitoring, separation* and *collection* more efficient with the help of sensor-enabled solutions, however an effective waste management practice requires considering the whole product lifecycle from design up to end-of-use stage, where various value-driven strategies can be adopted during the product lifecycle to avoid waste generation rate and maximize waste management practices. We should highlight that dynamic routing and scheduling optimization should not be the only motive for IoT-enabled infrastructure, but the real value of such infrastructure is when the leakage of product value gets minimum during its entire lifespan through the on-time and effective use of information collected from IT-enabled infrastructure. Anagnostopoulos et al. (2017) also provided a review of ICT-based waste management models and emphasized on the need for defining a novel framework for waste management efforts.

In the next section, we propose a framework for waste management in SCs with the aim of facilitating not only collection efforts but also value extraction efforts from every unwanted device discarded by end users.

5. An integrative framework for waste management in smart cities

To solve the waste management problem, a new form of waste collection and treatment is needed. In this section, a conceptual framework for waste management in future cities is introduced in which the waste management system is connected to the whole product life-cycle. We envision an ideal city with no waste, where the waste of one system is minimized and becomes the nutrients for other systems. The transition to becoming a Zero-waste smart city requires three strategies: waste prevention, proper waste collection, and finally proper value recovery from collected waste.

Following the aforesaid research perspective, the overall scope of the proposed framework involves three main interconnected elements as illustrated in Fig. 2:

- Element 1: Infrastructure for the collection of product lifecycle data.
- Element 2: Connected and involved citizens for sharing products and services to avoid waste generation and facilitate the adoption of novel business models with the aim of waste prevention, and value creation.
- Element 3: Intelligent and sensor-based infrastructure for proper upstream separation and on-time collection of waste when a product reaches its end-of-life.

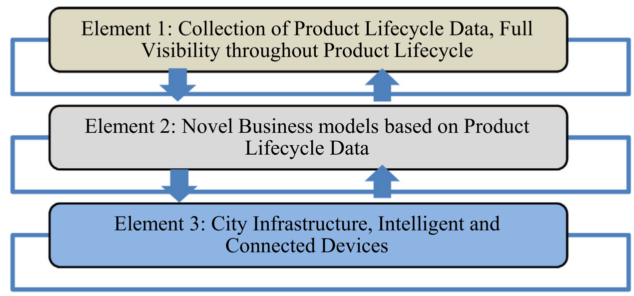


Fig. 2. The elements of the proposed framework for waste management in smart and connected communities.

This section discusses the necessity for addressing the design, development, and implementation of an infrastructure for the collection of product lifecycle data that takes into account the synergistic nature of the above three elements. Particularly, the proposed framework views '*waste*' as a '*resource*', puts emphasis on waste reduction '*upstream*', focuses on resource management (separating waste at the source to increase value recovery rather than treatment), and aims at increasing efficiency by adopting the concept of circular economy and economy of sharing.

Similar to the guidelines suggested by the Logistics Management Institute on the green supply chain (Logistics Management Institute, 2005), smart waste management initiatives should move from compliance to value creation. The traditional cost avoidance strategies on waste management are mainly focused on assuring compliance, minimizing risk, maintaining health, and protecting the environment. However, based on the 'emerging value creation' paradigm, smart waste management program should raise productivity, empower relations among various stakeholders, encourage innovation, and enable growth (Fig. 3).

A considerable number of survey and interview-based studies have been conducted to identify factors influencing the effectiveness of waste management practices. Improved legislation, enhancing public awareness, novel treatment technologies, experienced personnel, waste pickers management, designing waste collection practices based on citizens' demographic factors, considering social outcomes of waste management, centralized planning, and commercialization of the MSW industry are examples of strategies suggested for enhancing waste management efforts (Rybova and Slavik, 2016; Al-Khatib et al., 2010; Moghadam et al., 2009; Suocheng et al., 2001).

5.1. Element 1: Infrastructure for the collection of product lifecycle data

This element explores a model for data sharing between various stakeholders and communities in product lifecycles in order to facilitate on-time separation, collection, reduction, and recovery

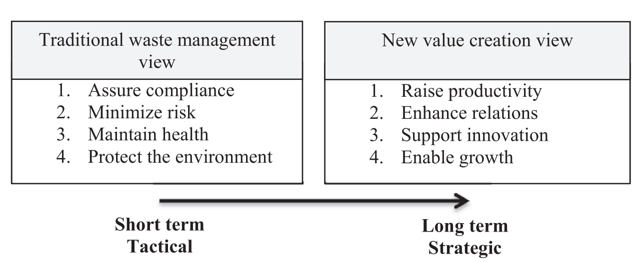


Fig. 3. Policymakers should view waste management efforts in SCs as a strategic decision, not a tactical decision (borrowed from the concept of a green supply chain in (Logistics Management Institute, 2005)).

of waste. We envision a city in which the waste generated is minimized and the waste collected from households will become the "food" for remanufacturing companies and waste recovery systems. While the focus of the IoT-enabled literature discussed in Section 3 was on developing an infrastructure for efficient waste collection and separation, the focus of the proposed concept in this paper is on waste reduction and recovery. The ultimate goal of the proposed concept is to facilitate closing product lifecycle loop through different philosophies and approaches suggested for resource recovery ranging from landfill mining to urban mining and circular economy. Cossu and Williams (2015) provided a comprehensive discussion on various approaches and terminologies used for materials utilization, and differentiate them based on different sources of materials and their origin (Natural vs. Anthropogenic materials). For example, urban mining is an extension of landfill mining in which elements are recovered from any kind of anthropogenic stocks such as buildings, industry products, and infrastructure (Cossu and Williams, 2015). Urban mining is particularly important to assure sufficient resource recovery from city-wide infrastructure and buildings.

The objective is to develop a framework for the collection of product lifecycle data and tracing the citizen data at individual product levels. The proposed platform is a promising solution for tracking various types of products ranging from consumer electronics to home appliances and even food packaging. A system architecture for information-sharing platform is needed for tracing product lifecycle data. To implement an infrastructure for collecting product lifecycle data, four main *questions* should be answered: (1) what type of data should be collected, (2) who should collect the data, (3) at what stage of product lifecycle the data should be collected, and finally, (4) how the data could be used for extending product lifespan and the closing product lifecycle loop. Answering these questions requires understanding the needs of various stakeholders connected via the platform. Fig. 2 shows different elements of the conceptual model for the proposed waste management model.

5.1.1. Different stages of the product lifecycle

Product Lifecycle Management (PLM) is an approach to collect and utilize product-related information continuously throughout the entire course of a product's lifecycle (Kiritsis, 2011). Within this model, information flows between the different stages of the product lifecycle create closed knowledge loops. All lifecycle participants have access to and can contribute to a shared product information database, with the objective of using this knowledge to improve sustainability-related decisions. The product lifecycle can be broken into **three main stages** as shown in Fig. 4 with the following components (Jun et al., 2007): (1) **Beginning of Life** (BOL) including Design and Manufacturing, (2) **Middle of Life** (MOL) including Distribution, Use, and Service/Maintenance and (3) **End of Life** (EOL) including Collection, Remanufacturing, Reuse and/or Recycling, and Disposal of residual waste. Different knowledge loops can be defined within the product lifecycle. The focus of PLM should be on extracting knowledge loops that facilitate the elimination of waste, the extension of the product lifecycle, and adoption of reuse, repair, and recycling strategies. Li et al. (2015) discussed the potential applications of 'big data' in PLM and summarized several existing applications including production scheduling, supply chain and mass customization based on big data.

The knowledge of the product lifecycle can help manufacturers move towards the elimination of waste and emissions. For example, the information of consumer behavior and product usage time can help remanufacturers estimate the future reusability of discarded devices (Mostafa et al., 2015), or estimate of product disposal time help remanufacturers offer timely buy-back prices for on-time return of used products such as consumer electronics for upgrade and recovery to designated remanufacturing channels (Sabbaghi et al., 2016). The use of smart meters for real-time monitoring of energy consumption of production equipment and concepts such as condition-based monitoring and maintenance are other applications of product lifecycle data.

Other examples include monitoring the rate of waste generation to help municipalities manage the on-time collection and recovery of the waste. Such information also can be used to redesign the size and geometry of trash bins for different regions. Overall, information sharing, collecting new types of data, the possibility of emerging new business models, and the capability of higher utilization of idle resources, reduction of wasted capabilities, and wasted lifecycle are other potentials for using product lifecycle data.

5.1.2. Implementation of product lifecycle management infrastructure

In the closed-loop PLM framework, PLM users have access to and are responsible for updating Product Data Knowledge Management (PDKM) systems which integrate and manage all product data (Anke and Främling, 2005).

- Manufacturers and suppliers establish and maintain product details and component specifications.
- Retailers and customers register products, provide information regarding maintenance or service events and provide feedback.
- Product embedded information devices (PEIDs) gather product data and send it to a PDKM application where it is made available for use. PEIDs possess data gathering, data processing and diagnosis, data storage, and communication functions. Some examples of PEIDs are on-board computers and RFID (radio frequency identification) tags (Jun et al., 2007).

This transformation has the potential to fundamentally transform the way citizens discard their devices, the ways remanufacturers and municipalities offer services to citizens, and ultimately, the way recycling infrastructure in cities will be managed. For example, Yang et al. (2009) have discussed how product lifecycle data enable preventive repair and maintenance services. Another example is when the feedback from recycling experts and service providers can return back to designers since the information flow is not interrupted after the product sale

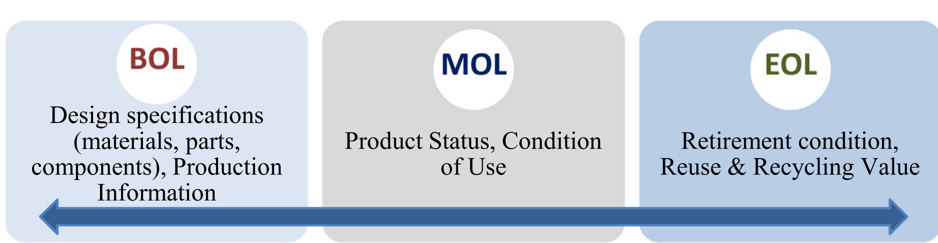


Fig. 4. Three main phases of product lifecycle and data available in each phase.

(Yang et al., 2009). These solutions will also present cities and manufacturers with opportunities in terms of on-time collection, governance and environmentally viable handling processes.

Current advancement in Blockchain and computing technology makes it possible to create decentralized shared PLM platforms among various users in the supply chain to facilitate the exchange of information between different stakeholders while satisfying data security and anonymity. It should be noted that the design and architecture of PLM systems should be defined based on *novel business models* (e.g., selling a service rather than a product, a sharing, and circular economy) rather than conventional business models. Element 2 of the proposed approach explains this aspect further.

5.2. Element 2: Novel business models: connected and involved citizens to share products and service for waste prevention

5.2.1. New business models

Bélissent (2010) discussed the importance of considering new business models to ensure the long-term viability of smart city projects. Kuk and Janssen (2011) discussed two different models of SCs in the Netherlands - in one case business models precede the information flow and data architecture and in the second model, the opposite direction is adopted. While the former model creates business value faster, the latter is more resource-intensive and relatively slower in bringing value to the general public.

To define a company's business model, four main questions should be answered (Boons and Lüdeke-Freund, 2013; Osterwalder and Pigneur, 2010; Frankenberger et al., 2013):

(1) Value proposition: *what* is the service or product offered by the business
(2) Value creation: *how* is the value created (e.g. processes, activities, supply chains)?
(3) Value delivery: *who* are the customers?
(4) Financial models: *why* is the value offered? What are the costs and benefits?

To fully adopt the capabilities of product lifecycle data platform, a new series of business models based on the concept of extending the product lifecycle and closing the product lifecycle loop are needed. The architecture and framework that is for the collection of product lifecycle data should be based on sustainable models of the economy such as the *economy of sharing* and the *circular economy* (CE) that not only cover the business aspect but also environmental and social aspects.

The sharing economy and smart societies are hands in hand concepts. The spread of intelligent technology and connectivity of digital devices make it feasible for communities to advance the concept of the sharing cities (Schaffers et al., 2011). An economic model in which the supply and demand sides are in immediate contact, mainly through some online platforms, is defined as the sharing economy (Zervas et al., 2014).

In the sharing economy model, since the supply side directly provides services or products to the demand side, the transaction costs are often limited. In the majority of sharing economy models, users can play the role of either the supply or demand side. In addition, the entity under trade is often 'access to service' rather than 'owning the good'. The population density and the resources constraints favor economic models that are based on shared resources (Gori et al., 2015). The sharing economy is also known as *Collaborative Consumption*. Hamari et al. (Yang et al, 2009) conducted a survey and reported that sustainability concerns, enjoyment to participate, and economic gains are motivating factors behind people's participation in the sharing-based business models.

The vision of SCs developed in this study is to promote the concept of sharing economy with the aim of waste reduction and extending product useful life. The scope of sharing could vary from sharing of resources and infrastructure to sharing of services, experiences, goods, and capacities (McLaren and Agyeman, 2015). Cohen and Muñoz (2016) categorized 18 potential sharing activities under 5 groups of energy, food, goods, mobility and transports and space sharing, where each of these five groups represents a new form of consumption production system and requires its own planning. Since the concept of waste management is closely connected to sharing food and goods, it is expected that sharing goods and foods highly influence the waste generation rate. To assure that the economy of sharing will result in a sustainable city, an optimal cooperation between private and public business models are needed to remove the conflicts between the objectives of service providers and local governments (Cohen and Kietzmann, 2014). According to Jenks and Jones (2009), people have different interpretations of a sustainable city, however, there is a general consensus of opinion, and common basic themes such as energy conservation, reuse and recycling efforts, and communication and green transportation that inform sustainable development efforts in a city.

Another economic model that will be the focus of the proposed framework is the circular economy concept. Favoring the circular economy is one of the six priorities highlighted by GDF SUEZ, a French utility company, for developing a sustainable city (Hall, 1988). While the concept of sharing economy is quite new in the literature, the circular economy model has been the point of attention for almost a decade (Fig. 5).

The concept of CE was originated in industrial ecology in 1970s, with the aim of adopting the concept of resource cycling that exists in the natural environment in industrial systems to improve the performance of such systems and reducing the need for the extraction of more resources by closing the product lifecycle loop and promoting reuse and recycling of resources (Preston, 2012). It is expected that a smart city will perform based on the principles suggested in a circular economy.

Traditional views to the circular economy, including many design methodologies in the design for X domain, largely focus on improvement of end-of-life recovery activities such as disas-

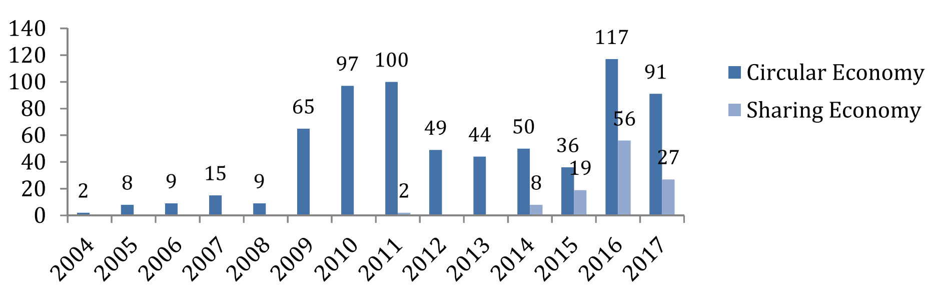


Fig. 5. The number of publications found in Engineering Village, Compendex, Inspec, NTIS, GeoRef and Knovel databases till July 2017 with titles including the term "Circular Economy" or "Sharing Economy".

sembly (Harjula et al., 1996) remanufacturing (Nee, 2015) and recycling (Gaustad et al., 2010), but fail to comprehensively consider the complete product lifespan, and the business opportunities that exist early on at the end-of-use stage. Although recycling has received a lot of attention in the circular economy domain, the circular economy is more beyond that just material recovery (Park et al., 2010b). The true success of a circular economy depends on new business models that extract the actual value that still is embedded in products. Examples of those business models are selling high-quality long-lasting products, selling a combination of short-lived and durable products, and selling service rather than products. The success of these business models depends on many factors ranging from the efficiency of supply chain and brand reputation to product design strategies (Roos 2014).

Kirchherr et al. (2017) reviewed different definitions of CE and commented that CE is sometimes mistakenly regarded as recycling and reuse efforts rather than a systematic shift in economic systems. In addition, the role of consumers and business models are often ignored as the main enablers of the CE. Ghisellini et al. (2016) discussed that CE has been emerged to provide a balance between three pillars of sustainability and to decouple environmental pressure from economic development. Witjes and Lozano (2016) also highlighted that CE has been proposed to cover the social and economic aspects of sustainability and to overcome the limitations of sustainable development efforts that were mainly focused on environmental issues. They emphasized on the need for new service-oriented business models and mentioned the collaboration between different stakeholders as a basis for developing service-oriented business models towards CE. Bocken et al. (2016) pointed out the role of both business model and product design strategies on the move to a CE in three aspects of slowing product loop (e.g. extending product lifecycle), closing the loop (e.g. reuse, refurbish, recycle), and narrowing the loop (e.g. less resource use). Hollander et al. (2017) also emphasized on the role of product design in the transition from a linear to a CE system, supporting new CE strategies, and business models. While manufacturers and businesses can benefit from new design strategies, which result in repairable, durable, and longer-lasting products, they rarely adopt these types of design policies. Instead, design for limited repairs and short-lived products are often adopted by businesses with the aim of increasing future demands and renew purchases (Cooper, 2004).

To alleviate the above-mentioned challenge on planned obsolescence by manufactures, one of the most pressing areas of research in need of exploration is the connection between business models and design for lengthening product lifespans strategies. For example, the possibility of adopting design-for-repair strategies in a business context and the associated consequences on business profitability has remained largely unexplored (Bakker et al., 2014). While a significant number of marketing studies have focused on how and why consumers choose to buy new devices, relatively little research has focused on consumers' usage and disposal behavior generally and repair specifically. Therefore, the business outcomes of eco-design policies require more attention in the literature.

Lieder and Rashid (2016) reviewed the CE literature and mentioned that businesses have been reluctant to adopt CE sufficiently since they still do not find sustainable development policies as economically viable solutions. They commented that the need for support infrastructure, collaborative business models, and ICT are among the factors needed for implementing CE strategy. Park et al. (2010a) studied economic growth and environmental challenges facing businesses in China and pointed out that the use of technological and evolving innovative practices is a feasible way to add value to organizations in moving towards CE. Halstenberg et al. (2017) emphasized on the role of product lifecycle data, and information sharing platforms such as Product Data Management (PDM) systems, and Enterprise Resource Planning (ERP) systems on facilitating the exchange of by-products between different organizations involved in industrial symbiosis. Often ERP systems connect different entities within one organization, we need to extend the concept of ERP to the entire supply chain and create an integrated system for the whole product lifecycle. The Blockchain technology is a promising approach for making this objective a reality.

Since one of the priorities of CE efforts is to reduce the waste and keep products at their highest value, product service systems as outlined in (Tukker, 2015) and sharing economy seem to be promising solutions toward CE. According to a report by Macarthur foundation (Kirchherr et al., 2017), a number of factors put cities well positioned to drive CE efforts including a high concentration of resources over small geographic regions, large-scale markets for new business models, opportunities for local governments to implement CE related policies, and infrastructure equipped with digital technologies such as geo-spatial information and asset tagging.

Zink and Geyer (2017) has questioned the core concept of CE and pointed out the rebound effect of CE in which the energy consumption of closing product lifecycle loop in some cases is higher than a primary production, and can offset the benefits of CE. Along similar lines, Haupt et al. (2017) discussed the concepts of closed- and open-loop collection and recycling rates and mentioned that recycling rate is not a proper performance indicator for a CE system.

To sum up the discussion on new business models, we should note that different business models offer different opportunities for value creation and resource utilization. For example, collaborative business models enhance companies' ability to build partnership, service-based business models increase manufacturers ability in accessing and controlling an equipment along its entire lifecycle as well as accessing new customer segments, cloud-based business models enables businesses to tailor products to individual demands, sharing economy models increase the cost-efficiency of the process and help companies focus on individuals as service providers, and finally circular economy approach enables companies to optimize their value-creation processes. Overall, the proposed framework in this paper supports manufacturers' value-creation processes by offering capabilities for making the product lifecycle more transparent through both data collection and analysis efforts.

5.2.2. The economic reasoning for the implementation of SC and CE strategies

An important question should be answered as if a circular economy or similar sustainability-related models are economically viable business models, then why companies still have not adopted the potentials of such model sufficiently (Planing, 2015)? In this section, we briefly review the motivation of key stakeholders to implement these models.

It seems that the principles of CE are not well integrated into different elements of business models. Perhaps, the most important impediment towards adopting sustainable practices is for organizations to identify business outcomes of such practices. Sarkis (2009) has emphasized the importance of helping companies identify a business case for their sustainability practices. He provided several examples of venues where businesses can gain value from sustainability practices. (1) cost reduction, (2) continuity of business and availability of resources, (3) new revenue lines (e.g. alternative uses of wasted materials and byproducts), and (4) brand reputation and legitimacy are examples of business outcomes for sustainability efforts.

The rise in raw materials prices, new business models enabled by information technology, and the change in consumer interests to a performance over ownership mindset are other motivations toward circular economy (Planing, 2015). Lacy and Rutqvist (2016) listed resources constraints, technological development, and socio-economic opportunities or empowering consumers as main drivers of a circular economy. According to Lovins et al. (1999), a fundamental rethinking is needed about the structure and reward system of commerce. Businesses should not focus on narrowly improving the eco-efficiency of their processes since it may result in a larger saving of resources in the production of wrong products, in wrong places delivered through wrong business models. Table 2 summarizes several motivations and challenges for businesses to move towards circular economy models.

William McDonough pointed out that businesses should focus on eliminating the concept of waste from every link in their value chains while forming the infrastructure for shared prosperity. He also emphasized that a paradigm shift is needed in the fundamental principles of commerce, where businesses should move beyond the previous paradigm of "How much can I get from how little I give?" to "How much can we give for all that we get?" (Lacy and Rutqvist, 2016).

5.2.3. Citizens' behavior

Consumer behavior is expected to play a critical and difficult-to-predict role in both generation and proper disposal of waste.

An extensive literature exists on understanding and motivating consumers recycling behavior, mostly survey-based analyses identifying influential factors. Examples of factors driving recycling behavior are: monetary incentive (Bucciol et al., 2015), social influence (Goldsmith and Goldsmith, 2011), regulations (Hicks et al., 2005), psychological factors (Oskamp et al., 1991), demographic (Saphores et al., 2009), convenience of recycling (Zhang et al., 2016), personal values (Nordlund and Garvill, 2002), awareness, ethnicity (Culiberg, 2014), and attitude (Huffman et al., 2014).

However, eco-behavior is not limited to only recycling behavior but covers preventive behaviors such as waste avoidance (Sekito et al., 2013), energy conservation (Chen et al., 2011), extending product lifecycle through repair, maintenance (Scott and Weaver, 2014), and other green behaviors such as sustainable consumption, purchase refurbished and used items (van Weelden et al., 2016), consume less, consume locally (Hubacek et al., 2016), and sharing (Hawlitschek et al., 2016) to name a few.

Innovative solutions to control waste require an understanding of consumer behavior and derivation of experimentally validated models that describe this behavior. A considerable number of studies in the social-psychology literature have focused on describing the linkage between pro-environmental beliefs and behavior applying theories such as the *theory of planned behavior* (TPB) (Ajzen, 1991), *theory of reasoned action* (TRA) (Park et al., 1998) and *value-belief-norm* theory (Kollmuss and Agyeman, 2010; Oreg, 2006). While understanding the determinants of consumer behavior has already been the point of interest in literature, and the role of external factors on environmental and recycling behavior is highly analyzed, there is, however, no work on studying the role of external factors related to IoT-based business models on motivating consumers' participation in waste management practices. Further, there is no integration of design-for-consumer participation in waste reduction and recovery into SC literature.

Table 2
Motivations and challenges for circular economy strategies and smart city models.

Motivations for moving towards circular economy
• Resource constraint and rise of commodity prices • Change in consumer mentalities toward performance-based business models than ownership • New socio-economic opportunities • Changes in the structure of value chains and shared prosperity • Technological development • Laws, regulations, consumer and producer responsibility • Brand reputation and legitimacy
Barriers towards the successful implementation of CE
• Insufficient infrastructure for advanced technologies (Su et al., 2013) • Poor enforcement of legislation (Zhijun and Nailing, 2007) • Insufficient public participation (Liu et al., 2009) • Lack of sufficient performance indicators and internationally recognized CE indicators (Geng et al., 2012; Geng et al., 2009) • The lack of a standard process of data collection and analysis

The understanding and prediction of human behavior play a critical role in managing services offered in smart communities and is a prerequisite for environmental solutions. Prediction of citizens' behavior mainly relies on the collection and analysis of personal data. While data collected from citizens are essential in improving the quality of services offered in smart communities, the individuals' data privacy and citizens' right remain a challenge in smart societies (Martucci et al., 2017).

In addition to the uncertain behavior of citizens, prediction of citizens' behavior is difficult due to the point that people do not make decisions based on maximizing the utilities. Individuals' decision-making is often based on heuristics and rules of thumb rather than rational decision-making (Gigerenzer and Selten, 2002).

The need to address the environmental-based behavior of consumers is not something new. In fact, addressing environmental-based behavior has a long tradition, particularly in social psychology (Oskamp, 1995) where it is accepted that sustainability initiatives cannot succeed without conscious pro-environmental behavior on the part of individuals (Oakley and Salam, 2014).

Research on green behavior has also applied established theories and models to analyze the pro-environmental behavior of individuals. *The oldest and simplest models* of eco-behavior advance a linear connection between environmental knowledge leading to awareness and concern (recognized as environmental attitudes), resulting in pro-environmental behavior (knowledge → attitude → behavior). The assumption behind these rationalist models is that educating people on environmental issues will directly result in more pro-environmental behavior (Kollmuss and Agyeman, 2002). This is the same assumption that still is used by governments and environmental NGOs to improve the public sustainable development. While much research shows a significant association between attitudes and consumer green behavior (Zhihua and Bo, 2010; Hansla et al., 2008), available research on the *theory of planned behavior and reasoned action* suggests that attitudes translate into actual behavior only if all influencing factors are favorable (Zhao et al., 2014; Ajzen, 1991) such as consequences and norms.

The discrepancy between holding pro-environmental attitudes and actual commitment to pro-environmental behaviors is referred to as the 'value-action' gap (Young et al., 2010). According to TRA, the person's relative strength of intention to perform a behavior depends on her/his attitude about the consequences of the behavior and how he thinks other people will view the behavior if they performed the behavior (recognized as social norms). Although TRA and TPB have extensively been employed in the literature, the underlying assumption behind these theories is that people act *rationally* and neglect unconscious motives.

Applying this assumption, many studies (including those in the environmental behavior area) have modeled consumer behavior as an optimization problem wherein behavior is fully explained by individuals maximizing their expected utility (Welsch and Kuhling, 2011; Chorus et al., 2013). However, assuming individuals as fully rational acting in a self-regarding manner, has certain limitations. In fact, when decisions are complex, the decision-making process is constrained by available information, time limitations, and cognitive constraints. Therefore, consumer choice generally deviates from perfect rationality (Gsottbauer and van den Bergh, 2011). A large body of evidence has been amassed in the literature which runs contrary to the perfect rationality and self-interest assumptions of TRA and TPB. Indeed, a range of theories have been developed to explain individuals' "*bounded or limited rationality*" including evolutionary theories such as the theory of constrained behavior by Heiner (1992), the theory of bounded rationality by Simon (1953), and prospect theory (and various heuristic processes) suggested by Kahneman and Tversky (1979). Specifically, prospect theory has been offered as an alternative to Neumann and Morgenstern's expected utility theory (Neumann and Morgenstern, 1944).

Many patterns of human judgment and decision-making under risk and uncertainty which differ from the rational choice expected utility theory, can be described through cognitive biases (Rachman, 1997). Biases are tendencies or cognitive shortcuts (heuristics) which individuals employ and which arise due to the mind's limited information processing capacity, social norms, etc. (Tversky and Kahneman, 1974). Two decades of research in this area have created a substantial list of cognitive biases (Kahneman, 1991) such as information framing, loss aversion, hindsight bias, overconfidence bias, base-rate neglect, representativeness/availability heuristic, and anchoring/adjustment heuristic, to name a few. To provide a few brief examples, research in the area of information framing has shown that subjects' choice among alternatives is affected by the way a problem is described, or even by whom the situation is described (Malenka et al., 1993), meaning that subjects may draw different conclusions from the same piece of information depending on how the information is presented. Loss aversion research has demonstrated that "the disutility of giving up an object is greater than the utility associated with acquiring it" (Kahneman, Knetsch, and Thaler, 1991). Anchoring and adjustment research has shown that human beings tend to rely too heavily on the first piece of information they receive and insufficiently weight subsequent information (Chapman and Johnson, 1994). Many real-life environmental-related decisions involve ambiguous information about risk. For example, protection against climate change (Yang et al., 2014), utilization of different energy sources (Viklund, 2004), and risk of purchasing refurbished products. Understanding cognitive biases and evolutionary theories of bounded rationality can help to explain consumers' seemingly irrational decision-making processes in such domains.

For all the above-mentioned reasons, the decisions made by citizens and the human behavior are hard to predict. Therefore, the rules and plans to operate smart communities with the ultimate purpose of waste reduction and value recovery are difficult to determine.

5.3. Element 3: Intelligent and sensor-based infrastructure for proper separation and on-time collection and recovery of waste

Element 3 is similar to the city-wide IoT-enabled waste management infrastructure discussed in Section 3. As highlighted from the literature, the infrastructure for waste collection are mainly focused on installing a set of data acquisition sensors in garbage bins with the aim of detecting the garbage level. The municipalities and waste collection service providers will have the option to track weight and identity of trash bins for each individual household and automate service management activities. Global System for Mobile communication (GSM) technology makes it possible to assign a unique ID to each garbage bin. As soon as the bin is full up to a specific threshold value, a notification signal will be sent to an authorized garbage collection vehicle (Bashir et al., 2013; Medvedev et al., 2015; Gutierrez et al., 2015; Patil et al., 2017). Medvedev et al. (2015) highlighted the role of intelligent transportation systems in offering new waste management services.

The IoT-enabled infrastructure is not only limited to smart bins and sensors, but it should be designed as an integrated platform of smart devices, decision support systems, PLM systems described in Element 1 for the sharing and CE-based business models, geospatial technology, transportation systems with real-time data sharing capabilities between service vehicles and drivers, and software packages to run dynamic route optimization and scheduling for waste collection and separation efforts. Smart bins have different applications ranging from tracking missing/stolen bins to facilitating the on-time recovery of perishable food and recyclable materials. However, before implementing smart infrastructure, a cost-benefit analysis is needed to justify the economic rationality behind using smart bins.

The importance of the on-time collection of waste is particularly important for product categories with a high rate of technological progress (e.g. consumer electronics) and a high rate of degradation (e.g. paper). The longer the products are stored and are not returned back for on-time recovery, the lower will be the second-hand market values (Sabbaghi et al., 2015). Furthermore, upstream separation of waste categories will improve the efficiency of downstream value recovery operations.

In addition, it should be noted that recently there has been a considerable advancement in waste treatment technologies, however, the use of ICT within these technologies is very limited due to the high investment cost and the heterogeneity of waste stream (Konig et al., 2015). Product recovery is becoming more dependent on data flows that connect users, products, manufacturers, and remanufacturing infrastructure. Design and operation of efficient recovery sites have come to require product lifecycle data. Opportunities should be explored to allow manufacturers leverage data generated within product lifecycle time to offer demand and supply-side services based on product lifecycle data. The replacement of material flows with information flows improves the sustainability of smart cities (Jin et al., 2014). In the new concept of cities, another input flow to any techno-socio-economic system is a data flow, where the data flow can be used to increase the efficiency of available infrastructures.

To sum up, an integrated infrastructure is needed for proper waste separation, collection, and handling. Al-Hader et al. (2009) suggested that the base for creating a city-wide smart infrastructure is the concept of Enterprise Resource Planning (ERP) in which the existing legacy systems and interfaces are integrated to form one single rich application. They suggested a list of required elements for an operational GIS connected with the available utility networks to develop a standardized geospatial data model. However, we should acknowledge that a comprehensive cost-benefit analysis is needed to provide suitable data for the evaluation of the infrastructure and the extent that the proposed infrastructure should be implemented.

6. Example: The use of tracking and data sharing technologies to identify e-Waste paths

While the unavailability of data on SC practices and their cost-benefit analysis in general and waste management in particular limits our ability in proving the full feasibility of the proposed concept, this section provides an overview of the previous work of two of the authors in the use of tracking technologies to collect product lifecycle for making waste management more transparent. The emphasis is on tracking individual electronic waste items and the way the tracking information will reveal helpful information about the lifecycle of each individual product towards policymaking and proper recovery operations. First, we give an overview of challenges in handling e-waste and then will discuss how tracking and data sharing technologies would enable manufacturers, city officials and policymakers with valuable information on identifying e-waste problems.

6.1. E-waste flows and the corresponding challenges

E-waste is one of the most complex pollution problems and the fastest-growing waste streams reaching an all-time high of 41.8 million metric tons worldwide in 2014 ("Discarded Kitchen, Laundry, Bathroom Equipment Comprises Over Half of World E-Waste - United Nations University" 2017). The terms Waste Electrical and Electronic Equipment (WEEE) or e-waste are commonly used to refer to old electronics (e.g., laptops, PCs, cellphones, solar panels, wearables) that are obsolete or no longer wanted by end users (Bhuie et al., 2004). E-waste is a great cause of concern due to its high volume and the value and toxicity of materials it contains (Cairns, 2005).

Despite the importance of e-waste removal chains, the actual path that electronic and household hazardous waste travels is complex and poorly understood. A significant portion of e-waste generated in developed countries is exported to developing countries for recycling and/or disposal (Perkins et al., 2014). Although the current trade data between countries do not enable an accurate estimation of e-waste flows (Commission for Environmental Cooperation, 2016), it is estimated that Asian and African countries are the final destinations for recycling and disposal of approximately 75–80% of the global e-waste generated (Perkins et al., 2014), and at least 50% of the US e-waste (BAN and SVTC, 2002; Kahhat et al. 2008).

E-waste exports result in an economic loss for the exporting country as well as severe environmental pollution and human health issues in the developing world in exchange of some economic gains (Wang and Gaustad, 2012; Kahhat and Williams, 2012). While the toxicity of e-waste materials is of enormous concern, illegal export has significant economic consequences (Lepawsky and Billah, 2011) since a big portion of e-waste is often recovered informally by burning or using of acid baths resulting in the recovery of only a few materials rather than the full value embedded in used products. The complexity of actual paths that electronic and household hazardous waste goes through and the resulting value leakage are poorly understood. Currently, for various economic reasons and due to existing laws and regulations, end-of-use products go through a chain of additional movements with unclear patterns and causality with poor visibility.

There is no transparency about the flows of e-waste within the US, so there is no comprehensive estimation about the portion of e-waste that may end up in formal recycling centers versus the portion that is exported, even for those products collected through formal channels. Travel distance, final fate, resulting value leakage, and network topology are examples of other unavailable information.

The opportunities that e-waste provides for recycling of rare earth elements, the growing rate of e-waste in smart cities, and the complexity of handling e-waste compared to other waste streams are other reasons behind selecting e-waste as a case study. According to Cossu and Williams (2015), e-waste is the backbone of urban mining due to its potential for recovering critical materials.

The next section describes the use of tracking technologies for facilitating the identification of e-waste paths, as one sample of waste management problems.

6.2. Tracking and data sharing technologies for increasing the visibility of E-waste paths

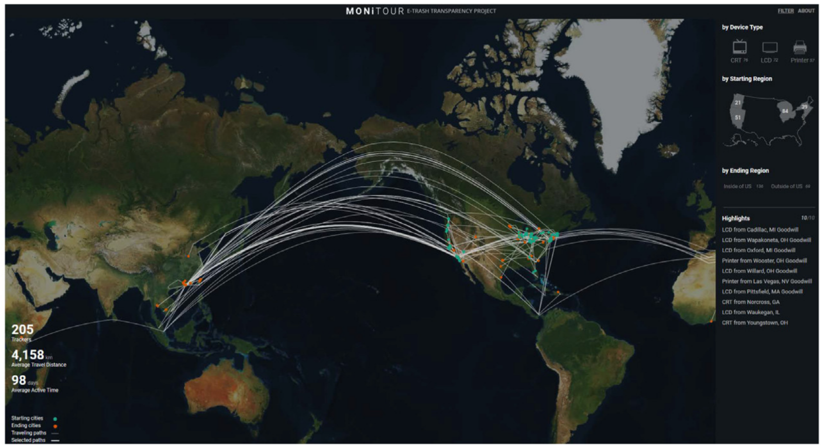
The use of tracking devices has been common in biology for understanding the life of wild animals. Recent advances in tracking technologies have enabled biologists to track animal movements in near real-time (Robinson et al., 2017). One example is Mary Lee, a 1500-kilogram white shark that was tagged with two tracking devices in 2012 and even has her own Twitter account, where her locations are reported to her 36,000 followers when she makes surprising movements in different locations (Tibbetts, 2017).

Advancements in location-enabled tracking technology are bringing us closer to understanding the global flows of e-waste. It should be noted that the nature of tracking devices is different from tracking animals in several aspects: first, biologists often see heterogeneity in migration routes taken by animals, yet such patterns cannot be expected from electronics due to the variability in product types, lack of recycling infrastructure, and locations of second-hand markets. Second, animal body masses often limit the possible tracking technologies. However, except for certain types of electronics, the rest can be equipped with current tracking technologies available in the market.

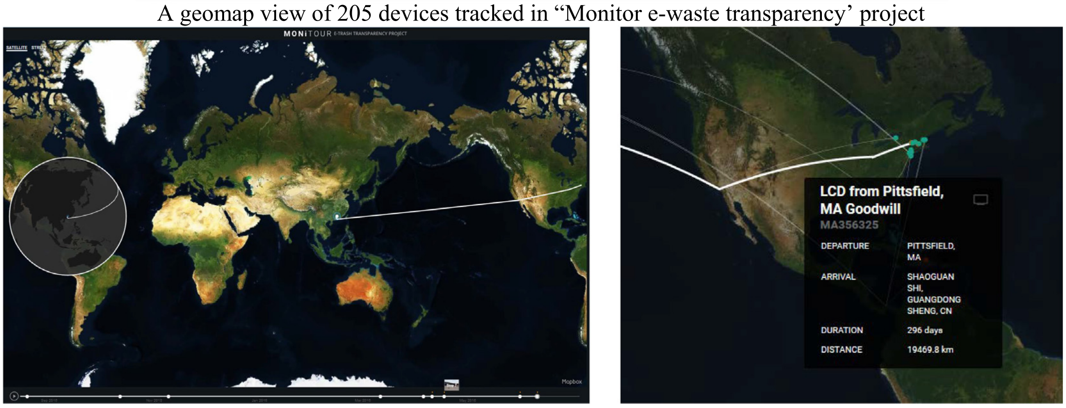
Several studies have shown the potential application of tracking technologies to prove the e-waste export problem. The tracking of broken television sets using GPS tracking devices in a project by Greenpeace International Group revealed the illegal efforts of UK formal recycling sectors by selling outdated items as second-hand devices to developing regions and violating EU regulations. Another study was by Offenhuber et al. (2012), where they installed GPS sensors on 2000 discarded items from 12 different waste categories in the city of Seattle to observe the movement of municipal solid waste. They found that among the solid waste, e-waste items have more random trajectories and travel considerably longer, where they have received some sensor reports from Mexican border and British Columbia regions. Interestingly, the longest travel distances were reported for products that are either valuable or valueless such as e-waste and hazardous wastes. Their analysis revealed that over 95% of the targeted trash reached to a proper end destination, but e-waste and hazardous waste did not follow the best practices.

In another study, the Basel Action Network (BAN) in a joint project with the MIT Senseable City Lab tracked certain types of electronics dropped in charities and recycling sites and showed the export of e-waste from the US to other countries, mostly Asia (Basel Action Network, 2017). The ability to track the transportation routes of electronic equipment has provided crucial information about where the used electronics end up depending on their origin (trash bin, take-back programs, and collection events) and how they recover outside of Original Equipment Manufacturers (OEMs) hands. Lee et al. (2018) illustrated that smartphones can be modified to last for more than three months to serve as affordable location trackers. Complementing the tracking of the devices, a team of researchers visited some of the sites where the e-waste ended up and confirmed that they were not recycling sites, but rather a combination of informal facilities and dump sites (OPB/EarthFix, 2016; UrbanNext.net, 2016). Fig. 6 shows an overview of the data collected in the "Monitor E-waste Transparency" project. Readers are referred to Lee's PhD dissertation as a reference for the details of deployments made in this project (Lee, 2015).

Although the example provided in this section does not fully fit into the three elements proposed in the framework, it shows the feasibility of applying sensor-based tracking technology in waste management issues.



A geomap view of 205 devices tracked in "Monitor e-waste transparency' project



Overview of an LCD monitor transporting from Pittsfield, MA to Wengyuan, China (total travel distance: 862 km, travel duration, 296 days)

Fig. 6. Examples of a map generated from the e-waste tracking project [Ref: http://senseable.mit.edu/monitour/].

7. Success factors for implementing the proposed framework

A considerable number of studies have been focused on suggesting methods for measuring SCs performance. A team of experts who jointly led the European Smart Cities project have discussed that the relative progress in 6 dimensions of governance (democratic processes), citizens (education), environment (energy and resource consumption), transportation, economy, and living (social and health services) determine the level of smartness of cities (Steinert et al., 2011). Several metrics have been suggested to help cities access their performance in obtaining both smart and sustainability goals. The maturity model developed by the British Standards Institute (BSI), standard indicators for city services and quality of life offered by the International Standards Organization (ISO) and the IDC Smart Cities Maturity Scape are examples of most widely adopted approaches (Clarke, 2017).

There are a number of enablers at work to increase the success of SC initiatives including efficient infrastructure, social and human capital, cultural participation, regulatory incentives, and proper management. The successful implementation of the proposed framework for waste management depends on too many factors. Some of those factors are listed in Table 3 under five main categories of data, technology, economy, the social aspect, and governance. Most factors would hold for SC projects in general, but some are more important for waste management practices in particular.

The amount of waste generation rate in a city is an indicator of the system design and operational inefficacies in the city's urban management system. For example, insufficient access to local markets, and inefficient waste collection infrastructure may influence product purchase and disposal behavior of consumers. Therefore, waste generation itself is often a good test of a society's sustainable development compliance. It is unlikely that SC alone provides all the necessary elements for proper waste management practices. While intelligent devices can unlock the circular economy potentials (Ellen MacArthur Foundation, 2016), other factors such as

Table 3
Examples of success factors of waste management practices in SC.

Aspect	Factors
Data	Automatic product lifecycle data collection Real-time data analysis Data-driven decision making Data sharing, open data Data security and citizen privacy (Martínez-Ballesté et al., 2013)
Technology	Intelligent & connected devices (Lombardi et al., 2012), new data acquisition and communication technologies Resilient infrastructure Standardization of technology (Kogan and Lee, 2014)
Economy	Novel business models Sharing economy, circular economy models
Social aspect	Citizens participation, green behavior Smart collaboration among stakeholders (Chourabi et al., 2012) Technologies compatible with local culture Reward-based systems
Governance	Strategic planning Non-governmental parties involvement (Nam and Pardo, 2011b) Laws and regulations compatible with circular economy concept

innovation, creativity, cultural change, and value-creating thinking are needed to pair the circular principles and intelligent assets.

Overall, implementing the proposed framework requires a high degree of collaboration among different stakeholders involved in the entire product value chain. While developing an integrated database might not be an issue by itself, convincing different players to invest efforts in on-time data collection is a challenge. Therefore, not only different players need to realize the business and sustainability outcomes of such platform but extensive efforts are needed to alleviate political, legal, and commercial barriers towards this integrated process. However, as we move forward to an Industry 4.0 era, it is expected that cloud-based business models are well regulated and better equipped with strategies for handling legal and commercial barriers such as intellectual property and data security. In addition, new business models emerging from big data initiatives help manufacturers realize the business opportunities of product lifecycle data.

An effective waste management requires implementation of best practices, not just atomization of existing practices. In addition, waste management approaches should be compatible with citizens lifestyle such that they do not reduce the flexibility in social life while reducing the waste generation rate and increasing citizens life customizations. It is expected that embedded sensors, data collected from them, and resulting real-time analyses move citizens toward sustainable behavior and serve as agents guiding environmental behavior. This requires further analysis of the role of different factors ranging from socio-demographic of citizens to individual conditions of the region. For example, municipalities need to consider different calendars and schedules for waste collection depending on the volume, type, and timing of waste generation in each neighborhood.

The number of case studies that investigated the idea of SCs as a new solution for sustainability purposes is limited. To name a few, Solano et al. analyzed three Spanish smart cities based on their sustainability strategies and concluded that governance, environmental management, citizen participation, and entrepreneurship are among the success factors in SCs (Solano et al., 2017). Mosannenzadeh et al. (2017) studied the implementation of an energy development project in the city of Bolzano, Italy and provided a framework to help urban planners measure the similarities and differences of their projects with previously implemented projects. Nijkamp and Perrels (2014) provided an overview of energy and environmental planning in 12 different European cities and concluded that inertia or the lack of resilience is a common element of urban change processes.

According to Dameri (2017), although the existing practices help independent institutions to measure the degree of technical infrastructure implemented in cities, the number of existing practices to really verify the actual impact of current smart programs on the quality of life of citizens is very limited. Lee et al. proposed a framework for analyzing the implementation of SC concepts in three cities of San Francisco, Amsterdam, and Seoul Metropolitan City. Six key conceptual dimensions including urban openness to enable citizen-driven innovation, service innovation, partnership, urban proactiveness, integrated infrastructure, and effective governance structure are recommended dimensions for SC evaluation (Lee et al., 2014). Lessons learned from the initiatives taken by the existing smart cities (e.g. Singapore, Barcelona, London, San Francisco and Oslo) can be used as guidelines for other cities putting long-term investments into SCs and the future of waste management.

8. Concluding remarks

The paper provides a review of existing studies on IoT enabled waste management practices and offers a conceptual framework for overcoming the current gaps in waste recovery. It discusses that the transition of SCs into zero-waste sustainable cities requires four inter-related primary strategies - waste prevention, upstream waste separation, on-time waste collection, and proper value recovery of collected waste. The aim is to envision the design and development of an IoT-enabled waste management framework for smart and sustainable cities with particular emphasis on connecting waste management practices to the whole product life-cycle.

The proposed framework rests on three core elements: (1) collection of product lifecycle data, (2) new business models based on connected and involved citizens for sharing products and service information to avoid waste generation, and (3) an intelligent sensor-based infrastructure for on-time collection and separation of waste to assure effective waste recovery operations. The first and second elements aimed to prevent waste, and the third element aimed to improve the efficiency of waste collection and recovery operations. The novelty of the proposed framework resides in the paradigm shift toward reducing waste and extending product lifecycle -- by defining a smart and connected infrastructure for the sharing and circular economies as well as by increasing the efficiency of waste collection activities. While the availability of product lifecycle data can support decision making at the end of life phase, the required infrastructure for collecting such data requires further studies.

An example of the use of data sharing technologies in e-waste management has been discussed to show the application of monitoring the lifecycle of individual products on a better understanding of the waste generation and recovery patterns.

Future work will improve this framework by taking a closer look at the effects of other factors such as regulation, policy, product design strategies, and technology on waste management. In addition, the proposed framework has taken a broad look at waste management and the issues emerging in this field. However, different waste types have different characteristics and management systems, sometimes not compatible with each together. The proposed product-lifecycle framework should be tuned and elaborated to be used based on the scope, needs, and boundary of each waste types. Furthermore, the proposed framework needs to be validated with real-world case studies to test the value of having access to product lifecycle data in solving waste generation and recovery issues in different regions and countries.

To conclude, some thoughts on future research directions in waste management context are summarized here under three categories of objective, effects of emerging technologies and enabling factors.

Objective: Traditional views to waste management, largely focus on improvement of waste collection efforts, but fail to comprehensively consider the *complete product lifecycle* and the circular economy opportunities exist over the entire product lifecycle. Waste management efforts should be focused on identifying value chains rather than waste removal chains. The purpose of waste collection and recovery infrastructure should not only be focused on automatizing existing processes, but rather on *implementing best practices* with the aim of creating values. Therefore, accessing the city needs and requirements is a required step before making a decision about the type of technology that should be adopted. Although sensor-based technologies and CPS have received sufficient attention in the SC domain, future cities are more beyond just high-performance technologies. The true success of SCs depends on *new business models* that extract the actual *value* that new technologies offer. In addition, the concept of waste in smart communities requires a *new definition*. It should go beyond just materials and cover all resources and values embedded in the system including materials, human capital, time, and efforts. It is expected that a smart city moves toward the elimination of all non-value added activities and resource.

Adversary effects of emerging technologies: While the concept of SC proposes to apply various sensor-based computing capabilities across mobile devices to encourage green behavior among consumers, the *adversary effect* of such adoptions is not clear yet. It is critical to understand in what ways do the SC influences the implementation of sustainability initiatives. While SCs are potential sites of breakthrough innovations, they are centers of resource use, electronics, and smart infrastructure that should be managed properly. While employing the concept of information flows can have a huge potential to reduce the uncertainties pertaining to the amount and quality of waste generation rate and makes planning operations more effective, it is important to acknowledge the potential of rebound effects and the *role of smartness in generating more uncertainties* as a result of making technology available to citizens as complex social-behavioral systems.

Enabling factors: An extensive research with contributions from across the fields of urban planning, economics, social science, engineering design and computer science is needed to fully understand various elements of an integrated waste management platform with the final vision of creating value rather than controlling waste. The design of a practical waste management concept requires *collaboration* among a multidisciplinary team of designers, behavioral scientists, computer scientists, consumers, civic society members, city leaders, manufacturers, recyclers, and remanufacturers. In addition, as new smart concepts are emerging for handling waste management practices, new sets of *environmental standards*, laws, and regulations should be developed to assure the quality of features established in smart infrastructure. In addition, future waste collection and management infrastructures should inter-operate with existing systems. The connection and *inter-operability* will facilitate the integration of waste management practices with other activities within smart communities.

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