Chapter 10
IoT for Sustainability

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Contents

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10.1 Global Trends

The COVID-19 pandemic has caused disruption to everyday life for millions of people across the globe. It has forced those in prosperous, developed countries to re-evaluate aspects of their societies that they previously took for granted. Occupations seen as low down the social scale are now reclassified as ‘essential workers’ while entire sectors of the economy have seen redundancies on an unprecedented scale. While some countries were relatively slow to respond to the crisis, the overall speed with which measures were introduced to manage the situation was startling. Virtually overnight, governments introduced financial support schemes for entire populations, transportation came to a standstill and face coverings became commonplace. Within weeks, millions of people accepted the restrictions of lockdown as an entirely reasonable obligation and working from home became the norm for those whose physical presence in the workplace was not essential.

One of the reasons that the world responded so dramatically to the virus was the speed at which it spread. Changes were reported by news channels in real time, and statistics such as the rate of infection and the daily death toll in different parts of the world brought home the immediacy of the threat. The experience has shown that transformational change is possible on a global scale when the situation is serious enough. However, the global pandemic is set against the backdrop of several other pernicious trends that are moving at a much slower pace and which consequently have not yet provoked a comparable response.

10.1.1 Climate Change

The first of these trends is global heating brought about by human activity. In the same way that some countries initially responded with complacency or scepticism to the pandemic, there was at first a great deal of resistance to the proposition that humans could have such a significant effect on their environment. With the findings of climate scientists now generally accepted, the International Panel on Climate Change (IPCC) produced a report in 2018 warning of the consequences of allowing the global mean surface temperature (GMST) to exceed pre-industrial levels (1850–1900 mean temperature) by 1.5 °C. These include species loss and extinction, risks to human health, livelihoods, food security and access to water. Economic growth is expected to be affected and extreme weather events will become more common. The surface temperature increase on land is likely to be higher than mean global figure, with the effect even more exaggerated in cities due to the urban heat island effect [31]. A 2020 update by the World Meteorological Organization reported that GMST was already 1.0 °C above pre-industrial levels and likely to reach 1.5° in one or more months between 2020 and 2025 [73].

Given the scale of the potential impacts of climate change, it is sobering to consider the slow pace at which measures to mitigate them are being introduced.

Part of the explanation must lie in the seemingly small quantities involved. A global change of 1.5 °C pales into insignificance for the average person when compared to several thousand deaths per day due to the virus. Likewise, the speed at which COVID-19 can spread is much more alarming than the slow increase in GMST over several decades. As the virus is brought under control, however, the experience could turn out to have beneficial effects. Having been sensitised to global threats and having seen the speed at which transformational change can occur, the general population may be ready to engage in urgent collective action to combat climate change and avoid its worst effects.

10.1.2 Urbanisation

Around 2007, the number of people living in cities exceeded those living in rural areas and the trend has continued since then. In 2018, 55% of the global population were living in cities up from 30% in 1950 [68]. This proportion is set to grow to 68% by 2050 which means that the number of city dwellers will nearly double in that time, assuming an eventual population of 11 billion. From some perspectives, urbanisation is a good thing. The high density of people in a relatively small area offers opportunities for efficiency, security and prosperity, but only if it is accompanied by good governance [68]. With poor management, in contrast, urbanisation can lead to pollution, environmental degradation and the phenomenon of ‘urbanisation without growth’ [6].

Currently, cities account for 3% of the Earth’s land area while consuming 75% of natural resources and accounting for up to 80% of greenhouse gas emissions [49]. The concentration of consumption means that the environmental impact of cities goes far beyond their boundaries. Rural areas face increasing pressure to satisfy the urban need for food with the associated burden of transportation. As they grow, cities are also increasingly vulnerable to natural threats such as water shortages and damage from extreme weather events. The coastal locations of many of the larger conurbations, for example, put them at risk from storm surges, rising sea levels, floods and coastal erosion [64].

A result of the global trend towards greater urbanisation is the emergence of megacities – those with over 10 million inhabitants. In 1990, there were 10 megacities located in relatively developed countries, but by 2018, this number had more than tripled with the new additions located primarily in Asia [68]. By 2030, nine more cities are predicted to join the megacity tier including London where the national per capita GDP is more than $42 K and Dar es Salaam where it is just over $1 K [76]. This disparity in wealth will entail contrasting local pressures and priorities for these two very different locations.

10.1.3 Linear Business Models

Human activity places other pressures on the natural world in addition to the consequences of global heating and urbanisation. In the dominant linear model of commercial production in developed countries, raw materials are obtained from the natural environment and turned into products which have a limited lifespan and are then discarded for new improved versions. It is argued that this model, characterised as the 'take–make–dispose' pattern, has fundamental limitations which are starting to be felt in the global economy [18]. Quite apart from the increase in business costs that result from dwindling supplies of raw materials, the linear model demands that ever greater areas of land are devoted to the extraction of material and entails ever greater accumulation of waste in the environment. The extractive activity reduces the area available for natural life, and the build-up of waste reduces the quality of habitats that remain.

A particularly salient example concerns the pervasive use of plastics in the global economy. Plastics are typically produced from non-renewable feedstocks derived from petrochemicals and represent around 8–9% of all fossil fuel consumption when energy required for their production is taken into account [47]. Plastics can be consumed either in the form of useful products or as disposable packaging often referred to as 'single-use plastic'. Plastic waste can be sent to landfill, incinerated or recycled but recycling rates remain low. Globally in 2020, around 14% of plastic waste is recycled and even in the EU which is one of the best-performing regions, the rate is only 30% [47]. Neither of the other disposal strategies are without their issues: The landfill approach requires progressively more sites, while incineration releases carcinogenic chemicals such as dioxins [80]. All too often, plastic waste is released into the environment where it can break down through natural erosion into microscopic particles now known as microplastics which can pervade previously pristine habitats and enter the food chain [80].

To combat the problems associated with linear business models, the World Economic Forum [72] advocates a deliberate and coordinated transition to a circular economy defined as follows:

> A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models [18].

The problems caused by linear business models have been growing slowly, and although there is considerable public awareness about them, action has been slow to emerge. In contrast to the COVID-19 pandemic, they are not perceived as urgent. Their effects are typically remote from everyday life and there is a great deal of inertia among commercial interests to move away from existing practices, especially where this would entail a fall in profitability.

10.1.4 Technology and Automation

As in the case of urbanisation, the advance of computing technology into all areas of life has both positive and negative aspects. In many instances, the motivation for greater reliance on technology is that it will improve efficiency. This in turn, the theory goes, will drive down costs for consumers and citizens, increase profits for shareholders and raise the average standard of living in a virtuous cycle of development. Indeed, this chapter goes on to discuss the role of the Internet of Things (IoT) in achieving a more sustainable society. However, it is also important to consider the undesirable consequences of the increased use of automation and machine intelligence. Since the industrial revolution, fears that technology would displace workers have not been borne out; instead, new technologies have created new opportunities and the labour mix has adapted to take advantage of them. A recent World Bank report is optimistic that the same pattern will repeat itself in the case of the revolution currently underway [74]; however, the same report also points out that according to some predictions, 47% of jobs in the United States, for example, could be displaced by automation.

To take a specific example, the imminent introduction of autonomous vehicles will probably mean redundancy within the next 20 years for the majority of those in occupations where driving is the main component. They numbered 3.8 million in the United States in 2015 [3]. On the other hand, fully automated vehicles are expected to enhance safety, make mobility available to all and to increase opportunities for those for whom driving is a complementary adjunct to their main occupation [53]. To avoid the undesirable social and economic effects of such a large disruption, organisations such as the World Bank recommend that governments already start to plan for the changes. Suggestions include placing greater focus on higher-order cognitive and socio-behavioural skills in early years education, enhancing social protections for those whose jobs are at risk and adjusting tax policy to cover the costs of these changes equitably.

10.1.5 Summary

The trends discussed in this section all test the assumptions by which society has developed, especially in Europe and North America, over the last century. They allow us to predict that cities will become larger, denser and more complex, and that technology will continue to pervade everyday life to an ever-increasing extent. They also highlight the pressing need to curb activities that contribute to global heating, and to redesign commercial activity around more equitable values. In order to avoid reaching the limits of a finite planet, transformational shifts in thought, behaviour, corporate governance and social equity are needed. The consequences of not addressing these issues could be dire. COVID-19 has given the entire world a new perspective on its current way of life. Following an examination of the concept of sustainable development, the question addressed in the remainder of this chapter is what role IoT might have in the response to these burning questions.

10.2 Sustainability

The dictionary definition of *sustainability* is simply the capacity of a system to maintain its present state indefinitely. In the two decades between 1970 and 1990, the popular understanding of sustainability gravitated towards a model built around three interlocking aspects, or *pillars*, as shown in Fig. 10.1. Essentially, the model encapsulates the idea that a comprehensive approach to sustainability must give equal attention to social, environmental and economic factors.

In 1987, the Brundtland report, commissioned by the United Nations in 1983, established the concept of *sustainable development* based on the identification of three interlocking global crises concerning the environment, global economic development and energy use. The report concluded that the risks posed by these crises constituted a long-term threat to human survival and were too large to be managed by individual nations. The report culminated in a call to action advocating a coordinated global effort to address the crises.

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts [5]:

- The concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
- The idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs.

Fig. 10.1 The three pillars of sustainability

By making explicit reference to human needs, the formulation neatly places human agency in the form of personal, political and corporate responsibility at the heart of sustainability. It also implicitly incorporates the concept of social justice in which the needs of poorer regions of the world are prioritised over those of developed nations. The second key concept directly challenges the false impression that natural resources are infinite and highlights the need to consider the long-term consequences of established ways of life.

10.2.1 UN Sustainable Development Goals

In 2000, the UN launched the Millennium Development Goals (MDGs) which set eight development targets to be achieved within 15 years. By 2015, the proportion of people living in extreme poverty in developing countries fell from 47% to 14%. During the same period, maternal mortality fell by 45% and ozone-depleting chemicals were virtually eliminated from industrial products [67]. To capitalise on the progress made on the MDGs, a new set of 17 Sustainable Development Goals (SDGs) were established in 2016 which have become the current benchmark for sustainability (Fig. 10.2). The declaration defined a series of measurable targets for each goal which UN signatories committed to deliver by 2030 [66].

The need for a balanced approach to achieving the goals may be demonstrated by taking an example. Figure 10.3 shows the renewable energy used by different countries as a percentage of total energy consumption. On this measure alone, some of the poorest countries in the world already achieve an energy mix with up to 80% renewables. However, for many of those countries the renewable fuel in question is

Fig. 10.2 Sustainable Development Goals ("https://www.un.org/sustainabledevelopment/" The content of this publication has not been approved by the United Nations and does not reflect the views of the United Nations or its officials or Member States)

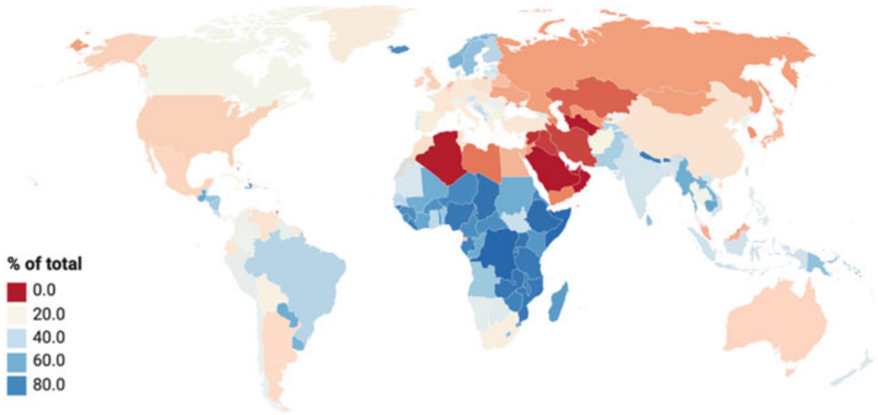

Fig. 10.3 Proportion of renewable energy consumed as a percentage of total energy consumption. (Data: World Bank, 2020 [77])

biomass burned on open fires which contributes to a range of pulmonary diseases [16, 75]. The impact on other indicators such as access to clean energy sources and the mortality rate for children under 5 is thus very negative. It is only by taking a multi-dimensional view that the complete picture can be fully appreciated.

The complexity and scale of the effort required to deliver the SDGs was summarised in the 2019 progress report which advocated a broad portfolio of measures based on technological improvements, lifestyle changes and localised solutions [16]. Coordinated action on consumption, production and conservation policy development would be needed to eliminate hunger (SDG2) while at the same time avoiding biodiversity loss (SDG13, SDG14) and preventing land degradation (SDG12, SDG13).

10.2.2 Perspectives on Sustainability

The SGDs reflect the United Nations' status as a supranational organisation with a global perspective. They are intended to capture the web of interconnected pressures faced at the planetary, regional and national levels. On the ground, however, context dictates that some issues take precedence over others. This section outlines some key tensions that cut through generic sustainability concerns.

10.2.2.1 Developing Versus Developed Countries

The Human Development Index (HDI) is a statistical indicator that takes values between 0 and 1. The closer to 1, the more 'developed' a country is deemed to

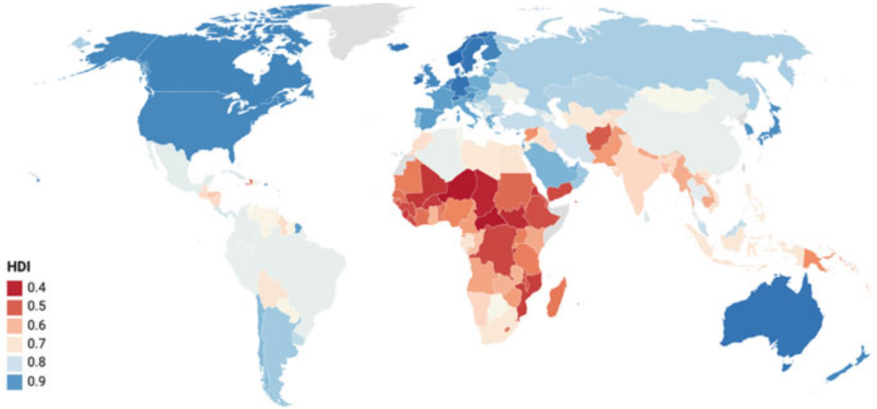

Fig. 10.4 Human development index by country. (Data: UN Development Programme, 2020 [69])

be. The measure is calculated using proxy measures for life expectancy and health, level of education (knowledge) and standard of living [69]. Figure 10.4 shows the data from 2019.

Many of the SDGs are deliberately aimed at raising the quality of life of those at the bottom of the HDI table. For more developed economies, goals such as zero hunger (SDG2) and clean water and sanitation (SDG6) have a much lower priority than others, since those problems have been largely solved. The environmental, energy and climate targets set by the European Commission for 2020, for example focus on the protection of biodiversity, cutting greenhouse gas emissions, sustainable cities and the development of the circular economy [21]. In a recent survey, leaders of developing countries were asked to rank the SDGs by priority. Across the board, poverty was the overriding concern with SDGs 4, 8 and 16 appearing in over 60% of leaders' top six priorities. By contrast, SDG12 and SDG14 were ranked the lowest priorities with figures of 15% and 5.4% respectively [13].

10.2.2.2 Urban Versus Rural

Urban and rural areas have contrasting characteristics that lead to different sustainability concerns. Most food production, for example, occurs in rural areas while urban centres represent concentrations of consumers leading to a net flow of agricultural products from rural areas to urban areas. This creates pressures on land use and biodiversity in rural areas leading to land degradation, deforestation and fragmentation of natural habitats that may be further exacerbated by climate change [42]. In urban areas in contrast, the concerns are much more to do with energy efficiency, the elimination of waste, transportation and pollution control [61]. Rural areas are also more susceptible to extreme poverty and poor access to services and utilities than urban areas [42]. In contrast, urban priorities revolve around equitable access to education and basic utilities, health and fitness of the population, air quality and noise levels [39].

10.2.2.3 Local Versus Global

The SDGs are primarily concerned with global trends and the statistical indicators used to measure progress against them are measured at the national level [52, 56]. Top-down strategies may be blunt instruments; however, trying to force through a one-size-fits-all approach that may encounter resistance. The 2017 'Listening to Leaders' survey, for example, found that leaders in developing countries prioritised the SDGs differently from ordinary citizens [13]. Leaders were much more likely to focus on economic growth, education and strong institutions, while citizens were more concerned with food security and the health of their cities.

To resolve potential conflicts, the UN acknowledges the need to promote and support localised, bottom-up initiatives. The 2019 progress report on Agenda 2030 stresses the importance of grassroots initiatives and the integration of local knowledge and traditional practices for sustainability [16]. The report notes a multitude of bottom-up efforts working towards the SDGs, but also highlights a lack of research into the realisation of global targets through the aggregation of these bottom-up projects.

One of the mechanisms for individuals to contribute towards the achievement of Agenda 2030 is through participation in citizen science activities. Citizen science typically involves volunteers taking part in data collection but can also include other types of scientific activity. With technology such as smart sensors, mobile computing and broadband Internet, the opportunities for data collection and aggregation, dissemination of results and awareness raising are unprecedented. As well as potentially increasing spatial and temporal data coverage, citizen science has the potential to fill in gaps that exist in traditional sources of data. For example, Fritz et al. [25] argue that the monitoring of food waste (SDG12), climate change (SDG13) and marine pollution (SDG14) are all suitable targets for citizen science in terms of both data collection and the development of monitoring methods.

10.2.2.4 Internal Versus External Focus

General system theory (GST) distinguishes between open and closed systems where an open system exchanges materials with its environment across the system boundary and a closed system does not [4]. GST provides a useful conceptual framework for the design and study of real-world systems such as organisations, countries, cities and ecosystems which are all open in the GST sense. A systems approach typically focusses on the internal workings of the system under study. Organisations, for example, have control over their internal operations and put a lot of effort into refining them to deliver value. Governments create regulatory regimes within which organisations operate and which define some of the exchanges between an organisation and its environment. Because the organisation has comparatively little external control, it avoids attempts to influence its environment because of the perceived risk of failure and wasted effort. From the point of view of sustainability, this is clearly unsatisfactory. Many problems of sustainability require organisations to attend to the external effects of both inputs and outputs.

In an attempt to embed holistic thinking into organisations and to operationalise the three pillars model, Elkington introduced the concept of the *triple bottom line* for company accounting [17]. Traditionally, the bottom line refers to the amount of profit per share after all liabilities have been accounted for. Elkington proposes that companies should routinely account for value in the environmental and social domains as well. The approach is sometimes called the *People–Planet–Profit* model for that reason, and the literature provides examples of management indicators related to regulatory certification or sanctions, and to quantitative measures of energy used, resources consumed or waste emitted [22]. Elkington situates his discussion in the context of developing trends such as evolving societal values and increasing transparency around company operations as well as against the backdrop of mounting environmental problems. He argues that companies who fail to evolve are likely to overcome by market forces.

The internal/external distinction can also be applied to any area of activity that consumes energy or resources. For example, automation may be applied in order to reduce the energy associated with a manufacturing process, but if the energy cost associated with the automation equipment is larger than the amount saved elsewhere, the effort is futile. The field of green computing seeks to improve the energy and resource efficiency of computing technology itself thus increasing the benefits of automation.

10.2.3 Computational Sustainability

In 2008, the United States National Science Foundation established the *Expeditions in Computing* programme aimed at funding teams to pursue transformative research agendas over a period of 5 years [65]. One of those programmes, led by Carla Gomes at Cornell University, set out to concentrate the attention and efforts of computer scientists on the challenges around sustainability. The programme established the Institute for Computational Sustainability (ICS) at Cornell as well as coining the term *computational sustainability* itself.

The landscape of computational sustainability research shown in Fig. 10.5 evokes a process of transformative synthesis in which computational techniques are combined in novel ways in pursuit of solutions to sustainability problems [26]. While the techniques themselves may be well-established, it is the intention behind their use and their adaptation to novel contexts which is the hallmark of computational sustainability. In the process, it is not just the application domain that benefits from this inherently interdisciplinary approach; the field of computer sci-

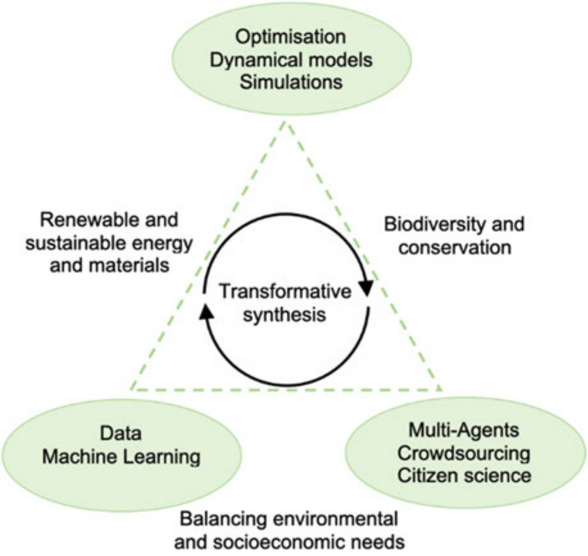

Fig. 10.5 Computational sustainability research landscape. (Adapted from [26])

ence is also enriched through the development of novel combinations of techniques. Publications in computational sustainability fall roughly into three categories as illustrated by these selected examples:

Renewable and Sustainable Energy and Materials

- Finding an optimal mix of renewable energy generation and storage using a dynamic planning approach [35]
- Li-ion battery charging optimisation with multi-arm bandits [29]
- Application of data mining to domestic energy use behaviour [9]

Biodiversity and Conservation

- Modelling bird species distribution using citizen science [63]
- Optimal design of wildlife corridors [14]
- Preserving genetic diversity using an artificial immune system algorithm [58]

Balancing Environmental and Socioeconomic Needs

- Estimating socioeconomic indicators from satellite data [20]
- Urban bike sharing [24]
- Air quality monitoring through citizen science [37]

As the examples demonstrate, the range of topics that fall under the banner of computational sustainability is very wide. It is also an associative field in the sense that work done for other reasons and without explicit reference to computational sustainability could still sit comfortably under its umbrella.

10.3 The IoT Fit

According to the International Telecommunication Union (ITU), the Internet of Things (IoT) is:

> a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving, interoperable information and communication technologies [32].

While other definitions also exist, the ITU formulation captures the essential concept of IoT bridging the divide between the physical and digital domains and offering opportunities to manage complexity through direct communication between things without the need for human intervention.

10.3.1 Architecture

Using a reference architecture to structure a complex system is a mature approach to simplifying the design process, ensuring testability and maintainability, and promoting interoperability and the application of standards. Architectures are often described in terms of layers in which each layer has a specific set of functions and responsibilities and communicates with neighbouring layers in a standardised manner. Currently, there is no single model for IoT and the number of layers in proposed architectures varies between three and seven. Of the three examples shown in Fig. 10.6, the three-layer model is generally agreed to be too simplistic for practical purposes but provides a useful conceptual overview. The ITU proposal makes a distinction between two different categories of service that exist at the top of the hierarchy but does not elaborate on the lower layers. The seven-layer

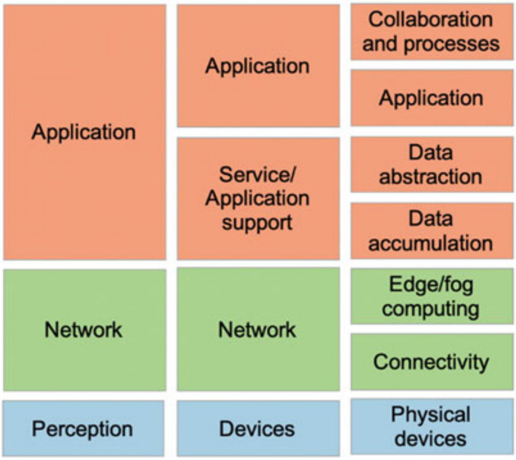

Fig. 10.6 Example IoT reference architectures: left: simple; centre: ITU model; right: IoTWF model

model, proposed by Cisco for the Internet of Things World Forum (IoTWF), makes allowance for data processing capabilities at lower levels in the architecture, an approach known as *fog computing*. The seven-layer model is widely used, and the concept of fog computing is crucial for some of the arguments presented later in this chapter.

Nodes
The lowest level of each architecture is concerned with the 'things' that are responsible for the coupling of the physical and digital domains. They typically include sensors, processing capability and communications, and may also be linked to actuators to provide bi-directional interaction with the physical environment. In many applications, a high-data resolution is critical to delivering the intended benefits. Many nodes are therefore required in the device layer to generate data at an appropriate rate. This places two extrinsic requirements on nodes: their cost must be kept as low as possible, and their power requirements must also be minimised. The result is that nodes are typically simple, resource-constrained devices.

Communications
All models include a communications layer, but the picture is complicated by the inclusion of fog computing. At the detailed level, most architectural models differentiate inter-node communication from the further transmission of data to the cloud using standard internet technologies. The device that bridges between these two networks is usually referred to as a *gateway,* and it is often the gateway device which hosts the resources required for fog computing.

Applications
The data processing in the top layer of the simple model is assumed to take place in the cloud, and that is also the case for the other two models which subdivide the application layer. The resource-constrained nodes do not have the capacity for any significant processing, and cloud service provides a solution that can scale to accommodate an arbitrary demand.

10.3.2 Fog Computing

Architectural models for IoT that rely solely on the cloud for processing and control have several weaknesses that make them unsuitable in certain situations. The main issues are outlined below.

Performance
In 2019, there were 7.6 billion IoT devices in operation and some predictions suggest that by 2030 there could be over 24 billion [44]. The consequent exponential increase in traffic will create network performance and congestion problems [50].

Latency
IoT applications that require a real-time response such as those in safety-critical or health-related contexts are adversely affected when network latency is high. The delay incurred by the transfer of data to and from the cloud in addition to any unavoidable processing time may render such applications unusable.

Security
The data collected and processed by some IoT systems may be sensitive for reasons of safety, privacy or commercial value. The longer the network path traversed by such data, the greater its exposure to potential interception or corruption.

Reliability
Network connections can fail for many different reasons. Relying on a cloud service for processing and control renders an IoT system vulnerable to all such interruptions.

To address these weaknesses while still preserving the ease of use and scalability of the cloud model, fog computing situates the storage and processing of data closer to the nodes, typically by increasing the capabilities of the gateway device. In the same way that natural fog is composed of low-lying water vapour, the term *fog computing* is intended to convey the idea of services similar to those in the cloud, but closer to the devices on the ground as illustrated in Fig. 10.7.

Many technological choices are available for the implementation of a fog architecture. One option would be to use a wireless protocol such as Bluetooth, CoAP or LoRa between the nodes and the gateway, with the backhaul network between the gateway and the cloud based on TCP/IP. In this situation, the gateway could be a small server with appropriate network interfaces. With the advent of

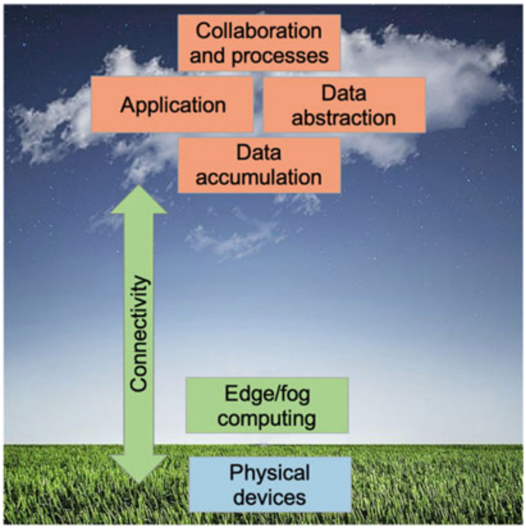

Fig. 10.7 The fog computing metaphor

5G services, an alternative implementation could be based entirely on mobile cellular technology. This particular variation, known as *multi-access edge computing* (MEC), has been specifically designed around a service-based concept to enable distributed computing for IoT [34]. In the MEC model, placing the additional storage and processing capability at the cell base station would ensure optimum performance.

10.3.3 IoT and Sustainability

In the most general terms, sustainability is the husbandry of resources and a major challenge is data visibility: resource stocks need to be measured and monitored, the flow of resources through their lifecycle needs to be overseen and controlled, and the quantities and effects of waste ejected into the environment need to be understood. The required data may be unavailable for a variety of reasons such as those listed below.

Geographical Scale
Measurement is difficult when resources are dispersed over a very wide area which may be difficult to access. Fresh water supplies and fish stocks are good examples. The accumulation of plastic waste in the ocean is only now being recognised as an environmental issue for similar reasons.

Complexity
Patterns of resource use may be difficult to monitor because of the complex web of flows that make up the resource lifecycle. The flow of food products in a city falls into this category – identifying specific inefficiencies and waste would require a great deal of effort and coordinated action by many people.

Cost
Monitoring and management activities themselves consume resources. Measurement equipment and staff required to operate it may represent significant expenditure which it might not be feasible for organisations to bear.

The characteristics of IoT make it particularly suitable for addressing problems of sustainability. An recent analysis concluded that 84% of IoT deployments were already addressing or had the potential to address the SDGs [78]. The ultimate goal of IoT is to connect everything regardless of geographical location, giving access to high-resolution data that was previously unavailable. Nodes are designed to be simple, cheap and robust, running for several years without requiring any maintenance. They operate independently of any fixed infrastructure and can be deployed without human intervention using a drone, for example. Over-the-air programming allows them to be updated without physical access, and some are even biodegradable such as those used in health applications [38]. The IoT has also encouraged the development of low-power, low-bandwidth technologies

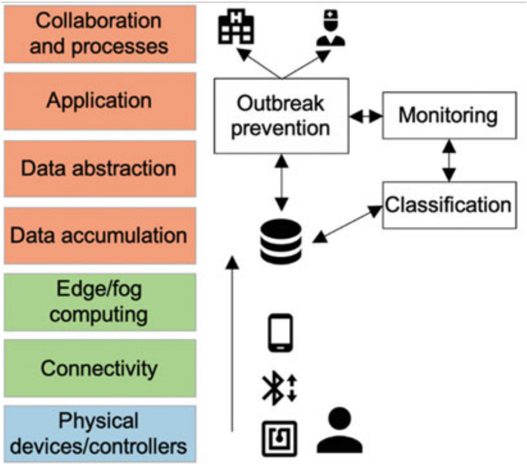

Fig. 10.8 Outbreak prevention system [57]

such as LoRa[1] and NB-IoT,[2] which vastly reduce the costs associated with data transmission. Thus, the IoT paradigm addresses by design the external and internal perspectives mentioned earlier. The next few sections describe some illustrative examples of IoT and their relationship to the SDGs.

SDG3: Good Health and Wellbeing

Following outbreaks of Ebola in East Africa in 2014, the U.S. Agency for International Development (USAID) launched a programme entitled *Fighting Ebola: A Grand Challenge for Development* [71]. One of the crowd-sourced innovations to come out of that work was a wearable sensor capable of monitoring 11 vital signs and transmitting them over Bluetooth [62]. Several groups proposed incorporating such sensors into IoT systems, such as the one shown in Fig. 10.8 where it is aligned with the IoTWF seven-layer architectural model.

The sensor transmits data to a mobile device which relays it over the Internet to a cloud datastore. Thereafter, classification and monitoring are performed by cloud applications and alerts are sent to hospitals and medical personnel as required [57]. In the proposed scheme, the mobile device does little more than forward the raw data to the cloud; however, because of the capabilities of modern smartphones, there is the potential for it to act as a fog node and perform local analysis or aggregate the data before it is uploaded to the cloud.

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[1] https://lora-alliance.org/

[2] https://www.gsma.com/iot/narrow-band-internet-of-things-nb-iot/

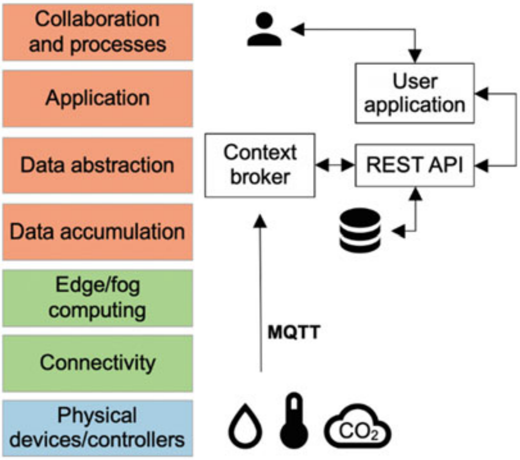

Fig. 10.9 Water management via IoT [46]

SDG6: Clean Water and Sanitation, and SDG12: Responsible Consumption and Production

In response to the extremely dry climate and shortage of fresh water in south-east Spain, Muñoz et al. [46] propose an IoT system to monitor and manage the supply of water to agricultural producers. As a result of agricultural production in the area, freshwater reservoirs face depletion and are supplemented by desalinisation plants. The purpose of the proposed system is to optimise water management by providing feedback to the desalinisation plants so that they can tailor their production to fit the demand.

The architecture is based on the FIWARE[3] open source standard for IoT applications which is driven by the European Union. The system offers standard-based interfaces for interoperability. Devices send data to the cloud using MQTT,[4] a simple, message-based protocol that allows heterogeneous devices to communicate easily. FIWARE is one of several flexible IoT platforms that aim to make the development of IoT applications as simple as possible. It incorporates a broker process which relays data via MQTT from one element to another. A REST API provides access to a database for the broker as well as for third-party applications. Figure 10.9 summarises the architecture proposed by Muñoz et al. aligned with the IoTWF reference model. The estimated cost saving on desalinisation as a result of the system was estimated at 87% mainly due to a lower electricity requirement.

SDG15: Life on Land

With a long history of wildlife conservation work, the Zoological Society of London are introducing a new version of their remote monitoring system, Instant Detect.[5]

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[3] https://www.fiware.org/developers/

[4] https://docs.oasis-open.org/mqtt/mqtt/v5.0/mqtt-v5.0.html

[5] https://www.zsl.org/conservation/how-we-work/conservation-technology/instant-detect

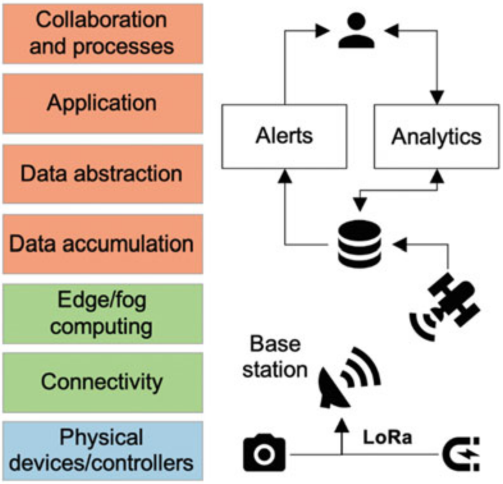


Fig. 10.10 Wildlife conservation [40, 59]

The system has already contributed to the protection of endangered species in North America, Africa, Australia and Antarctica, and the upgrade will add new capabilities.

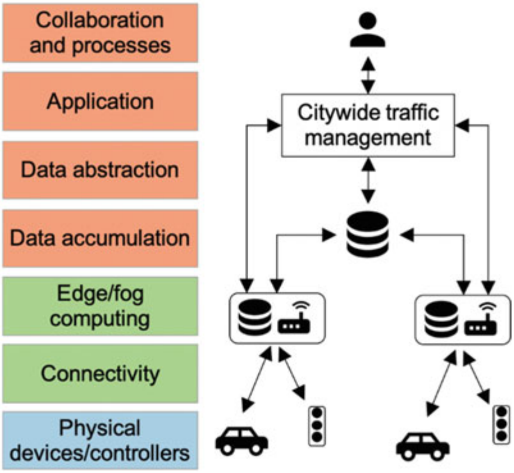
The new architecture relies on LoRa for long-range, low-power communications on the ground, and uplinks to the Iridium satellite network to transmit data to a cloud repository. Sensor nodes equipped with cameras perform local image-recognition processing to determine whether an image needs to be uploaded. Nodes may carry a range of other sensors including metal detectors to identify potential poachers. Figure 10.10 illustrates the architecture of Instant Detect 2.0.

SDG11: Sustainable Cities and Communities

With large and growing numbers of people living in cities, issues related to transport management are becoming more important. Road traffic generates large quantities of airborne pollutants such as carbon monoxide, nitrogen oxides and particulates which are harmful to health. A great number of studies have shown that pollutant levels in busy cities can often exceed recommended levels [1]. Keeping traffic flowing smoothly, avoiding unnecessary stopping and starting and making it easy to find parking spaces can all help to minimise emissions. Many studies have proposed IoT-based solutions for managing traffic flows and for the provision of other services such as collision avoidance and clear routes for emergency vehicles. The example shown in Fig. 10.11 proposed by Mohammed et al. [43] makes heavy use of the fog computing model to provide time-sensitive services such as traffic signal control, and to avoid unnecessary network exchanges between vehicles and the cloud.

In many schemes for urban traffic management, the vehicles themselves are classed as fog nodes because of their onboard computing facilities. It has been suggested that they could be incorporated into an ad-hoc networking relationship

Fig. 10.11 Urban transport management [43]



with other vehicles and with the roadside units, which comprise the fixed fog nodes to provide greater network resilience and flexibility [48].

10.3.4 Smart Cities

Because of the peculiar complexity of the system of systems that makes up the fabric of a modern city, the concept of the *smart city* has become prominent in the IoT literature. Over the last two decades, papers published under the heading of smart cities have covered a very wide range of specific topics. Some take a holistic approach, focussing on city-wide architectures to support multiple homogeneous services, while others focus on specific use cases. One review identified 40 distinct bursts of activity in the academic literature around particular keywords which are shown chronologically in Fig. 10.12 [82].

In an attempt to rationalise the smart city concept, another review identified 84 different definitions spanning the period from 2000 to 2019 which were categorised as *technocentric*, *humanist*, or *collaborative* [15]. The technocentric school focuses on technology as the main driver of smart city development. It emphasises the top-down development of infrastructure from which social benefits follow as a result. Early definitions of the smart city appear to take this optimistic view. The humanist perspective is espoused by the European Union and its main driver is the development of human capital characterised by education, culture and wellbeing. In the humanist view, technology is treated as an enabling tool which does not always match the needs of the citizens if it is introduced in a top-down fashion. The humanist approach also highlights the risk of social polarisation as a result of unequal access to technology. Figure 10.12 shows consistent efforts to define the smart city in humanist terms compared to the bursts of enthusiasm that seem

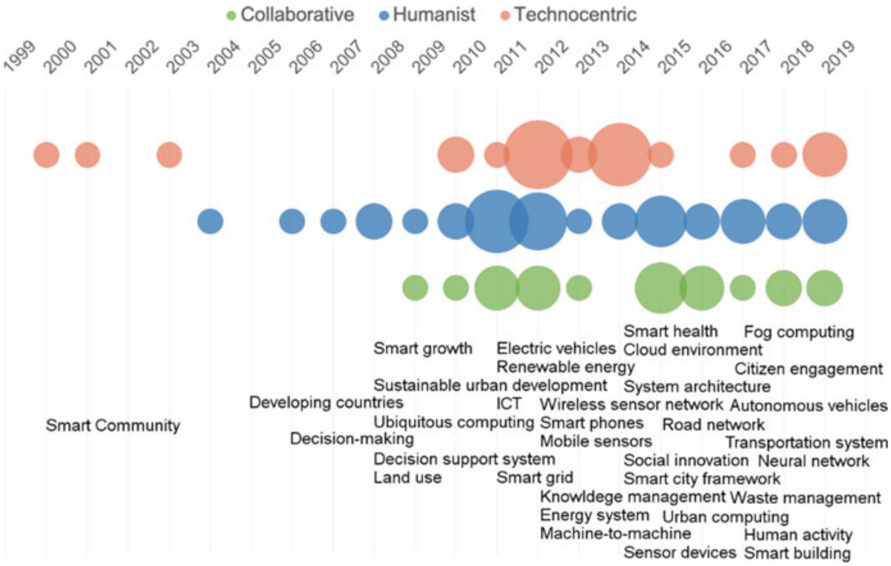


Fig. 10.12 A chronological illustration of the smart city concept [15, 82]. The size of the coloured bubbles represents the number of smart city definitions published in the relevant year

to characterise the technocentric view. Finally, the collaborative approach sees the interaction between stakeholder groups as the defining characteristic of the smart city. Development comes about through a mix of top-down and bottom-up approaches mediated by technology.

Fog computing has a special place in the smart city literature [81]. The weaknesses of the cloud-only model discussed above are intensified by the complex web of socio-technical interactions present in the urban environment and the density of activity. Some authors have asked whether attempts to manage cities through technology will eventually fail as complexity increases, accountability is lost and technology consumes more energy than it saves [10]. However, the fog computing model offers some technological solutions by embedding localisation in the design of smart city architectures. The OpenFog consortium highlights traffic congestion, public safety, energy consumption, sanitation, and public internet connectivity in its smart city scenario [50], and other applications of the fog model are abundant in the current literature [33].

10.4 Taking Stock

IoT is a new technological field which is developing so quickly that new architectures, devices and use cases are being proposed almost daily. Its potential for increasing efficiency in many domains is clear and the correspondence between the characteristics of IoT and the requirements for sustainability is a natural one. Commercial efforts to develop the technology are intense, and 84% of current IoT projects can be said to be addressing the SDGs at least in part. With such a positive outlook, then, where is the problem? The answer lies in resisting the technocentric approach and addressing the wider implications of IoT deployments, especially in developing countries. Technology has a role to play in sustainable development but is far from being the only consideration. The principles of computational sustainability place a new responsibility on technologists to take this type of measured approach to their work and to take account of the wider context:

> Our vision is that computer scientists can and should play a key role in helping address societal and environmental challenges in pursuit of a sustainable future, while also advancing computer science as a discipline [26].

The remainder of this section presents a series of issues for IoT in relation to sustainability which follow from the earlier discussions. By making them explicit, the intention is to highlight the potential for unintended consequences of IoT projects which might otherwise undermine progress towards the SDGs.

10.4.1 Selective Focus

A recent report from a European think tank on IoT for sustainability identified the four most common IoT use cases as smart manufacturing, healthcare, energy and mobility in smart cities [55]. The report also presented statistics to show that 63% of IoT projects in 2018 were concentrated on SDGs 7, 9 and 11 [79] while some SDGs were hardly addressed at all (1, 2, 13, 14, 15). There are three obvious reasons that could be put forward to explain this phenomenon. The first is that the selective approach represents local requirements and should therefore be respected. This response does not stand up under scrutiny, however. Since local concerns are known to differ, they should balance each other out when aggregated into global statistics. The second possibility is that there is some bias in the way the statistics were collected which means that projects with certain characteristics are over-represented and that others are overlooked. This proposition is certainly true at least in part. The statistics come from a dataset of 643 projects collated by market insights company, IoT Analytics.[6] The company's main business is in compiling insight reports for commercial operators to inform commercial strategy. Only 10 of the projects in the dataset fell into micro category indicating that they had an impact for fewer than 10,000 people. In contrast, 95% of the projects were classified as small or medium corresponding to city and country scale respectively. Additionally, the majority of projects were led by the private sector (70%) and originated in Europe or North America (80%). The third explanation for the uneven

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[6] https://iot-analytics.com/

attention is that the popular SDGs are those where commercial interests anticipate the most profit. SDG7 (Affordable and clean energy), SDG9 (Industry, innovation and infrastructure) and SDG11 (Sustainable cities and communities) are precisely those with the scale and financial resources to attract large commercial providers. In contrast, there is little financial incentive to deploy large-scale IoT systems to protect marine life or alleviate poverty.

Whatever the actual reason for the apparent disparities in coverage of the SDGs, a more balanced approach is clearly required. As argued above, concentrating on certain goals at the expense of others can have undesirable consequences.

10.4.2 Top-Down Solutions

The official indicators by which progress against the SDGs is measured are statistics gathered at the national level. To improve their performance against the targets, governments may be tempted to impose solutions in a blanket fashion. The same might be true at the level of the city or region where relevant authorities make decision on the inhabitants' behalf. Country- or city-wide projects are attractive to commercial providers because of the benefits they offer through economies of scale. Installing a large-scale system allows for the selection of a single set of technologies, simplified communications and centralised planning all of which greatly simplify the task. Large-scale installations come with risks, however. The first is that the technology may be quickly superseded which either means that the customer must continue to use obsolete equipment or invest in an upgrade. The larger the deployment, the more an upgrade will cost. Second, once a large amount of money has been spent with a single supplier, the customer is locked into the relationship since the costs of moving to a different supplier are too high. Third, a single solution over a wide area offers an attractive target for cybercriminals. A single weakness could allow access to the whole network of connected devices where a more heterogeneous mix would be more resilient.

As well as technical issues, there may be social consequences of solutions introduced in a top-down manner. Securing buy-in from the local community is more difficult when a solution is imposed from the outside. In addition, it is argued above that a generic solution may not address localised needs. A further risk associated with imposed solutions is the sense of disempowerment and helplessness that may be created among the intended beneficiaries, especially when the imposed solution is perceived as complex [10]. Finally, there is a risk that a top-down solution may suppress small-scale, bottom-up initiatives because of central control over the official system, for example, or because appropriate interfaces for interoperation are not provided. This would have the undesirable effect of excluding potential insights from citizen science and other participatory activities.

10.4.3 Digital Colonialism

The Internet is already dominated by a few large corporations, primarily from the United States. Guided by current commercial wisdom, these entities are still intent on growth despite their current reach, and developing countries represent a major opportunity to extend their user base. Many of them sponsor development programmes in which they offer free products to developing nations, or form investment partnerships with governments for the provision of services at much reduced rates [2]. Microsoft, for example, recently announced that it would be investing $1.1 billion over 5 years to create a cloud services region for Mexico [41]. The press release claimed that the initiative was about ‘democratizing the access to technology’ and highlighted a number of activities included in the programme such as a project to monitor pelagic sharks off the Pacific coast. While the immediate outcomes of the programme will undoubtedly be positive, the longer-term consequence will be an extension of the corporation’s sphere of economic influence at the expense of any potential local competitors. The result will be a net flow of revenue from Mexico to the United States and to Microsoft in particular.

The phenomenon of digital colonialism has been well documented in the literature. Michael Kwet [36] describes three specific ways in which large corporations seek to dominate markets in poorer regions of the world which are outlined below.

Economics
Digital corporations use their financial resources to enter markets quickly and create a dominant and potentially monopolistic position that no local competitor can challenge. Kwet cites the example of Uber which takes a 25% commission on every trip.

Architectural design
Companies who build technical infrastructure are positioned to ensure their own control over major parts of the technical ecosystem. The significant infrastructure elements for IoT are the communications equipment and the cloud services in the upper layers of the IoT architecture.

Intellectual property
Technology corporations can leverage their existing products to fulfil local needs crowding out competition. Licensing arrangements entail a net flow of revenue from the recipient country to the home country of the provider. One example where a country has resisted this type of domination is China where an internal technology ecosystem has been built by deliberately excluding foreign players.

An example of apparent corporate benevolence that is often held up for criticism is Facebook’s Free Basics[7] programme which offers a range of Internet services

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[7] https://developers.facebook.com/docs/internet-org/

at no cost to users. The free facilities are completely controlled by Facebook, and although users can pay to access services outside the walled garden, many do not have the resources to do so [2]. The offering also allows Facebook to collect data to create profiles of users in developing countries where it later intends to expand its presence [11]. Nor are such initiatives exclusive to the large household names of the technology industry. A deal between Zimbabwe and Chinese company CloudWalk will see the company collect data from facial recognition, and an arrangement for UK company Babyl to provide health care services in Rwanda will allow the company to establish a monopoly position through its ownership of medical data [70]. While addressing some immediate issues, such relationships only serve to entrench existing inequalities between countries.

10.5 Cellular Architectures

To realise the full benefit of IoT for sustainability, the positive aspects need to be exploited while keeping any negative consequences under control. Considering the foregoing discussion, the following set of recommendations can be proposed.

Complexity must be contained
The cloud-centric approach is not viable for certain use cases, and large-scale developments such as smart cities become unmanageable as they become more complex [10]. A fog-first approach is therefore appropriate.

Small-scale, bottom-up developments must be welcomed
To avoid the inertia created by top-down solutions and to exploit the ingenuity of ordinary people and communities; interoperability between devices and systems is vital. Governance therefore needs to be localised so that decision-making is not taken out of the hands of the users.

Heterogeneity is better than homogeneity
Large homogeneous installations are more vulnerable to cyberattacks. Heterogeneity provides greater resilience and is a prerequisite for the aggregation of many small-scale developments [19].

Infrastructure ownership must be equitable
To avoid digital colonialism, the infrastructure should be community-owned where possible. This also safeguards buy-in from the local community, reduces inequality at all levels and ensures that local solutions are tailored to local needs.

Equal attention should be given to all SDGs
A concentration of projects around a small number of SDGs may be detrimental to the overall progress. A balanced approach needs to be actively pursued.

While any attempt at a comprehensive solution to the issues discussed in this chapter must be doomed to failure, it is possible to suggest an approach that addresses the requirements listed here. Against the backdrop of the global trends outlined at the beginning of the chapter and in the face of the COVID-19 pandemic which has underscored the needs from radical, transformational thinking, the next few sections explore at a theoretical level the concept of a cellular architecture for physical environments for which IoT provides the blueprint.

10.5.1 Resilience

COVID-19 has demonstrated the fragility of what used to appear robust. While some scholars distinguish between sustainability and resilience [19], the capacity to withstand shocks is fundamental to a community's continued existence. The trend towards a greater concentration of people in cities means that they are increasingly identified as 'emergency-prone' environments [12]. Not only do infections spread quickly among their dense populations, but many other types of weakness can be identified including the risk of fire, flooding, coastal erosion, chemical concentration, heat stress and failure of utility distribution systems [12, 19, 31, 64]. Several authors have suggested hyper-localisation as a strategy for managing density and improving the urban experience typified by the '20-minute neighbourhood' concept [28]. Primarily aimed at delivering social benefits, the model proposes a planned urban fabric where most needs can be satisfied within a 20-minute walk, cycle or journey by public transport. Extending this idea, each neighbourhood could be designed to be as self-sufficient as possible as a radical response to the threats posed by climate change [45]. This cellular approach would include the local storage of water and energy, local food production using urban farming methods and the ability of each 'cell' to function autonomously at least for short periods. Changing the traditional planning mindset and embedding resilience planning in city governance procedures would be the greatest challenges. IoT technology is a natural fit for enabling cellular structures with its ability to deliver visibility of resource data. Additionally, the fog computing model enables reliable and responsive local processing which does not depend on external facilities.

10.5.2 Energy Distribution

The supply of electricity to city dwellers is just one example of a complex system where a single fault could affect many thousands of people. The typical electricity grid is designed as a centralised system in which electricity is transmitted from huge generation facilities through three hierarchical levels of network to the eventual consumer [30]. The accelerating integration of small-scale renewable sources into this top-down structure is a destabilising factor which has prompted some radical re-thinking of grid design. One potential solution is to build an inherently distributed architecture around the concept of inter-connected microgrids [27]. As the name suggests, a microgrid is an independent, localised power network that does not depend on external supply or control. Generalising the problem to include other types of energy including heat, biogas and hydrogen leads to the concept of the energy hub which could be used to manage the distribution of energy within and between neighbourhood cells [51]. Local energy storage would also need to be integrated, and the intermittent connection of electric vehicles adds further complication [8]. The smart grid concept, based on dynamic control of supply enabled by smart meters, can be invoked to manage small-scale structures just as well as today's utility-scale services [30]. IoT architectures incorporating fog computing provide an ideal control solution.

10.5.3 Local Clouds

The fog computing model is fundamental to the concept of the smart city and to cellular architectures in particular. It satisfies the need for autonomous local data storage and processing without precluding connections to cloud services where appropriate. Although the majority of fog computing examples in the literature envisage a simple fog layer composed of homogeneous devices, the OpenFog reference architecture actually allows for hierarchical arrangements of fog devices in arbitrary configurations [50]. This adaptability allows the paradigm to support neighbourhood cells of any size. Because it is already structured into cells, the mobile communications network is ideally placed to provide the uppermost level of a fog hierarchy. Lower layers could then be sized appropriately for their function. Interoperability is essential in this scenario to ensure that low-cost solutions such as those built on individual or clustered single-board computers are acceptable [23].

The advantages of localised clouds are not restricted to the technological dimension. The placing of infrastructure within the area of use rather than in a remote data centre makes the possibility of local ownership and operation much more realistic. While this might be challenging for mobile network operators, it is an essential element of an equitable deployment. It is a safeguard against digital colonialism in the IoT domain and encourages local engagement, innovation and the development of human capital.

10.5.4 Smart Villages

Given the trend towards larger and denser cities, it is natural to focus on the urban environment; however, the cellular model is equally applicable to the rural case due to its self-sufficient character. Leaders in developing countries have consistently expressed the need for economic development and access to technology [13]. The cellular approach offers a way of structuring small-scale, rural projects so that their benefits are maximised in the short term and their long-term value remains with the local community. This is implicit in the IEEE 'Smart Village' programme[8] in which volunteer engineers deploy renewable energy generation and localised microgrids to enable rural communities. By introducing a data layer based on the fog computing model, the IEEE concept could evolve quite naturally into a comprehensive cellular approach as outlined here.

10.6 Current and Future Challenges

The COVID-19 pandemic has dealt the world a shock from which it is struggling to recover. Costa & Peixoto [12] describe several examples of cities which are mobilising IoT technologies to detect viral outbreaks, trace contacts of infected people and manage the flow of information to health professionals. Other authors are imagining similar IoT-based responses to the crisis [7, 54, 60]. These initiatives demonstrate the power of the IoT concept and the range of problems it can be made to address. While responding to the immediate situation is important, the longer-term threats to human life require more radical thinking. There needs to be a willingness to imagine different ways in which technology – including IoT – can be used to improve the quality of life for all without risking that of future generations.

IoT technology is developing apace. Three clear trends are:

- The shrinking material and energy footprints of devices
- The evolution of communications networks to support low-power, low-bandwidth protocols
- The increasing availability of cheap, robust sensors

It is important that these trends continue, and pressure to further reduce power requirements by such means as ambient energy harvesting needs to be maintained. Greater interoperability between devices is also essential if the maximum benefit from IoT is to be realised. Listed below are several other areas for development which focus less on the technology itself and more on its context of use.

Greater data visibility across all SDGs
While the data needs of some SDGs are well-served, other are not. There is scope for IoT projects to be initiated which are aimed at filling the current data gaps.

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[8] https://smartvillage.ieee.org/

Public projects

Market forces are insufficient to address all of the SDGs. Public authorities at local, national and international level need to initiate projects to address those such as SDG14 (Life below water) which are not attractive to commercial interests. The deployment of sensors and the aggregation of data will be crucial to these efforts.

New commercial models

As well moving from linear to circular business models generally, there is also a need to alter the balance of power between large corporations and citizens of developing nations to protect their interests for the long term. A more cooperative approach needs to be developed in which local communities can participate in the ownership and operation of technical infrastructure more readily.

Harmonisation of localised models

The cellular model advocated in the previous section needs considerable elaboration and there are many dimensions to explore. The discussion highlighted several existing examples of localised structures including mobile cellular architectures, fog computing and microgrids. A comprehensive cellular model assumes that the reach of these and other localised facilities will neatly coincide. This assumption needs to be tested through modelling and simulation.

Definition of a reference architecture for cellular infrastructure

An understanding of how the various elements that make up a neighbourhood cell needs to be developed. A reference framework, possibly imagined as a series of layers, would be beneficial.

Protocols for inter-cell communication

A further assumption of the cellular model is that communication between cells and from a cell to the cloud are straightforward. This is also something to be tested through modelling and simulation and extends to material and energy flows as well as data.

10.7 Conclusion

The risks of ignoring the unsustainable aspects of human activity are great, but the slow pace at which they are gathering makes them easy to ignore in the short term. The COVID-19 pandemic has shown that transformational change is possible, however, and provides a salutary lesson on the interdependency of human life and other planetary processes. As the world recovers, attention is focussed not only on methods for avoiding and containing future outbreaks, but also on the processes by which the virus moved so quickly from being a biological curiosity to a global threat. This new period of reflection and international cooperation offers an opportunity to re-evaluate other dimensions of human society and their consequences.

Sustainability is an immensely complex issue with multiple dimensions, some of which conflict with each other. The 17 SDGs provide one means of rationalising the complexity. In the end, though, sustainability must be thought of as an emergent property arising from the interactions of myriad lower-level processes. Achieving the UN goal of sustainable development requires a holistic approach that gives equal attention to all dimensions of the problem simultaneously. Technology has an important role to play in many of the component areas, but it is vital to avoid the optimism of a purely technocentric perspective. Although the IoT is capable of facilitating efforts to increase sustainability through the fine-grained monitoring and control of physical resources, no technology is inherently benign. It is the engineers, developers, policymakers and entrepreneurs who decide how the technology is used. They can choose to employ it to promote sustainable development, or they can further entrench destructive linear business models and exacerbate existing inequalities.

The cellular architecture suggested here is an attempt to bias the design of IoT systems towards greater overall sustainability. It takes advantage of features already present in the fog computing model to imagine a more distributed approach than one based on a cloud-first assumption. It further positions the IoT as the main coordinating technology for the localised management of utilities and data processing services. Hyper-localisation has the potential to enable greater resilience in the face of external shocks, more equitable ownership of infrastructure and a better fit with local requirements. Improved interoperability is the main technical barrier to a more distributed approach, while at the socio-economic level the issue is that the commercial interests of large technology providers remain the dominant driving force behind large-scale IoT projects. An inherently distributed strategy challenges the centralising assumptions built into current business models and cloud-first architectures, but in the wake of the pandemic there is perhaps more willingness to re-evaluate them. Greater cooperation and a more holistic response to shared threats would allow the theoretical benefits of the IoT for sustainability to be fully realised.

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