End-users’ requirements underpinned by IoT layered architecture to the development of smart sustainable cities

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Abstract: It has been claimed that the adoption of a smart and sustainable city concept is one of the most effective ways to eliminate the risk of unsustainable living. Since the sixties, the Kingdom of Saudi Arabia was transformed from a country of traditional settlements to a modern urban setting. However, this development has been based on conventional methods of city construction and building practices. Therefore, the main aim of this primary research is to establish the fundamental aspects of developing a sustainable and smart city framework that can be applied to most Saudi Arabian cities and societies. A qualitative research methodology is adopted to determine end-user requirements, with more than 500 well-informed participants from 17 different cities. Subsequently, the main contributions here can be summarised as follows: (a) evaluating public willingness regarding smart sustainable city movements, (b) establishing requirements for a sustainable and smart city framework based on end-user perspectives, (c) providing a decision makers with a robust generic framework of sustainable development across Saudi Arabian cities, and (d) an Internet of Things (IoT) architecture for SSC Adoption and implementation along with an integrated socio-organizational, financial, and technical generic framework for smart sustainable city adoption in the Saudi Arabian context.

1 Introduction

In the history of human civilisation, the inhabitants of different lands have employed a variety of settlement modes or styles with cities foremost among these [1]. In the modern world, following successive industrial revolutions, cities are categorised in various ways. The title of this article includes two terms: ‘smart’ and ‘sustainable’, which is necessary to define at the outset, so that the intention of this work is clearly understood. The creation of sustainable cities is a desirable objective for developers and engineers, but to meet this objective, a number of different techniques and strategies must be employed. In other words, a sustainable city is achieved via the implementation of a range of different techniques, such as those of the smart city and compact city [2, 3]. Despite these different categorisations, all of these concepts of a city share a common goal, namely to improve the quality of life of the inhabitants, and to preserve the natural resources for subsequent generations [4, 5]. In the developed world, steps have been taken to establish a target for reducing the use of non-renewable resources. Technology and sustainable concepts play a crucial role in this global movement. The main aim of this study is to explore public views and attitudes regarding the move towards smart and sustainable cities in Saudi Arabia and to identify the socio-economic requirements of the end-users of such cities. The ultimate purpose is to assist with the related decision-making and to enable policy-makers to identify the potential challenges in the Saudi Arabian context, and to act appropriately to manage these challenges.

Research has indicated in [6] that due to the discovery of oil in Saudi Arabia, fossil fuels remain the main driver of the construction boom and urban sprawl in the country. However, there is still a lack of pioneering research regarding the implementation of a sustainable and smart framework for the Saudi Arabian context, as a pre-assessment of Saudi Arabian cities has indicated that the cities have been designed and built unsustainably [7]. However, the government has taken progressive steps by introducing a new era of strategic planning [8] that seeks to achieve prosperity through the creation of sustainable cities and societies. This is illustrated in the Saudi Arabian 2030 Vision, which presents the intention to embrace the principle of sustainable development in every level of the industry. Hence, this study presents literature and research relevant to smart and sustainable cities. It also proposes a new internet of things (IoT)-based genetic framework, which demonstrates the influence of socio-organisational, financial, and technical factors on the design and implementation of smart sustainable cities in the Saudi Arabian context and the built environment in general.

2 Related work

Urban sprawl and population growth are key factors that hinder the development of metropolitan areas worldwide. Recently, many cities have embraced numerous initiatives with the aim of enhancing city competitiveness [9, 10]. It has been argued that the principle of sustainable development, which seeks to establish better environmental, social, and economic circumstances, is an effective solution for improving the quality of living [11, 12]. Therefore, cities must be extensively planned and developed to reach a satisfactory level of sustainable development. Various terms have been proposed to reflect these developments, such as ‘sustainable cities’, ‘green cities’, ‘digital cities’, ‘smart cities’, ‘intelligent cities’, ‘information cities’, ‘knowledge cities’, ‘resilient cities’, ‘eco-cities’, ‘low-carbon cities’, and ‘liveable cities’; and even combinations, such as ‘low-carbon eco-cities’ and ‘ubiquitous eco-cities’ [13]. However, the problem facing policy and decision-makers is that each of these terms comprises distinct concepts, which has implications for how they are expressed and applied to the ground [13].

According to the extant literature, the most common term employed regarding city evolution is that of the ‘sustainable city’ [13]. A sustainable city, by definition, is a city that connects social equity, economic productivity, and environmental quality, to meet the needs of the present, without compromising the ability of future generations to meet their own needs [7, 8]. The city of Malmö in Sweden is a good example of a sustainable city [3]. As noted previously, the term ‘sustainable’ denotes a broad concept that incorporates many technical aspects under the umbrella of city design and operation. The concept of the smart city is the key to...
this sustainability and seeks to achieve the principles of sustainable development. A smart city can be defined as a safe, secure, environmentally-aware, and efficient urban centre of the future, which employs advanced information and communication technologies (ICTs) to stimulate sustainable development in its economic growth, and to promote a high quality of life for its inhabitants [9]. According to the International Electrotechnical Commission, a smart city can be defined as one in which the improvements to the quality of life, services, sustainability, and resilience are accelerated by the effective integration of physical, digital, and social systems, together with the transformative use of data and technology. Therefore, the two terms ‘smart’ and ‘sustainable’ are often conflated in the extant literature [14, 15]. A smart, sustainable city (SSC), which is generally defined as one that integrates a number of technological aspects to improve the quality of life of the residents is expected to tackle the current problems faced by cities or those they will face in the future, such as those of security, infrastructure protection, and property vacancy. Traffic-related issues, including traffic jams and traffic accidents, are further examples of these problems, and one option for addressing them is via a modal shift, introducing an electric vehicle charging infrastructure.

The way cities are developed and managed is of fundamental importance for sustainable development. Some recent studies have highlighted how ICT can be used to achieve cities’ climate targets by lowering energy use and greenhouse gas (GHG) emissions in other sectors. These initiatives include proposals such as dematerialisation and demobilisation, as well as comprehensive concepts for smart logistics and smart cities [17]. Furthermore, Hilty et al. stated that the ICT can be used as an enabling technology for optimising design, process, operations, commissioning, and decommissioning in different practices and sectors [18]. Nonetheless, IoT is a new concept that has been recently introduced to this area of research [19–21]. This concept, according to Madakam et al. [22], IoT can be defined as ‘an open and comprehensive network of intelligent objects that can auto-organise, share information, data and resources, reacting, and acting in the face of situations and changes in the environment’. Furthermore, the same authors [22] pointed out eight prerequisites to successfully implement IoT that are (a) dynamic resource demand, (b) real-time needs, (c) exponential growth of demand, (d) availability of applications, (e) data protection and user privacy, (f) efficient power consumptions of applications, (g) execution of the applications near to end-users, and (h) access to an open and interoperable cloud system [22]. It requires three main essential components for seamless IoT computing: (a) hardware layer: consists of sensors, actuators, cameras, embedded communication hardware etc. (b) Middleware layer: consists of on-demand storage and computing tools for data analytics with cloud and big data analytics. (c) Presentation layer: easy to understand visualisation tools that can be tailored for the different applications [21, 22].

In 2012, GeSI published a report that focused on the potential for reducing GHG emissions in six different sectors: power, transportation, agriculture, building, manufacturing, and consumer services [23]. Based on a projected business-as-usual scenario in 2020, the study also calculated potential emissions savings in each of these sectors, resulting in an overall reduction potential of 16.5% of total global GHG emissions. However, other studies have indicated significantly lower potentials. For example, Bio Intelligence Service (2008) from [23] predicted a 4.6% decrease within EU-27. The pursuit of a global CO2 reduction target has become a mandatory practice in the developed world. For example: (a) New York in North America has committed to reducing GHG emissions by 30% by 2030 compared with the 1990 level. This target has been set with a particular focus on improving the energy efficiency of buildings through renovations and new construction. (b) Sydney in Southeast Asia and Oceania has established a long-term plan to reduce GHG emissions by 20% by 2012 and 70% by 2030 compared with 2006 levels. To reach this target, Sydney has launched the Sustainable Sydney 2030 vision, which has provided a long-term strategic plan to transform Sydney into a groundbreaking green city. (c) Globally connected London in Europe has also committed to reducing GHG emission by 60% by 2025 compared with the 1990 level, by developing a range of programmes within London that intend to find effective ways of addressing climate change. (d) Iskandar Malaysia in East Asia has pledged to reduce GHG levels by 50% by 2025, by looking beyond the rapid growth of social and economic needs to tackle environmental challenges [3].

In summary, cities are among environmental ambitions and telecommunication industries are seeking to understand how best to apply the smart city concept and utilise ICT to facilitate the reduction of energy and water use. This requires having a better understanding of what types of ICT investment provide the best benefits for the environment and society. Telecommunications industries are also interested in understanding which enabling technologies their customers most need and want. However, the Climate Group [24] noted that different cities have different needs because of their unique challenges. Therefore, a multitude of solutions is required with adjustments made according to specific demands and criteria [25]. In this way, smart city design and operation differ from one region to another, and many factors influence the principal requirements of a sustainable and smart city, such as environmental and economic as well as socio-cultural characteristics [2].

Currently, a smart city can be described by a set of components or domains. A number of research papers have presented the key indicators of a smart and sustainable city. One of the most detailed of these studies was a report carried out by Giffinger et al. [26] using a model with the following characteristics: smart economy, smart environment, smart governance, smart living, smart mobility, and smart people. Each characteristic was described by a set of factors used by both Giffinger et al. [26] and later Cohen et al. [27]. In total, 74 indicators were selected, 48 (65%) of which were based on local or regional data, and 26 (35%) of which were based on national data. In addition, Lazaroiu and Roscia [28] found that it was not possible to identify absolute indicators of smart cities in Europe, as the authors deemed them to be a combination of subjective and objective factors, and argued that it could be misleading to consider smart city indicators as measurable in a single way. However, the study did report a set of 18 common smart city indicators as follows [28]: (1) pollution, (2) innovative spirits, (3) CO2, (4) transparent governance, (5) sustainable resource management, (6) separated littery, (7) education facilities, (8) health conditions, (9) sustainable, innovative and safe public transportation, (10) pedestrian areas, (11) cycle lanes, (12) green areas, (13) production of municipal solid waste, (14) GWh household, (15) fuels, (16) political strategies and perspectives, (17) availability of ICT-infrastructure, and (18) flexibility of labour market [28].

3 Saudi Arabian context

Since 1980, Saudi Arabia has witnessed a significant construction boom and is currently the leading country in the Middle East for construction projects and urban sprawl. The geographical and environmental nature of Saudi Arabia has made this development challenging, as the Kingdom is the world’s 13th largest country by area, with many cities spread across its 13 regions [29]. Furthermore, Saudi Arabia has an extremely hot arid and desert climate except in Asir Province and some cities on the western coast [30]. Oil revenue has historically been the main driver of growth across Saudi Arabian regions and cities. However, the recognition of climate change and global warming influences as well as of the unsustainable practices of the country’s national development plans and advancements has changed many aspects and perspectives regarding the overall development objectives of the Kingdom. For example, the recent unveiling of the Kingdom’s 2030 vision is a clear movement towards sustainable living and green practices. This seeks to diversify the Saudi Arabian economy away from its reliance on fossil fuel revenues [31].

The construction industry is a key contributor to meeting the objectives of the Saudi Vision 2030, as the Ministry of Municipal and Rural Affairs has proposed a number of different initiatives to
accelerate the fulfilment of the national transformation plan objectives [32]. The fundamental goal of these initiatives is to improve urban development in Saudi Arabia via the application of sustainable, green, and smart city strategies, and also to raise the level of citizen satisfaction and increase city competitiveness and urban development [33]. In addition, the transformation plan has been established to cover wider aspects of city management, such as minimising negative environmental impacts, improving economic factors by attracting local and foreign investments, and creating more opportunities for job seekers [8].

These initiatives will be directed and carried out through multiple phases in partnership with the private sector, targeting five Saudi cities by 2020. Incidentally, a recent study conducted by the Ministry of Municipal and Rural Affairs examined 17 major cities, which accounted for nearly 72% of the Kingdom's total population. The outcomes of the study revealed an inconsistency in the cities' preparedness to transform into smart cities. For instance, Makkah City was the leader of those looking to embrace the smart city concept, followed by Riyadh, Jeddah, Madinah, and Ahfa [8, 33].

The progression of sustainable development in the Kingdom has been stimulated by the launch of a number of global projects such as NEOM, whereby the Saudi government intends to build a capital city that applies all the principles of sustainable development. According to articles published by the Saudi News Agency, the new region will focus on nine specialised investment sectors: the future of mobility, biotechnology, food production, technical and digital sciences, advanced industrialisation, media production, entertainment, the future of water and energy use, and eventually the future of living [34].

4 Research method

This research paper sought to address the following research question: (Q1) what are the key features or criteria that constitute a generic SSC framework that is suitable for the Saudi Arabian context? To answer this question, a qualitative approach was adopted, whereby a systematic review of the extant literature in the field was conducted, alongside a survey that was distributed to Saudi Arabian citizens. The principal phases of the research consisted of (a) conducting a systematic literature review with a significant focus on local and international SSC trends; (b) conducting a qualitative survey distributed to Saudi Arabian citizens; (c) proposing a generic IoT-based framework, based on both the survey respondents’ perceptions, and international SSC practices; and (d) proposing a generic framework for enhancing the development of the social, technical, and governmental aspects of SSCs in Saudi Arabia. Since the SSC movement is a relatively new concept for Saudi Arabian citizens, this primary research should be considered an early phase in the development of applicable models that are intended for use throughout the Saudi Arabian context. The survey employed in this study underwent an evaluative and piloting phase, in which seven academics reviewed the survey and provided feedback. Their insights and contributions were used to improve the academic standing of the survey.

As illustrated in Fig. 1, the survey was designed to obtain the demographic information of the participants and to question what they deemed to be the priorities in embracing the principles of SSCs. A five-point Likert scale was then employed to enable the participants to rate the key features of a smart sustainable city, derived from the literature review, in the form of open-ended questions. Finally, a comment box was provided, to allow the participants to include additional suggestions and comments. The main body of the survey included the key systems, civil infrastructure, and services aspects of an SSC. Fig. 1 illustrates the structure of the survey.

The survey was distributed to citizens in more than 17 different Saudi Arabian cities and/or districts. It was hosted by SurveyMonkey, which generated a web link that was sent to the participants. The snowball and nomination techniques were the main sampling methods employed to ensure the inclusion and participation of well-informed participants from different sectors. The survey was open for five months and collected more than 500 participant responses. It should be noted that the two Saudi national researchers involved in this study possessed a range of resources and information regarding Saudi Arabia cities, the ways in which they are designed, and how they operate, together with good social connections in different cities across Saudi Arabia. It was this wealth of knowledge and resources that inspired the researchers to conduct this qualitative social science study to explore the end-users’ requirements of SSCs in the Saudi Arabian context, and also to determine an appropriate framework that would enhance the establishment of the SSC model in Saudi Arabian cities and society.

5 Findings and analysis

This section presents the outcomes of the consultations (obtained through the questionnaire) and then discusses these findings to identify the end-user requirements for developing a smart sustainable city within the Saudi Arabian environment. As shown in Table 1, the total number of responses obtained was 514. The majority of respondents were aged between 18 and 40, so the results reflect the concerns of young Saudi citizens. Nearly all the respondents came from different cities within Saudi Arabia. All participants had been educated to a high school degree level of higher. Nearly 82.45% of respondents were employed, with 51.02% working in governmental sectors.

Fig. 2 presents the responses regarding important sectors that should embrace the principles of sustainable development and apply smart and modern strategies. It shows that 24% of respondents considered the building sector to be the most important sector for development. This was followed by the wastewater and transport sectors at 20% each. The third most important sectors identified by the respondents were the electricity and telecommunication & internet sectors, with 15% each. The agricultural sector was identified as the least important sector, having been selected by just 3% of the respondents.

Other important sectors identified by the respondents were: environment, education, media, strategic, industrial, municipal, health, construction and buildings, police and traffic, and services. However, the majority of the respondents commented that all sectors are important because regardless of whether they are governmental or private, they should collaborate to achieve sustainability. Moreover, the participants also emphasised that all ministries and agencies, whether public or private, must achieve the smart solutions planned as a result of the views of the country’s government and citizens. Most of the respondents believed that development cannot be deemed to be sustainable unless it encompasses all sectors at the early stages of the planning and development, since planning is the basis of any development, and a country's strategy should be applied regardless of the developmental polarisation across the geographical regions. The respondents also highlighted that there should be cooperation between those involved in municipal and rural affairs, civil defense, and the water and electricity sectors. They believed that
the municipal sector should undertake the general supervision of projects in neighbourhoods, such as the development of restaurants, buffets, slaughterhouses, and roads, as these should be overseen by a sovereign authority with the power to enforce sustainability and environmental protection policies.

Many of the respondents placed a significant emphasis on the importance of the waste management sector, due to the impact of sewage on the environment, including its pollution of soil, air, and water resources, as well as the streets, as a result of large leaks and damage to the asphalt layer, along with its negative impact on public health, and on the appearance of an area. The respondents from an agricultural background stressed the importance of the water sector, due to its impact on the agricultural sector, especially because of the limited regional resources, such as water, and the poor irrigation practices currently employed that engender a general inefficiency in water consumption. However, most of the respondents focused on the housing sector, and the ways in which projects in neighbourhoods, such as the development of parks. In addition, many of the respondents highlighted the importance of the education sector to the successful implementation of sustainable development, as it plays a crucial role in establishing the necessary awareness of the SSC concept.

| Categories       | Responses |
|------------------|-----------|
| age              | <18 0.81% |
|                  | 18–25 20.61% |
|                  | 25–30 14.95% |
|                  | 30–35 17.58% |
|                  | 35–40 18.59% |
|                  | 40–45 9.29% |
|                  | 45–50 6.67% |
|                  | >50 11.52% |
| city             | Riyadh 17.81% |
|                  | Jeddah 9.11% |
|                  | Mecca 2.43% |
|                  | Medina 3.04% |
|                  | Eastern Province 6.07% |
| Northern borders | 0.61% |
|                  | Hail 15.38% |
|                  | Qassim 2.23% |
|                  | Najran 33.20% |
|                  | Jizan 0.61% |
|                  | Asier 3.44% |
|                  | Tabuk 0.61% |
|                  | AlBaha 0.40% |
|                  | Taif 0.00% |
|                  | Alkhij 0.61% |
| Wadi al-Dawasir and al-Sallayl | 0.20% |
| Alqurit | 0.00% |
| Hafr Al Batin | 3.85% |
| Other | 0.40% |
| qualifications | High school 12.37% |
|                  | Diploma 10.95% |
|                  | BA 50.10% |
|                  | MA 16.84% |
|                  | PhD 8.72% |
| job              | Other 1.01% |
| Government sector | University student 17.55% |
|                  | Private sector 19.39% |
|                  | Free business 3.47% |
|                  | Other 8.57% |

Meanwhile, a high number of respondents noted the importance of the inclusion of the health sector in smart, sustainable development via the adoption of advanced intelligent technologies in healthcare and management. Finally, according to the views of various respondents, it is necessary to establish a new sector, such as a smart development sector, or smart sub-departments within each of the existing sectors, which collaborate and coordinate with one another to facilitate the creation and integration of the relevant strategies between sectors.

5.1 Smart practices within a smart building

Fig. 3 presents the average ratings given by respondents to statements regarding smart practices within a smart building. ‘Installation of solar panels to reduce dependence on the electricity grid’ was rated highest with an average score of 4.47. This was followed by ‘the presence of motion sensors to control the lighting in the building and dispense with manual operation’ (4.42), ‘eliminating normal air conditioning and using the air-friendly environment with high efficiency’ (4.4), ‘having an intelligent counter that periodically displays the amount of consumption’ (4.32), ‘the presence of sensors to control the flow of water instead of manual controls’ (4.31), ‘the presence of monitors and intelligent displays to show the quantities of consumption and the quality of life’ (4.30), ‘the presence of monitors and intelligent displays to show the quantities of consumption and the quality of the internal environment of the building’ (4.14), ‘the physical cost of purchasing an electronic program with all its tools is to guarantee the security and safety of the building’ (4.1), and ‘paying more than the usual cost of building a house with high-quality insulated materials’ (4.1). High cost may be a barrier to the adoption of smart sustainable technologies. The government could support the production and development of smart cities so that beneficiaries are not burdened with further construction costs. Most smart practices would be useful if support programmes were provided for the cost of installing and creating them. The government could adopt a modlar system for evaluating buildings and linking support with payment for consumption to comply with regulations. The presence of smart buildings may be effective when established through a comprehensive methodology and careful planning of all elements of the building and thus the district and city.
requirements were related to one of the following sectors: environment and waste management, education, media, industrial and manufacturing, government and municipal, health, city and buildings, national security and traffic, public services, telecommunications and internet, agricultural, electricity, transport, and trade and business.

5.2 Satisfaction level regarding current practices

Overall, Fig. 4 shows that the respondents demonstrated low levels of satisfaction regarding current practices and technologies in modern cities. Electrical and power grid services were rated highest with an average score of 3.12. Public facilities & parks and methods of construction, which achieved average scores of 2.4 and 2.39, respectively, followed this. Communication and internet came fourth with an average score of 2.25, followed by roads & transport with an average rating of 2.2. Water sanitation network was given an average score of 2.11, and solid waste disposal and management methods achieved the lowest average rating (2.09).

5.3 End-user requirements

The main outcome of this study was the identification of end-user requirements for the development and adoption of the SSC in Saudi Arabia. These requirements were obtained from the responses to the survey and were filtered to discard all of the redundant and unrelated responses, retaining only those deemed to be the most important and relevant. These requirements were then organised according to their relevant sectors and categories, the latter of which were as follows: social, organisational, technical, and financial (see Table 2). In addition, within each category, the requirements were related to one of the following sectors: environment and waste management, education, media, industrial and manufacturing, government and municipal, health, city and buildings, national security and traffic, public services, telecommunications and internet, agricultural, electricity, transport, and trade and business.

5.4 Holistic IoT architecture for smart sustainable cities

One of the main outcomes of this study was the proposal to employ a holistic IoT layered architecture for the adoption and implementation of smart cities. While building a holistic IoT architecture is not an easy task, it can be achieved. This study proposes that the first step is to review existing IoT architectures, such as [21, 35, 36], and then to merge the results of the review process with the outcomes of the survey employed by this study. Fig. 5 illustrates a holistic IoT layered architecture that supports the implementation of the socio-organisational, financial, and technical end-user requirements. This architecture takes into consideration the socio-organisational, financial, and technical requirements of the key important sectors highlighted by the responses to the survey: environment and waste management, education, media, industrial and manufacturing, government and municipal, health, city and buildings, national security and traffic, public services, telecommunications and internet, agricultural, electricity, transport, and trade and business.

The IoT layered architecture for developing SSCs consists of the following layers:

- **Storage and hardware layer**: this layer consists of high-quality hardware that hosts advanced virtualised machines. Also, it can have dedicated traditional storage containers or cloud storage solutions or hybrid storage solutions.
- **Business control and process layer**: this layer is responsible for managing processes and controlling business logic. It is responsible for various units and application programme interfaces such as geospatial information engine, data flow/management unit etc.
- **Application and views layer**: different smart applications concerning smart cities are gathered in this layer. It is built based on the business control and processes layer. Many smart applications could be developed and integrated into this layer such as smart-health, smart-business, smart energy grid, and smart-building applications.
- **Sensing layer**: this layer has been connected with other layers through two main layers: (a) application and views layer and (b) network & connectivity layer. It hosts different types of sensors that can be used with many objects inside the smart city. Many sensors could be hosted and integrated within this layer such as air pollution sensors, fire sensors, early warning systems etc.
- **Security, supervision, and governance layers**: This layer should exist in between the following layers: (a) application and views layer, (b) business control and processes layer, (c) storage and hardware layer, and (d) network & connectivity layer. This layer concerns the security, and supervision aspect of the data flow and migration between all layers. Also, it should provide an authorised institution with a full/partial governance on data migration, transactions, and access.
- **Data access, availability, and management layers**: it is responsible for data accessibility, availability throughout aforementioned layers. Furthermore, it manages data and flow within all layers.
- **Network and connectivity layer**: this layer provides all different types of network connections either: wired or wireless. In terms of hardware and software, it is recommended that this layer uses the latest networking technologies to keep up with new changes in other sectors. It is important to point out this layer has a sub-layer called ‘connection nodes’ that works as a gathering point for all communications to/from different layers within this architecture.

This holistic IoT architecture could be utilised in SSC adoption and implementation via addressing gathered requirements for end-users. Thus, it should be always maintained to accommodate new requirements and functions.

5.5 Generic IoT-based framework for establishing SSCs in Saudi Arabia

A generic IoT-based smart, sustainable framework for facilitating the adoption of smart city technologies in the Saudi Arabian built environment was developed, according to the results of the literature review, together with the views of the survey respondents. The following objectives inspired the development of this framework: (a) to establish a vision, and its basis, for a smart, sophisticated, and sustainable city; (b) to maximise the utilisation of ICTs to improve the infrastructure of SSCs; (c) to gather and take advantage of big data integration to improve smart cities’ operational and informational procedures; (d) to use innovation to create holistic SSCs; (e) to facilitate collaboration among the key players, both local and global; and (e) to design the collaboration, coordination, and communication of all actors and mechanisms across the entire SSC value chain.

Fig. 6 presents the proposed generic IoT-based SSC framework for the Saudi Arabian built environment. The top of the figure illustrates the proposed integration of the socio-organisational, financial, and technical requirements to facilitate the adoption of smart technologies, engendering the creation of SSCs. At the bottom of the figure is a list of the sectors deemed to be important.
Table 2  End-user requirements (socio-organisational, financial, and technical) for the development and adoption of an SSC

| Sectors          | Categories                  | End-users requirements                                                                 |
|------------------|-----------------------------|----------------------------------------------------------------------------------------|
| buildings        | social, financial, and technical | considering the sustainable design of a building at early construction stages          |
|                  |                             | hiring consultation agencies to assist citizens in reaching the best practices for smart and sustainable buildings |
|                  |                             | using sun lighting, shading, and natural ventilation etc. as a passive operation method for buildings |
|                  |                             | using local materials in construction and maintenance                                    |
|                  |                             | utilising modern and smart technologies in the construction, management, and operation of buildings |
|                  |                             | installing sensors, meters, and cameras for better control and safety                    |
|                  |                             | providing residents with building user guidance for the use of e-services in the buildings |
|                  |                             | designing a digital platform for better management and reduction of water and energy consumption |
|                  |                             | increasing the content of environmentally friendly and recycled building materials        |
|                  |                             | adapting state-of-the-art construction standards and tools to promote sustainable practices |
|                  |                             | maximising green surfaces (gardens and walkways) amongst buildings                      |
|                  |                             | improving land use by maximising building density and connectivity                       |
|                  |                             | improving the current existing infrastructure to incorporate sustainable and smart practices |
|                  |                             | completion of all infrastructure and services before occupation                          |
|                  |                             | transparency and accountability of public projects (public consultation as a key stakeholder) |
|                  |                             | maximising shaded walkways for pedestrians                                              |
|                  |                             | developing a digital platform to control municipal activities                              |
|                  |                             | preserving heritage sites and promoting tourism                                          |
|                  |                             | enhancing road and street lighting (applying solar energy technology)                    |
|                  |                             | improving the quality of public services such as public toilets, parks, pavements, and walkways |
|                  |                             | promoting cycling                                                                        |
|                  |                             | getting the best out of public access to Wi-Fi (announcement and warning systems)        |
|                  |                             | allocating leisure space, parks far from main roads, and highways (polluted areas)       |
|                  |                             | providing the public with more facilities and equipment for green waste management and disposal methods |
| utilities (water and electricity) | social and technical | availability of renewable energy technology                                             |
|                  |                             | transforming the national electricity grid into a smart grid                               |
|                  |                             | availability of wastewater treatment plants                                               |
|                  |                             | constructing rainwater-harvesting systems at both building scale and city scale          |
|                  |                             | building automated utilities networks to detect leakage and controlling flow             |
|                  |                             | providing the local market with water conservation fixture                                 |
| materials        | technical                   | labelling environmentally friendly building materials                                   |
|                  |                             | enhancing the use of biomaterials for the construction of buildings and maintenance      |
|                  |                             | supporting local markets to develop and import eco building materials                    |
|                  |                             | evaluating materials by calculating embodied energy                                       |
|                  |                             | protecting raw materials as much as possible for the next generations                   |
|                  |                             | protecting habitats, natural resources, environments, and heritage                       |
|                  |                             | evaluating environmental impact before constructing factories of building materials      |
|                  |                             | using digital platforms to manage and control pollution caused by building materials factories |
|                  |                             | using digital platforms to manage building material lifecycle                             |
|                  |                             | launching public awareness programmes to recognise the benefits of recycled and reused materials |
|                  |                             | enhancing the use of local materials                                                    |

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| Sectors                  | Categories                          | End-users requirements                                                                 |
|-------------------------|-------------------------------------|-----------------------------------------------------------------------------------------|
| telecommunications and   | technical                           | providing optimum quality ICT devices                                                  |
| internet                |                                     | promoting smart mobile applications                                                    |
|                         |                                     | supporting local markets with updated smart equipment to apply the concept of the IOT  |
|                         |                                     | improving the telecommunications and internet sector to cover a wider context            |
|                         |                                     | encouraging the public to come up with innovative management systems for their activities|
|                         |                                     | universal access to high-speed internet                                                 |
| transport               | organisational and technical        | implementing intelligent traffic management systems                                     |
|                         |                                     | smart parking systems, especially in crowded cities                                      |
|                         |                                     | creating smart mobile applications for management (schedule journeys, identify fast routes etc.) |
|                         |                                     | building curated or vibrant streets                                                     |
|                         |                                     | controlling and managing pedestrian and vehicle traffic and congestion                 |
|                         |                                     | creating a rapid transit system, such as rail, metro, or underground                    |
|                         |                                     | improving overall city connectivity and accessibility                                   |
|                         |                                     | providing well-organised mobility systems and equipment for the disabled and elderly    |
| economy                 | industrial, manufacturing and trading| empowering the public to form local economic visions that seek to exploit economic opportunities |
|                         |                                     | flexibility in the labour market to include labour from outside cities, states, and nations|
|                         |                                     | embracing ICT in companies' business, processes, and activities                         |
|                         |                                     | utilising smart technology to improve advanced businesses                               |
|                         |                                     | establishing mobile applications to enhance e-commerce                                  |
|                         |                                     | mandating markets, retailers, pharmacies etc. to use e-systems and services            |
|                         |                                     | developing smart novel models in business production, distribution, and consumption     |
| education               | social and organisational           | raising public awareness regarding smart sustainable development                        |
|                         |                                     | publishing a governmental plan and vision to reach every citizen                        |
|                         |                                     | availability of trained technical supports for educational and maintenance work         |
|                         |                                     | establishing education programmes in schools and universities regarding smart technologies and their implications |
|                         |                                     | measuring the level of public awareness on a regular basis regarding sustainable development and smartness |
|                         |                                     | consulting local citizens on ways to improve collaboration between the government and public |
|                         |                                     | providing regular training programmes to improve public technical skills in all services |
| health                  | social and technical                | improving e-health services                                                              |
|                         |                                     | launching awareness programmes using technology to control epidemic disease             |
|                         |                                     | engaging patients and families in e-programmes for health and wellbeing                 |
|                         |                                     | establishing smart practices for rapid responses and administration of critical incidents|
|                         |                                     | availability of data collected from smart devices to extract valuable insights           |
|                         |                                     | observing and assisting the early detection of health issues                            |
|                         |                                     | assimilating the data collected from tests instantly                                   |
|                         |                                     | providing smart health care units for patients and elderly people                      |
|                         |                                     | establishing updated spatial information regarding public health (geographic information system map) |
|                         |                                     | conveying information to doctors and staff in real-time                               |
|                         |                                     | improving effectiveness in the overall healthcare system                                 |
|                         |                                     | providing policemen with hi-tech equipment (e.g. finger and eye prints to identify criminals) |

with an emphasis on integration, interoperability, transaction, communication, coordination, and cooperation among them. The central section presents the three main categories of the framework, while the left-hand-side shows how such an infrastructure could provide support for all the requirements of an SSC, including the physical components, such as building materials and resources.
According to the generic framework proposed, the SSC technical solutions would be located at the top of the infrastructure, and provide all the necessary functions for monitoring, managing, governing, and controlling the smart applications developed for an SSC. This would be achieved through the use of state-of-the-art artificial intelligence and internet-of-things technologies, with consideration given to security, ownership, and intellectual property when working with sensitive data that could be transferred throughout internet-based portals.

The decision-makers and key players responsible for the establishment and development of SSCs should also consider the financial requirements involved. Some of these are presented above the SSC technical solutions, and include (a) a long-term economic vision, (b) smart employment systems, (c) financial support programmes, (d) the involvement of public and private financial
sectors, (e) smart budgeting and funding criteria and standards, and (f) the reduction of perceived financial risks. It is vital that the financial requirements are addressed carefully when adopting any smart, sustainable solution, due to the high cost of such technologies. It is also important to note that the requirements identified here are not the only financial requirements, as it is likely that more remain to be discovered and developed.

6 Conclusion
Cities around the world are responsible for 70% of energy consumption and ~80% of GHG emissions. Conventional methods of city design and operations are no longer suitable. This is due to the serious environmental degradation that has had an adverse effect on the quality of social and economic factors. In Saudi Arabia, progressive planning has been implemented to embrace the principle of sustainable development. However, little research has been conducted regarding the development of sustainable and smart cities suited to the Saudi Arabian environment. This lack of research motivated the current study, which sought to propose a holistic set of requirements for smart and sustainable cities that were applicable to the Saudi Arabian context, as well as a strategic roadmap intended to enhance such development in Saudi Arabian cities. An in-depth knowledge of public perceptions is one of the key factors for achieving robust social-technical end-user requirements, so more than 500 well-informed participants contributed to the outcomes of this study. Furthermore, a holistic IoT architecture for adopting and implementing the smart sustainable cities’ framework is presented. The outcomes of this primary research were divided into three parts. Firstly, current practices and participants’ related satisfaction levels were evaluated. Secondly, a set of end-user requirements for a smart sustainable city was proposed. The main categories of these end-user requirements were: buildings, municipality & public services, awareness programmes, materials, telecommunications & internet, health & wellbeing, utilities, safety & security, transport & mobility, and the economy. Finally, the study proposed a framework for enhancing the adoption of smart city practices based on socio-organisational, financial, and technical factors.

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