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Internet of Things (IoT): Opportunities, issues and challenges towards a smart and sustainable future

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ABSTRACT

The rapid development and implementation of smart and IoT (Internet of Things) based technologies have allowed for various possibilities in technological advancements for different aspects of life. The main goal of IoT technologies is to simplify processes in different fields, to ensure a better efficiency of systems (technologies or specific processes) and finally to improve life quality. Sustainability has become a key issue for population where the dynamic development of IoT technologies is bringing different useful benefits, but this fast development must be carefully monitored and evaluated from an environmental point of view to limit the presence of harmful impacts and ensure the smart utilization of limited global resources. Significant research efforts are needed in the previous sense to carefully investigate the pros and cons of IoT technologies. This review editorial is partially directed on the research contributions presented at the 4th International Conference on Smart and Sustainable Technologies held in Split and Bol, Croatia, in 2019 (SpliTech 2019) as well as on recent findings from literature. The SpliTech2019 conference was a valuable event that successfully linked different engineering professions, industrial experts and finally researchers from academia. The focus of the conference was directed towards key conference tracks such as Smart City, Energy/Environment, e-Health and Engineering Modelling. The research presented and discussed at the SpliTech2019 conference helped to understand the complex and intertwined effects of IoT technologies on societies and their potential effects on sustainability in general. Various application areas of IoT technologies were discussed as well as the progress made. Four main topical areas were discussed in the herein editorial, i.e. latest advancements in the further fields: (i) IoT technologies in Sustainable Energy and Environment, (ii) IoT enabled Smart City, (iii) E-health – Ambient assisted living systems (iv) IoT technologies in Transportation and Low Carbon Products. The main outcomes of the review introductory article contributed to the better understanding of current technological progress in IoT application areas as well as the environmental implications linked with the increased application of IoT products.

1. Introduction

With rising technological developments in society, new possibilities have occurred and that could simplify our daily life and provide more efficient services or production processes. Digitalization has allowed "smart" (Zheng et al., 2019) to become the epicentre of already ongoing technological developments. In fact, IoT technologies are nowadays assumed to be one of the key pillars of the fourth industrial revolution due to significant potential in innovations and useful benefits for the population. On the other side, each development utilizes limited resources leaving behind different environmental footprints, (Li et al., 2020a), especially different kinds of pollutants, (Zeinalnezhad et al., 2020). Internet of things (IoT) based technologies bring a completely new

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perspective on the further progress of various fields, such as for instance in engineering, (Zaidan and Zaidan, 2020), agriculture (Farooq et al., 2020), or medicine (Salagare and Prasad, 2020), and in other fields that have not been explored yet. Some potential application areas in IoT technologies are still unknown or insufficiently clear on how to approach them which is an evident indication that more intense research activity should be conducted in this challenging field towards new and important potential benefits for society. Therefore, the relevance and importance of IoT technologies in future terms are more than clear and should play an important role.

The rise of IoT technologies is currently intense and according to projections for the next 10 years, over 125 $\cdot 10^9$ IoT devices are expected to be connected, (Techradar, 2019). The expected investments in IoT technologies are also high with expectations being over 120 $\cdot 10^9$ USD by 2021, with a compound annual growth rate of about 7.3%, (Forbes, 2018). The general present market structure of IoT technologies is presented in Fig. 1, where it is evident that the majority of the market is focused on smart cities and industrial IoT.

If recent projects in IoT technologies are being analysed than most of them are in the field of smart cities and industrial IoT. Other significant potentials are connected buildings, connected cars and energy segments (Forbes, 2018), but lower than the first mentioned fields. It is also found that the most rising trend in the number of IoT projects currently is as expected in smart cities, connected health and smart supply chain segments, with an annual rise over 30% in the EU and USA. Industrial IoT, connected cars and agriculture segments has recorded a decrease in the number of realized projects, i.e. over 25% in the USA and EU, (Forbes, 2018). From a perspective of high upcoming population pressure on cities and because a population of almost 11 $\cdot 10^9$ is expected by the end of the century (Pewresearch, 2019), the smart city concept could become a vital one to allow for a normal operation of highly populated cities.

In order to support the rapid technical development of IoT technologies, as well as novel potential applications areas, specific technical issues would need to be resolved, (Techradar, 2019). One of the main issues is associated with the development of different tools for the monitoring of network operations (Kakkavas et al., 2020), then issues with security tools and their management, (Conti et al., 2020), issues with software bugs, demanding maintenance of IoT networks, and finally security issues related to IoT networks, (Almusaylim et al., 2020). The important problem linked with the efficient implementation of IoT technologies is linked with the available speed and coverage of wireless networks (Wi-Fi), where expectations are high due to noticeable increases in Wi-Fi network coverage in the period of 2017–2022 as well as increases in Wi-Fi speed Fig. 2. In a global sense, increases in Wi-Fi

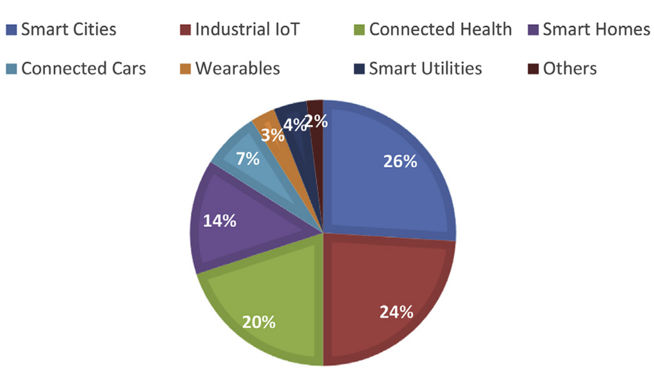


Fig. 1. General market structure of IoT technologies (Nižetić et al., 2019).

	2017 (Mbps)	2022 (Mbps)	Rise
Global	**24.4**	**54.2**	2.2↑
Asia Pacific	26.7	63.3	2.4↑
Latin America	9	16.8	1.9↑
North America	37.1	83.8	2.3↑
Western Europe	25	49.5	2.0↑
Central and Eastern Europe	19.5	32.8	1.7↑
Middle East&Africa	6.2	11.2	1.8↑

Fig. 2. Expected increase in global Wi-Fi speeds in period of 2017–2022 (Zdnet, 2018).

speed are expected for more than a factor of two, i.e. from about 24 Mbps to more than 54 Mbps. The most intense increase in Wi-Fi speed is expected in the Asian region, (Zdnet, 2018).

The lowest Wi-Fi speed is noticeable in the Latin America and Middle East&Africa regions, which are an indication of potential problems for the efficient implementation of IoT products or novel more advanced upcoming technologies.

An increased implementation of IoT technologies would lead to a more intense utilization of fossil technologies to ensure the necessary energy supply for IoT production lines. The production of electronic equipment is causing potentially unbalanced waste of limited metals and resources in general, which could become a critical issue in the long run. Unfortunately, the recycling rate of electronic waste is low and currently in the amount of about 20% (Thebalancesmb, 2020) which makes matters questionable regarding the available resource capacity to produce IoT products when taking into accounts the rising market demands. The production of electronic gadgets has led to the consumption of various chemicals, water and finally fossil fuels that have all left environmental impacts. As already tackled, different metals are also being used to produce electronics such as copper, silver, gold, palladium etc. One of the major issues is the led content in e-waste and its severe impact to the environment. Recycling in the previous sense is very important, where the present recycling rate of electronic equipment is certainly not sufficient and must be increased. Globally, the annual rise of the recycling rate ranges from about 4% to 5% (Thebalancesmb, 2020). The legislation related to the e-waste is one of the main drawbacks since more than 50% of world population is still not well covered with proper legislation related to e-waste, (Globalewaste, 2017), which is preventing the further development of e-waste facilities. The market value of raw materials from e-waste is estimated to be more than $50 \cdot 10^9$ Euros, (Globalewaste, 2017). Certainly, more strategic and targeted actions are needed in the e-waste issue to secure a more balanced and sustainable development of IoT technologies. Overall, the annual generation of e-waste is more than $44 \cdot 10^9$ metric tonnes, which is equivalent to more than 6 kg per inhabitant annually, (Globalewaste, 2017). A potential exists and must be better utilized to ensure a sufficient quantity of valuable raw resources.

It should be highlighted that there is no doubt in what IoT technologies would bring to the table, such as various useful benefits to society and an overall improvement in life quality. Each technology has specific issues and drawbacks that need to be detected and closely investigated on time, since IoT technologies have the potential to change our lives and habits. Several important facts need to be emphasized when addressing IoT technologies to be able to understand the long-term effects associated with the fast development of IoT:

- IoT technologies have caused an increase in the utilization of limited resources or raw materials where some of them have become rare or are already rare (for instance, specific precious metals for electronics),

- The prices of electronic devices have become more acceptable, which means an increase in production volume, finally more resources are being utilized. A rebound effect is possible in that sense,
- The long term environmental impacts of IoT technologies are unknown. A noticeable amount of energy would be needed to support the production and operation of IoT devices,
- An increase in electronic waste is expected due to the large estimated number of IoT based devices in the near future,
- In some sectors, IoT technologies could have social impacts due to the reduced necessity for labour and limitation of direct social contacts, which is vital and an important aspect for each human being.

The main point of the above raised issues is not to indicate and create a negative attitude towards IoT technologies but to carefully analyze the overall aspects in order to secure a smart and sustainable development of IoT technologies, which are a valuable opportunity for humanity.

1.1. Necessity for smart technologies

The world is rapidly changing, i.e. developing in a technological sense and is being driven by the present economic system globally. Unfortunately, each technological development has got its price, which can be sensed through the intense utilization of limited fossil-based resources and the production of various impacts to the environment, (Chen et al., 2020a). The population is constantly growing with an annual rate of about 1.1% per year with the current population being over $7.7 \cdot 10^9$ (Data.worldbank, 2020). As previously addressed, the population concentration is in cities and according to UN projections, about 68% of the population will be living in cities by 2050, (UN, 2018). A significant infrastructure pressure is expected in cities due to boosted urbanization, thus novel technological solutions would be key to secure the normal operation of cities in the given complex and demanding circumstances. In the previous sense, the general application of IoT and smart technologies would have an important role and could help to bridge some major infrastructure related issues in cities. The necessity for IoT technologies is closely linked with ongoing technological advancements and digitalization where a variety of different electronic products need to be somehow connected in a useful manner. There is a necessity for more efficient services and flexible processes in general, which could be obtained with the proper implementation of IoT technologies. IoT technologies have allowed for a variety of efficient services and smart networking, applications or devices that can ensure useful synergic effects and produce benefits. The major advantage of IoT technologies is their connectivity aspect that has enormous potential, Fig. 3.

Various benefits are possible and would be gradually integrated in our lives thorough upcoming years in different application areas and will be briefly discussed in the upcoming section of the introductory review editorial.

1.2. Application areas

The application areas of IoT are various and based on current available technological solutions, the most represented application sectors are shown in Fig. 4. The most important and most progressing application areas of IoT are related to the industry (Osterrieder et al., 2020) and smart city concept (Sivanageswara Rao et al., 2020), with respect to the number of realized projects.

The transportation (Porru et al., 2020), smart energy management in buildings (Douglas et al., 2020) or management of power networks (Martín-Lopo et al., 2020), as well as the agriculture sector (Villa-Henriksen et al., 2020) are also promising, having significant potential.

The development of specific IoT application areas strongly depends from several key factors such as:

- general available advancements in electronic components,
- available software solutions and user friendly surrounding,
- solutions related to sensor technologies and data acquisition,
- quality of network, i.e. network connectivity and infrastructure,
- sufficient energy supply for production and operation of IoT devices.

In the continuation of the review editorial, some key IoT application areas will be briefly addressed together with the main developments and current challenges.

1.2.1. IoT in industry

The application of IoT technologies in industrial applications would allow for an increase in efficiency regarding the production process and would ensure more efficient communication and networking between operators and machines, Fig. 5. Finally, it would allow for more competitive companies on the market with more efficient quality control with a minimization in losses. A critical feature would be the development, design and integration of various useful sensors in the industrial applications (Li et al., 2020b), to form integral and effective management systems. More intense research efforts are needed towards an efficient application of IoT technologies in the industry and to better understand how IoT technologies could be implemented in specific industries where benefits would be possible. Progress is crucial in the sense of how to connect different industrial sensors, use and process the collected various data to enable enhanced industrial processes, i.e. ensue for instance smart IoT based Computer-Integrated Manufacturing, (Chen et al., 2020b).

1.2.2. IoT in smart city concept

The role of IoT technologies in the smart city concept (Janik et al., 2020) is crucial to bridge the already mentioned global infrastructural challenges in cities, which are linked with the current increase of population in cities. IoT technologies in smart cities would enable the utilization of different devices, which would increase the life quality in cities as well as the efficiency of different daily services such as transportation, security (surveillance), smart metering, smart energy systems, smart water management, etc. Different sensing devices would receive information, which would be processed towards efficient and useful solutions. The main benefit of IoT technologies in smart cities would be directed to the early detection of different problems or infrastructural faults (such as issues with traffic jams, energy supply, water shortage, security incidents, etc.). In smart cities, many sensors are installed and linked with many other devices over the internet which gives information to the users as for instance parking spaces, any malfunctions, electrical failure and many other issues. Developing these technologies would help in leading the cities towards smart grids, smart healthcare, smart warehouses, smart transportation, smart waste management, smart communities, etc. Different implementation challenges towards the smart city concept exists, Fig. 6 and should be solved for various applications, (Fig. 7).

The most present implementation challenges are linked with the efficient integration of different sensing technologies, development of a suitable network infrastructure, education of population, investigation of the sustainability aspect, such as carbon footprint, etc.

The application of IoT technologies in smart homes, (Moniruzzaman et al., 2020), within the smart city concept allows

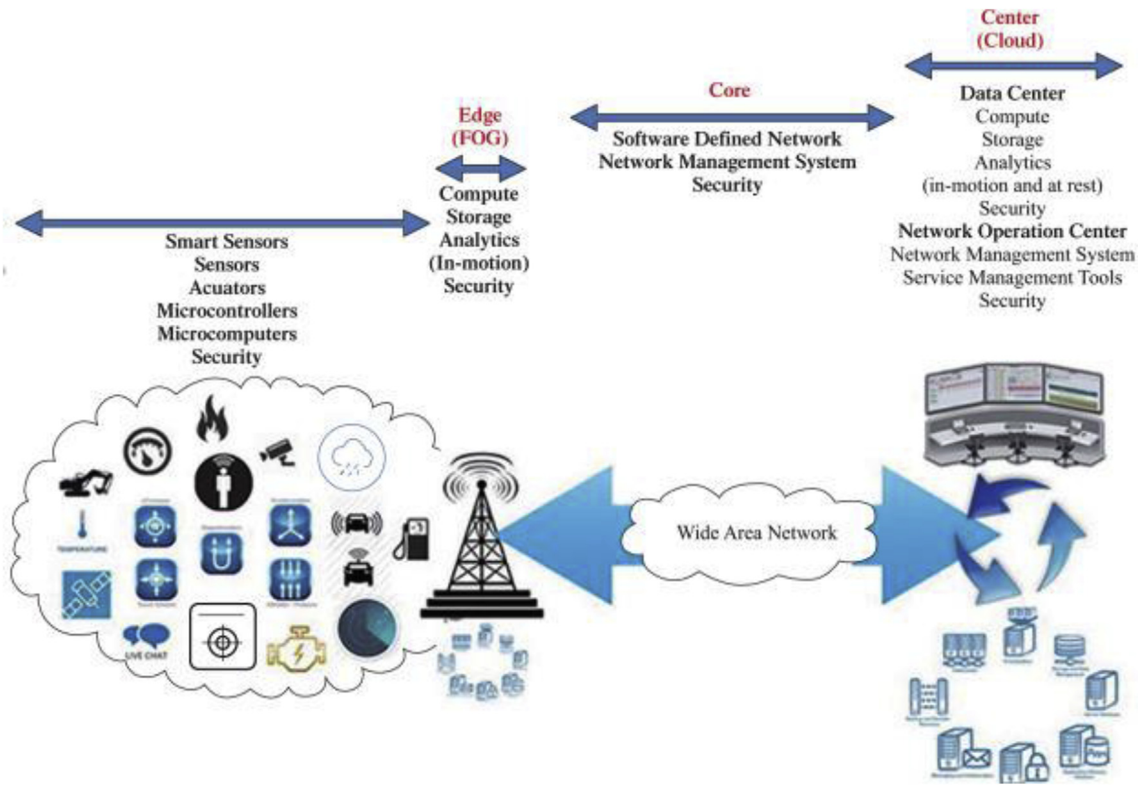


Fig. 3. General structure of IoT network and connectivity (Zhang et al., 2018).

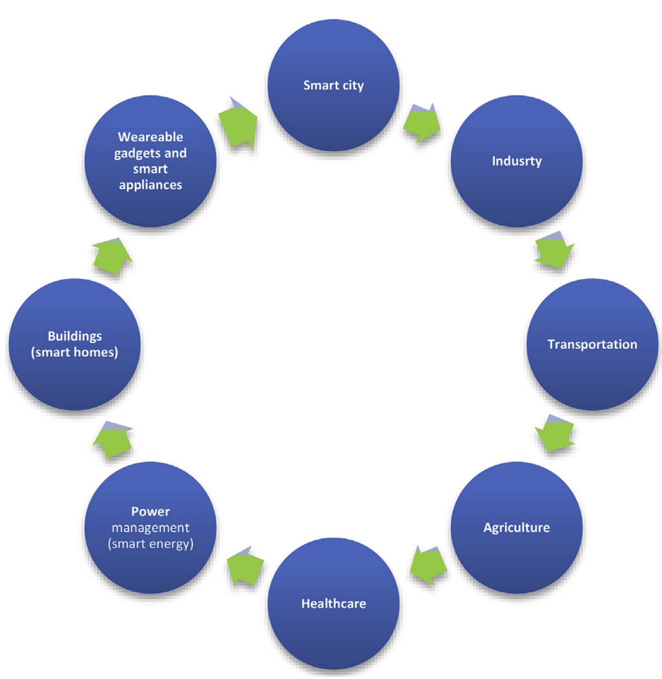


Fig. 4. Application areas of IoT technologies.

for an increase in the life quality within residential facilities, bringing novel and attractive technological solutions. Both, energy and fund savings could be reached with more efficient time management, which is a valuable feature in our present economic system. Different control options are possible within the smart home concept and enable an efficient integration of renewable energy technologies in homes (Stavrakas and Flamos, 2020), and their efficient balancing (efficient supply and demand).

1.2.3. IoT in agriculture

Efficient agriculture production is a necessity for our population to prevent the potential lack of food resources in future terms caused by different factors, (Hussain et al., 2020). The first factor is constant population growth, as already emphasized, the second is linked with climate change issues (Yang et al., 2020), which is causing a reduction in the yields of important crops, or some areas are even becoming unsuitable for efficient agriculture production. The food waste issue is one of the major problems (Keng et al., 2020), since it has become a global problem, especially in developed economies. It is estimated that more than 28% of available agriculture areas is “reserved” for food waste and unfortunately more than $800 \cdot 10^6$ people are currently hungry, (Fao.org, 2020). The implementation of IoT technologies in agriculture can certainly help to secure sufficient food demands and increase the efficiency of agricultural production processes in general. Various useful data about crops could be collected and used for yield monitoring and the detection of potential diseases in advance that can significantly reduce the yields of specific crops. The monitoring of soil and nutrients would rationalize agricultural production processes and lead to water savings that are precious in some specific geographical regions, which could be utilized through smart irrigation systems, (Xin et al., 2020). A more precise seeding could also be ensured and fertility crop management in general, Fig. 8. There are some issues linked with the efficient application of IoT technologies in agriculture production. Different sensing and monitoring technologies should be developed and a better education of farmers should be provided (i.e. development of standard education modules for farmers). Due to a large quantity of collected data, farmers

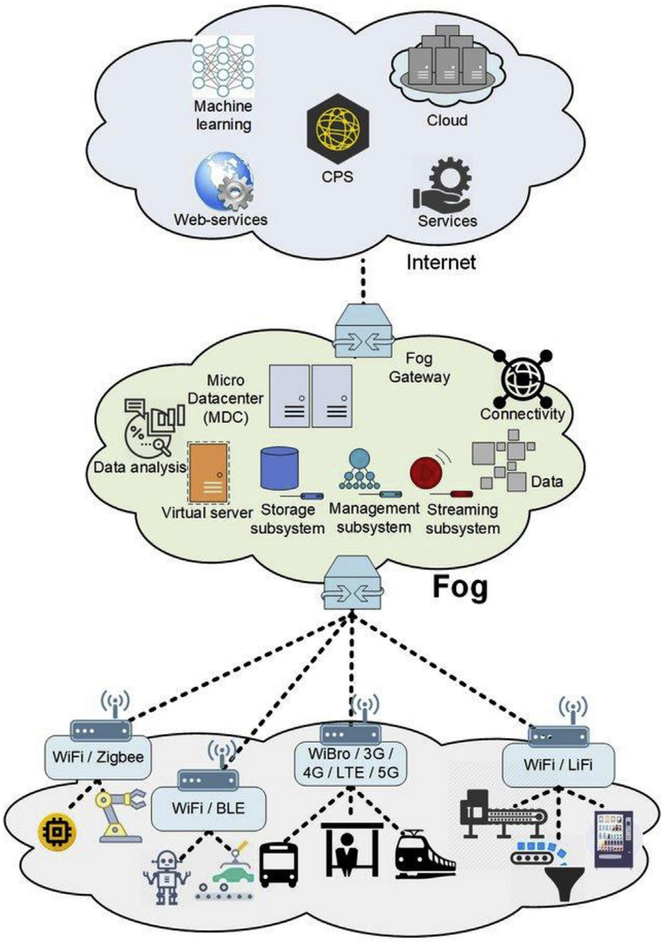


Fig. 5. General concept of IoT industrial application (Aazam et al., 2018).

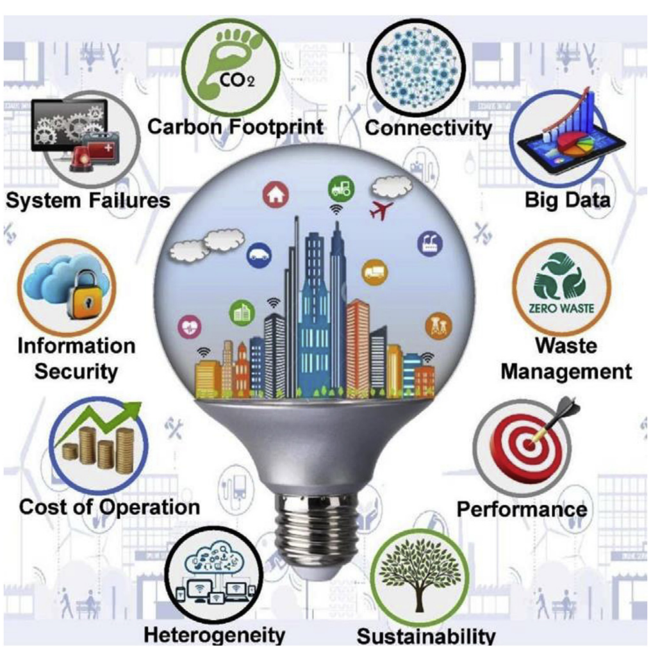


Fig. 6. Different challenges in Smart City concept (Bhagya et al., 2018).

could be potentially overwhelmed, (Ec.europa, 2017). Therefore, there is a necessity for the development of standard trainings (education modules) for farmers coupled with the development of more user-friendly software solutions.

The application of IoT technologies in the agricultural sector would lead to advancements that could drastically modify current production procedures in agriculture, (Shafi et al., 2020) (Fig. 8).

1.2.4. IoT in waste management

Waste management towards a circular economy concept (Fan et al., 2019) is a vital current population problem, where there is certainly a role for IoT technologies that could help provide more efficient waste management in specific areas (Voca and Ribic, 2020) and recycling of different limited resources, (Qiu et al., 2020). Currently, various technological solutions are being developed to support the smart waste management concept, (Das et al., 2019). Some of them are already available on the market for wide implementation, (Iot.farsite, 2020). The developed solutions are mostly directed towards the smart monitoring of waste bins (Dhana Shree et al., 2019), i.e. bin filling level detection, waste temperature and fire detection, bin vibration occurrence and bin tilt, presence of waste operators, waste humidity, bin GPS location etc. In general, smart waste management systems, can be effectively supported by IoT devices, Fig. 9. IoT technologies could also be used for the smart coordination of waste trucks (Idwan et al., 2020) and efficiency waste utility companies could be ensured in that manner, which would be followed by a reduction of harmful emissions (pollutants) created by garbage trucks, (Kozina et al., 2020). From the perspective of smart technologies, the proper and IoT based waste management of electronic waste is very important (Kang et al., 2020) to secure sufficient raw resources to produce electronic equipment as already highlighted. IoT technologies could also be used for the reduction of food waste through intelligent appliances and a developed management structure in that sense, (Liegeard and Manning, 2020).

Innovative IoT based technological solutions are expected to be developed in upcoming years, especially from a smart city concept perspective and that could support smart waste management systems and a circular economy concept.

1.2.5. IoT in healthcare

One challenging implementation field of IoT technologies has been detected in the healthcare system in general, through the e-health concept, (Farahani et al., 2020). An increase in the service quality of healthcare systems could be utilized through IoT support (mainly collection of patient health data) and finally with the improvement of patient safety and care since it could also lead to an increase in patient life expectancy. There is an enormous potential in smart medical devices for different purposes (Papa et al., 2020) that can be utilized for the monitoring of various vital and valuable human functions such as heart rate, skin temperature, movement monitoring, etc. Remote health monitoring is also an interesting perspective that could be utilized with the proper support of IoT devices and products. The prediction of different symptoms and prevention of potentially life hazardous states and diseases could generally be enabled, (Muthu et al., 2020). Assistance to the elderly could also be ensured by monitoring a patient's general health condition and nutrition status (Nivetha et al., 2020), that would be supported via IoT devices. Rehabilitation after a serious disease could also be efficiently supported with IoT technologies, especially in cases of home rehabilitation circumstances, (Bisio et al., 2019). One of the main issues and challenges in this specific IoT

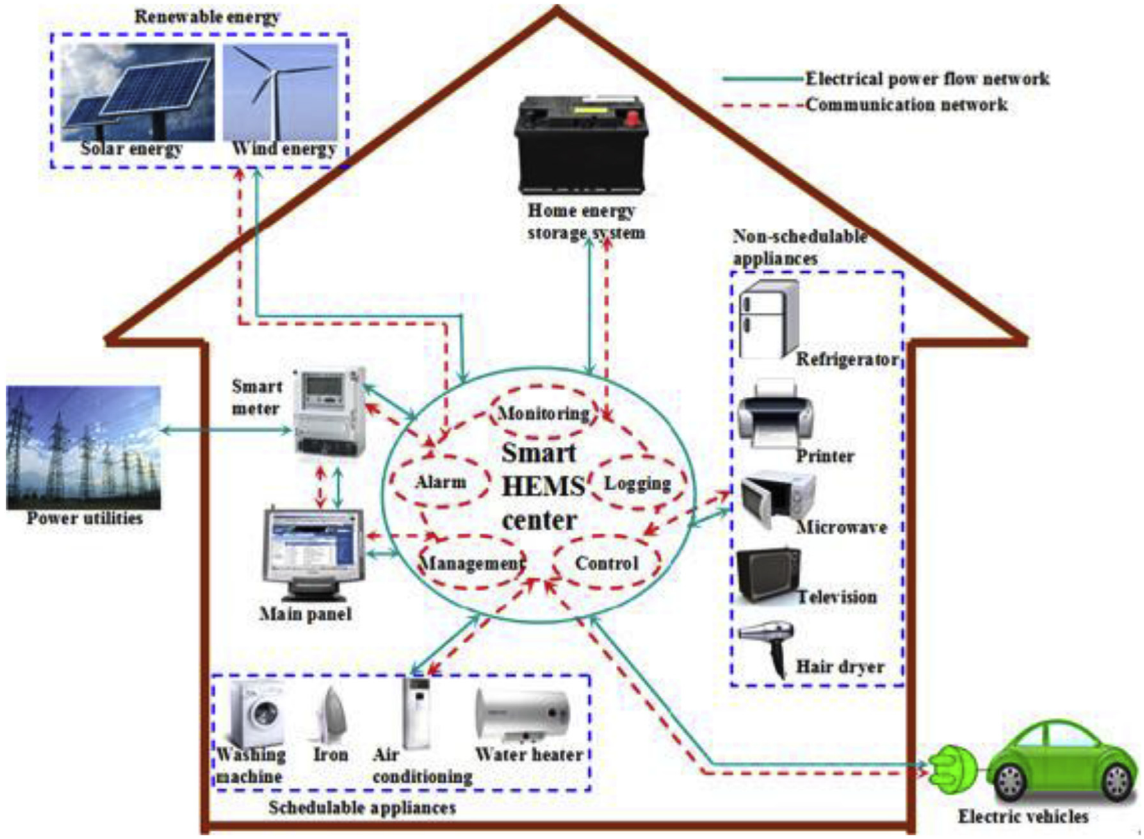


Fig. 7. Various smart home management systems (Zhou et al., 2016).

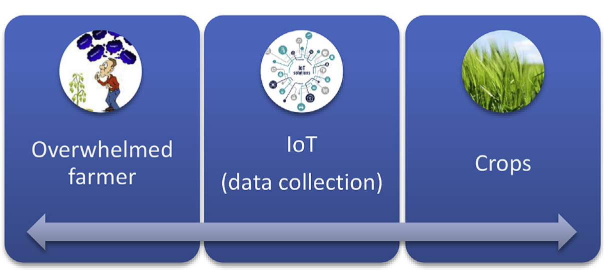


Fig. 8. IoT in agricultural production from farmer's perspective.

application field would be to ensure proper cyber safety due to potential attacks that could occur within healthcare monitoring systems, (John et al., 2019). Significant progress in upcoming years is expected in the field of software development for health care systems, i.e. especially in hospitals. Namely, different devices could be linked via advanced software solutions as for example MRIs or CT devices and connected with laboratory data to create a smart hospital information system. The previously mentioned approach would allow for the better treatment of patients, detection of medical priorities and support for medical staff in monitoring and therapy decisions. IoT systems could also be used in hospitals for the efficient maintenance of a large number of medical devices (Shamayleh et al., 2020). Equipment costs could be reduced in hospital systems due to the early detection of severe equipment malfunctions that could affect the accuracy of specific readings from medical devices. The development of smart and based IoT solutions in healthcare systems could also be very useful in the case of severe global pandemic states (data collection and fast data diversity, resources of medical staff and resources, medical triage, etc.), such as is the recent corona virus situation that has severely threatened the global population, (WHO, 2020). The healthcare sector is probably one of the most challenging areas for IoT, thus important progress is expected in the upcoming year with serious benefits for the population.

1.2.6. IoT in transportation

Transportation modes will be significantly changed in upcoming decades, (Jonkeren et al., 2019), especially due to the expected rising implementation of electric cars on the market, (Capuder et al., 2020). The upcoming ban of Diesel based vehicles due to environmental issues (Li et al., 2020c) and finally development of alternative transportation technologies, such as hydrogen based vehicles for example (Ajanovic and Haas, 2019), would change the shape of future transportation systems. In general, there is a demand for more environmentally suitable transportation options that are already being gradually developed with an expected penetration on the market. A necessary development of transportation infrastructure is needed for specific vehicle technologies to ensure desirable vehicle autonomy. Nowadays, the IoT emerged in the "internet of vehicles" concept (Shen et al., 2020), which just proves its potential in this important area. The most significant IoT application area is in the case of the smart car (vehicles) concept, (Chugh et al., 2020). The smart car concept considers the utilization and optimization of different internal functions in the car that are supported by IoT technologies. The application of IoT would upgrade driver experience and increase in comfort and safety. Specific data are collected in the smart car and associated with the main operating parameters such as tyre pressure, fuelling, early detection of potential failures, regular maintenance indicators, etc. In

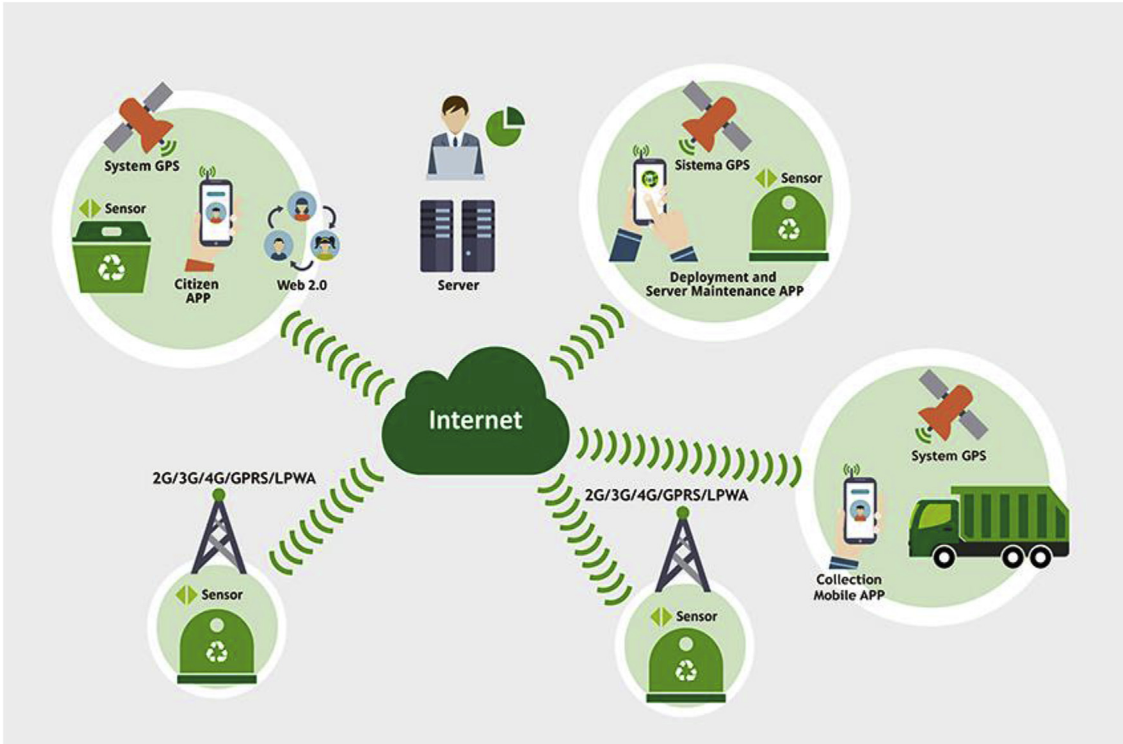


Fig. 9. IoT in smart waste management system, (Quamtra, 2020).

general, improved service as well as added value for customers could be obtained with a targeted utilization of IoT technologies, which finally can improve competition in the automobile industry between vehicle manufacturers. The challenging aspect of IoT application is in the case of autonomous vehicles, (Padmaja et al., 2019). Location, direction as well as a planned path of the autonomous vehicle could be efficiently supported with IoT in general as well as the monitoring of safety systems for autonomous vehicles, (Bylykbashi et al., 2020). The most important issue with autonomous vehicles is the prevention and avoidance of crash vehicle accidents, which could be solved with a targeted utilization of IoT devices, (Abdou et al., 2019). Smart parking is also currently one of the most developing IoT areas when considering the transportation sector in general terms. Different research efforts are provided in that sense with the main goal being to enable the latest status of available parking space, control and monitoring of different useful parking space information in real time, (Luque-Vega et al., 2019). Again, the development of sensor technologies, i.e. smart parking sensors is very important to enable efficient and accurate service, (Perković et al., 2020a). The maintenance and failure prevention of different vehicles could also be supported by IoT (Saki et al., 2020), which could improve security and the lifetime of vehicles. Taking all the previously addressed into account, IoT technologies could completely change the driving experience and generally improve the quality of transportation systems from various aspects.

1.2.7. *IoT in smart grids and power management*

Energy transition (Biresselioglu et al., 2020) has become a necessity due to the potential shortcomings of fossil fuel resources in future terms and for the reduction of different pollution impacts that are associated with the utilization of various fossil-based technologies, (Bielski et al., 2020). Since a more intense implementation of renewable energy technologies has already been occurring, the efficient and advanced power management of electric grids has become an important aspect. Efficient demand side management with accurate and flexible smart metering technologies are key factors to enable smart power management in smart grids, (Mendes et al., 2020). The most important role of IoT technologies in smart grids is to save electricity (Rishav et al., 2019), with efficient distribution of electricity, Fig. 10. The collection of specific grid data through IoT devices, and later their analysis with the proper software, could help improve grid reliability and efficiency. The economic aspect of electricity could also be improved with IoT due to the already mentioned efficiency improvement as previously highlighted. Useful benefits could be ensured both for customers and service providers.

A demand side management in households is also an important application area of IoT, (Rahimi et al., 2020). Homes are typically equipped with different appliances that are becoming more advanced, creating the possibility for an efficient operation with the regulation of IoT, (Tawalbeh et al., 2019). The efficient and smart forecasting of electricity demands for households could also be effectively supported by IoT technologies, (Nils et al., 2020). An expected higher penetration of renewables in households through hybrid energy systems as an example (Gagliano et al., 2019), would also require a smart operation strategy that could be utilized by IoT through integrated smart nano-grids, (Kalair et al., 2020). A growth of IoT products and technologies in smart power management is expected to enable accurate forecasting and different load strategies in the case of renewable generation, (Pawar et al., 2020). The elaborated main issues and challenges above just reflect the importance of IoT devices in smart grids and power management.

1.3. *Review methodology*

By addressing all the above raised general challenges towards an efficient and suitable implementation of IoT technologies, it is evident that more intense research efforts are needed to lead to further advancements in this dynamic research topic, with a strong

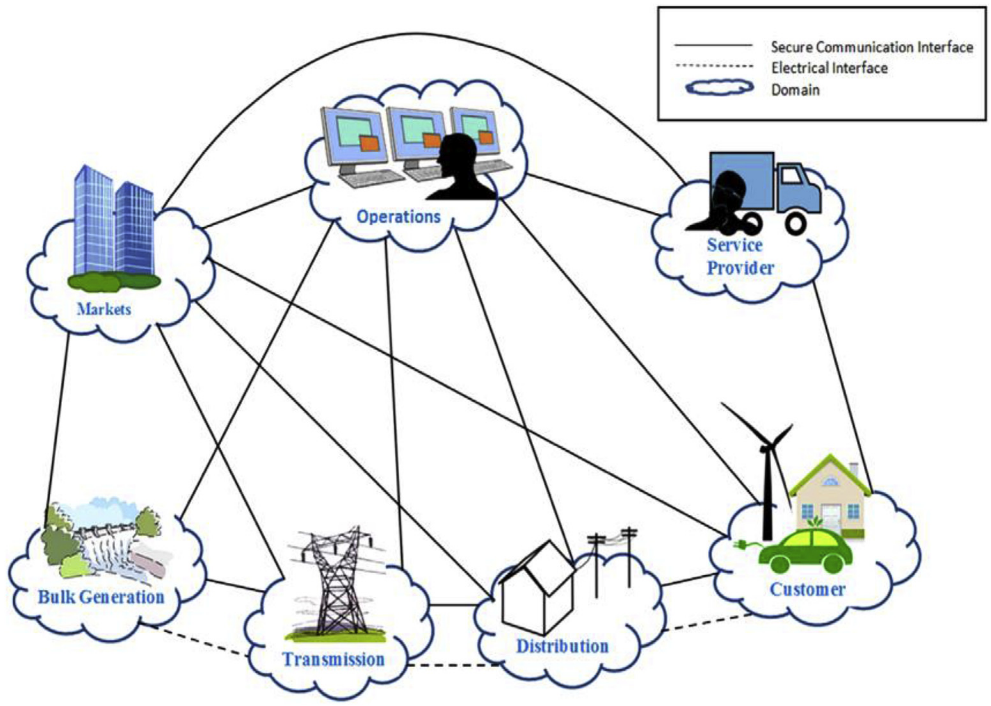


Fig. 10. Concept of smart grids (Tuballa and Lochinvar Abundo, 2016),

application potential. A synergy of different research efforts in the field, mainly focused on the targeted topical area is needed. The main contribution and novelty of this review editorial is in line with that. Further main topical areas are addressed in the herein review introductory editorial;

- IoT technologies in sustainable energy and environmental issues,
- IoT enabled Smart City
- E-health – Ambient assisted living systems
- IoT technologies in Transportation and Low Carbon Products

The main objective of the herein presented review editorial is to address and discuss the latest advancements in the above specified and key IoT application areas. This review editorial serves as an introduction to the Virtual Special Issue (VSI) of JCLEPRO devoted to the 4th International Conference on Smart and Sustainable Technologies (SplTtech 2019) held on 18–21 June 2019, in Bol (Island of Brač) and Split, at the University of Split, (Croatia). The herein presented introductory review editorial was directed to the selected and accepted publications from the international conference SpliTech2019 and published papers were divided into four main topical areas as already specified above. Overall 38 papers were initially selected and invited for potential inclusion in the VSI SpliTech 2019. After conducted peer-review process, based on the JCLP procedures, 29 of them were selected for inclusion in the VSI SpliTech 2019. Authors from following countries have contributed VSI SpliTech 2019: China, India, Australia, Canada, Italy, Croatia, Serbia, Greece, Poland, Czech Republic, Spain, Cyprus, Turkey, Norway, Iran, Germany, Brazil, Malaysia, Pakistan, Dubai and United Kingdom. Besides the selected VSI SpliTech2019 works published in the JCLEPRO, the other relevant and latest works from the existing literature in the field were also addressed using the Scopus database, (Scopus, 2020). Based on the conducted review as well as selected contributions in this VSI the key issues were identified, discussed and highlighted in the conclusion section.

2. IoT technologies in sustainable energy and environment

The rapid development of information technologies caused in one sense the necessity for "energy digitalization". The increasing application of renewable energy technologies and development of efficient policies will be key points in upcoming decades to be able to secure global energy transition goals, (Tzankova, 2020). Referring to the previous, the development of alternative renewable energy sources would also be valuable, (Nižetić, 2010). Different energy scenarios or options have been considered in recent years involving a high share of renewables via hybrid energy options (Nizetic et al., 2014), or for instance the possible application of alternative energy sources such as hydrogen technologies in different implementation fields (El-Emam et al., 2020), or vehicle applications (Matulić et al., 2019). The focus of the research is to investigate the techno-economic viability of different energy concepts in order to secure a suitable mix of energy technologies that would support an efficient energy transition. An improvement in the energy efficiency of different renewable energy technologies is also important, especially in the case of photovoltaics (Grubišić-Čabo et al., 2019) and wind generation technologies (Marinić-Kragić et al., 2020), to secure large scale projects. The efficiency of specific production processes (Giama et al., 2020), is also vital and certainly needs to be carefully investigated and analysed, to reduce energy intensity and provide a circular economy concept in specific application areas, (Xu et al., 2020). The main research efforts should be directed towards the upgrade of energy saving technologies followed with the increasing utilization of renewable energy sources, (Klemeš et al., 2019). Recent technological progress in the field of IoT technologies has enabled different opportunities for the possible application of IoT concepts in the energy sector and environmental protection to secure a sustainable development.

Energy and environment are two of the most important elements of Smart Cities and are very often closely interrelated concepts. The available challenges in energy management to use and generate energy in the most efficient manner possible, and the development of a sustainable energy structure can take advantage of Internet of Things (IoT) and Internet of Energy (IoE) technologies, Fig. 11 (Mohammadian, 2019) or in the case of battery charging protocols (Fachechi et al., 2015).

The climate change and global warming impose a paradigm shift in the exploitation of resources and in more efficient energy resource management: production, distribution and consumption, as an integral part of this vision. The energy transition must point to an infrastructure change at the center of which there are the so-called smart grids. With the advent of smart grids and new technologies, the energy industry is inexorably changing. The most interesting aspect is that smart grids ensure flexibility in demand and allow consumers to participate in the energy system, as prosumers. Smart grids exploit digital and innovative technologies to manage and monitor the transport of electricity from all sources of generation to promptly, quickly and effectively satisfy the demand of end users. Smart grids are raising reliability, system resilience and stability, and minimizing disruptions, costs and environmental impacts. Some of these new technologies such as Distributed Generation (DG) and microgrids provide energy locally, creating larger and more reliable networks and reducing the line overload. Energy storage complements the energy from renewable sources while microgrids help reduce any blackouts by providing energy locally. Unlike the existing power system of a unidirectional system, which distributes electricity generated from a power plant to the consumer, the microgrid is equipped with a local power supply and storage system centered on independent distributed power sources. It is an energy network that can connect with an existing power system as needed and the self-sufficiency of energy such as electricity and heat by using multiple distributed power sources independently. In addition to giving owners the ability to generate their own energy, microgrids also reduce the dependency on energy providers by helping reduce costs and avoid peak usage charges. The microgrid can produce revenue if it were to produce a surplus of power, which could be sold to the energy provider. Recent works in the energy related field are discussed in the upcoming section of the paper to highlight IoT implementation areas and clarify the benefits in specific engineering applications.

In microgrids, IoT technologies are introduced mainly to realize a smart system able to autonomously schedule loads and/or detect system faults and then improving the efficiency of the energy consumption. The work (Nayanatara et al., 2018) proposes a renewable energy based microgrid management strategy to use renewable energy (solar energy from a photovoltaic panel and wind energy from a wind turbine) effectively reducing the energy usage from the power grid. IoT technologies are used to realizing a smart scheduling algorithm able to control schedulable loads as per the needs of the consumer. Authors demonstrate that the proposed energy management system installed in an institution enables low power consumption and reduced costs. In (Sujeeth et al., 2018) an IoT-based automated system that constantly monitors the current and voltage flowing through various branches of a DC microgrid, detects and controls the fault clearance process during fault conditions that has been developed. The system is capable to alert the user during overcurrent faults, ground faults and short circuit faults. As the operation of a microgrid is automated, the need for human decision making is eliminated and the minimum reaction time to react to fault conditions is drastically reduced. The work (Majee et al., 2018) is also focused on the issue of fault management within a microgrid exploiting the IoT. The concept of IoT is used to solve the issues of microgrid reconfiguration occurring due to faults, changing energy usage patterns and the inclusion and removal of distributed energy resources.

Smart grids can automatically monitor energy flows and adapt to changes in energy demand and supply in a flexible and real-time manner. These smart systems can benefit from technologies such as machine learning (Chou et al., 2019) and artificial intelligence (Bose, 2017) to perform predictive analyzes and better configure all

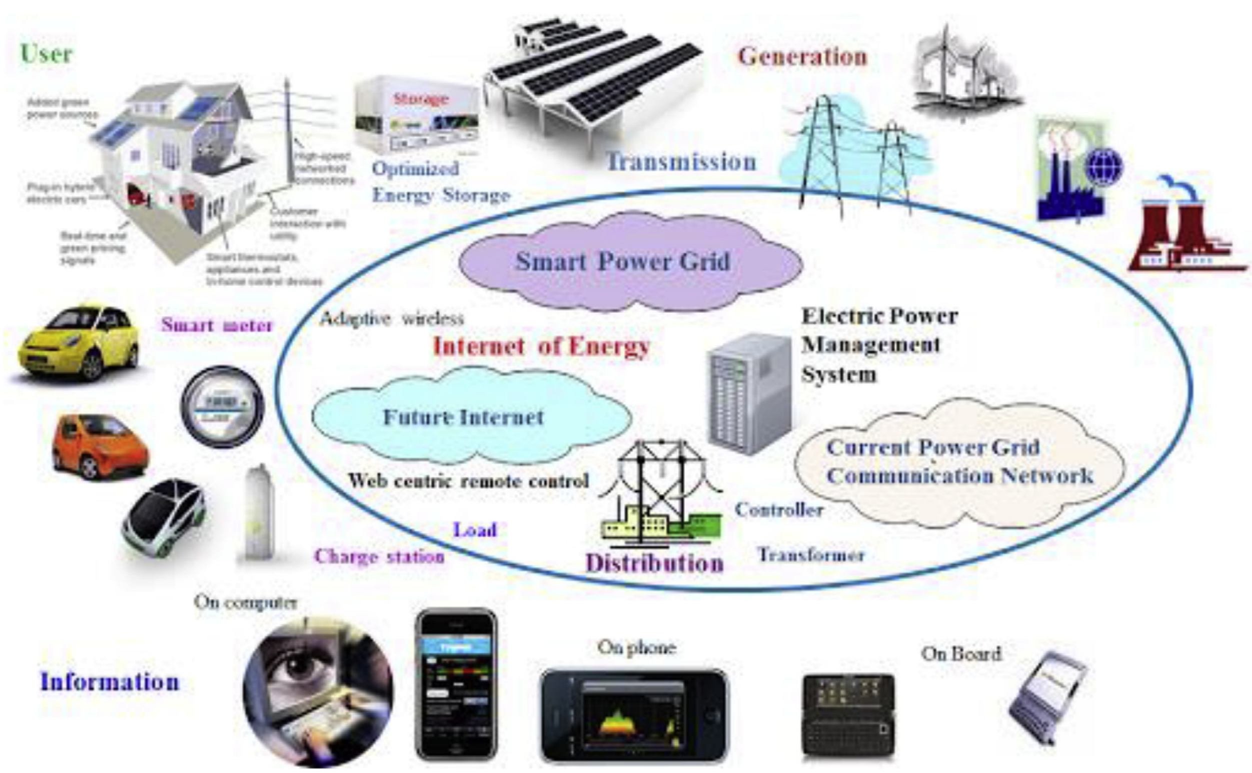


Fig. 11. IoE architecture (Mohammadian, 2019).

the devices. To do this, however, smart grids require adequate and equally intelligent measuring instruments. Here, smart metering tools could be efficient solution, reaching the consumers and suppliers, providing them with information on consumption in real-time. With smart meters, consumers can adapt - in terms of time and volume - their energy consumption to different energy prices during the day, saving on their energy bills by consuming more energy in periods of lower prices. In this perspective, the possibilities generated by improved digitization and sensorization, utilizing to the Internet of Things solutions, has led many research works to focus on realizing innovative IoT-based hardware and software solutions. These solutions are capable of providing real-time information about the quality usage of appliances, data consumption, and energy flow information (Morello et al., 2017). present an interesting study on the role of advanced smart metering systems in the electric grid of the future through the realization and the experimental validation of a smart meter, Fig. 12. The cost effective three phase smart energy meter, IoT enabled, multi-protocol and modular, capable to collect, process, and transmit several electric energies related information, mainly focused on consumer-side, to any smart energy control system was proposed by (Avancini et al., 2018), Fig. 13.

Several solutions are also based on the use of the Arduino platform (Arduino, 2020) and a few sensors for the realization of low-cost smart meters (Patel et al., 2019) or for instance Arduino based solutions (Saha et al., 2018). Although smart grids are fundamental elements when it comes to energy sustainability, it is reductive to identify the concept of smart energy only in them. In fact, smart buildings also play a crucial role. The energy efficiency of building structures using smart technologies provides an increasingly intelligent management of resources, avoiding waste, improving the life quality of people and making the buildings themselves more resilient in the face of current climate changes. Thanks to building automation and IoT not only individual buildings but also entire neighborhoods can be controlled remotely from an energy point of view and in terms of the security. For example, it is possible to carry out checks on air pollution remotely (Becnel et al., 2019), monitor fire systems (Cavalera et al., 2019) or, furthermore, immediately detect any intrusion by outsiders (Dasari et al., 2019).

Smart buildings are able to monitor actual energy needs, optimizing consumption and therefore counting not only on green energy, but also on a high degree of energy efficiency. The virtuous process that passes from smart energy allows to count on Nearly (Net) Zero Energy Building (NZEB) (Rushikesh Babu and Vyjayanthi, 2017) and on a wider energy sustainability.

The most common use of IoT for energy and environmental sustainability is in the home automation systems, which allow

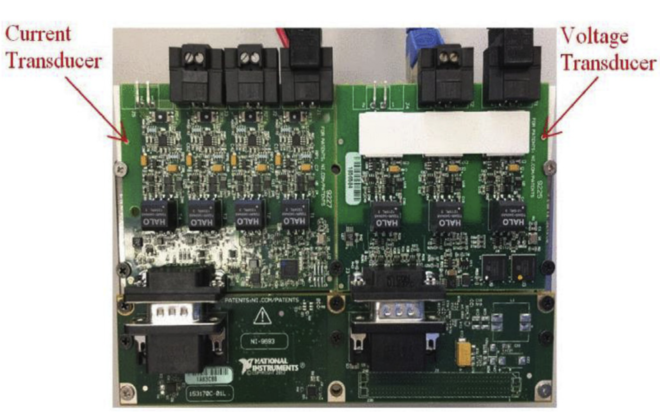


Fig. 12. Proposed smart power meter, (Morello et al., 2017).

homeowners to live comfortably and manage energy consumption through connected devices. In this field, numerous applications have been implemented and, despite the common goal of creating an Energy Management System (EMS) for home, the techniques used to achieve it can be very different. For example (Li et al., 2018), propose a self-learning home management system that exploits computational and machine learning technologies, Fig. 14. The proposed system has been validated by collecting real-time power consumption data from a Singapore smart home. In (Al-Ali et al., 2017), an EMS for smart home is realized exploiting off-the-shelf Business Intelligence (BI) and Big Data analytics software packages to better manage energy consumption and meet consumer demands. In this work, the proposed system has been validated realizing a case study based on the use of HVAC (Heating, Ventilation and Air Conditioning) Units. Smart energy solutions such as those analysed provide real-time visibility of consumption and billing data, helping consumers to save resources, while energy and service companies can better balance production to meet actual demands, reducing potential problems. As the main effect, the energy consumption of families is reduced, also decreasing our impact on climate change.

In addition to buildings and homes, industrial facilities and enterprises also deal with the adoption of innovative energy efficiency solutions to optimize resource consumption and reduce costs, but they need to evaluate a high number of factors to adopt the best energy efficiency measures. The work (Suciu et al., 2019) proposes an IoT and Cloud-based energy monitoring and simulation platform to help companies monitor energy production and consumption, forecast the energy production potential and simulate the economic efficiency for multiple investment scenarios.

The concept of sustainability is increasingly linked to that of circular economy, which is now considered the key to this new paradigm. Unlike the traditional linear economy, based on the so-called “take-make-dispose” scheme, which provides for a complete utilization of resources, the circular economy model promotes reparability, durability and recyclability. In practice, the circular economy aims to minimize waste through reuse, repair, refurbishment and recycling of existing materials and products, focusing attention on designs that last over time. In this system, the IoT is considered an essential element, as it offers new opportunities in various sectors, such as manufacturing, energy and public services, infrastructure, logistics, waste management, fishing and agriculture. Especially in the field of waste management, research has made great strides through the creation of innovative systems capable of concretizing the concept of digital economy. In the work (De Fazio et al., 2019) the activities related to the research project called POIROT were discussed, which exploit innovative hardware and software technologies, aiming to realize a platform for the inertization and traceability of organic waste. In detail, the main project objective is to realize a targeted transformation, through technological processes, regarding the organic fraction of urban solid waste, into inert, odorless and sanitized material, identified and traced to be employed for building applications or as thermal acoustic insulator, Fig. 15.

Several works propose solutions to support waste management at a domestic level, simplifying the waste separation to avoid problems due to improper waste management including hazards for human health or environmental issues. For example (Al-Masri et al., 2018), propose a server-less IoT architecture for smart waste management systems able to identify waste materials prior to the separation process. This allows reducing costs related to the waste separation process from hazardous materials such as paint or batteries (Kumar et al., 2017). propose a hygienic electronic system of waste segregation. The proposed approach eases the segregation of wastes at source level and thereby reducing the human interaction and curbs the pollution caused by improper segregation and management of wastes at source level.

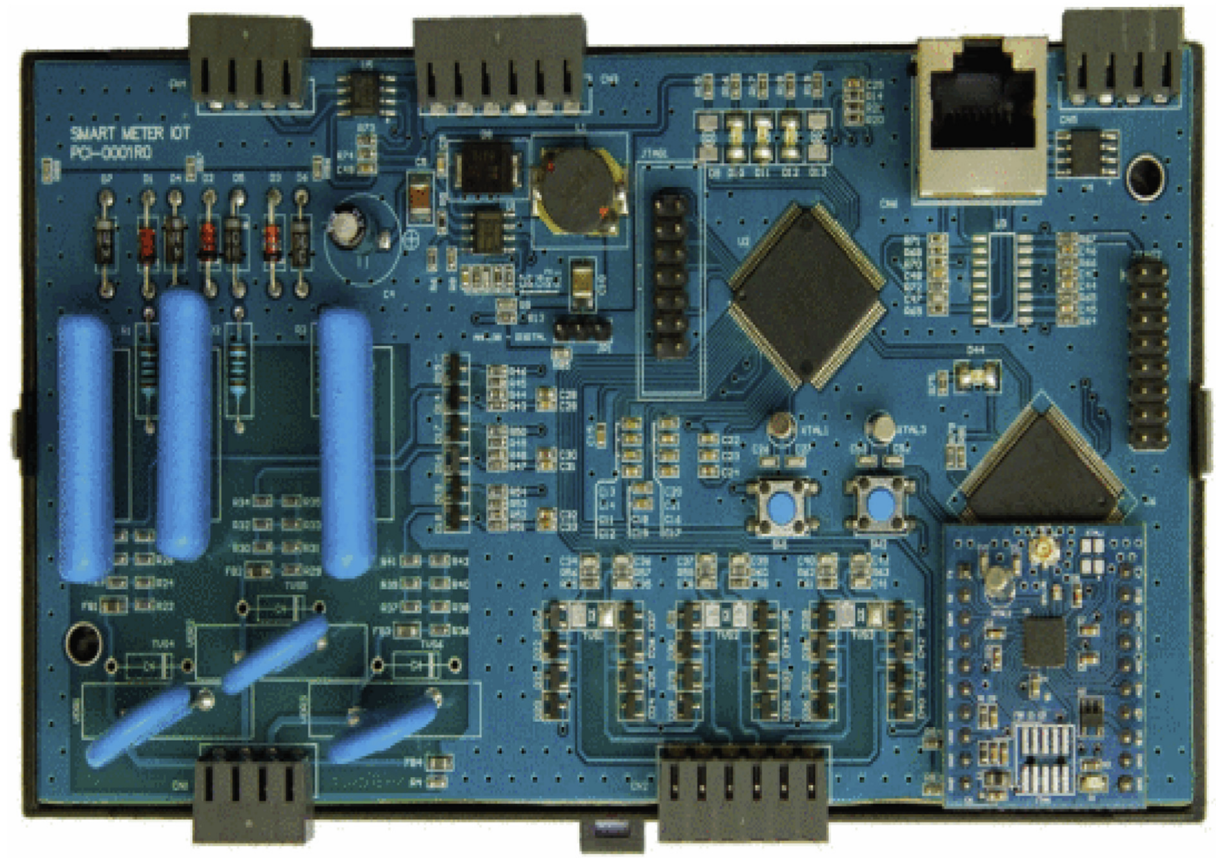


Fig. 13. Photo of created IoT enabled smart energy meter (Avancini et al., 2018).

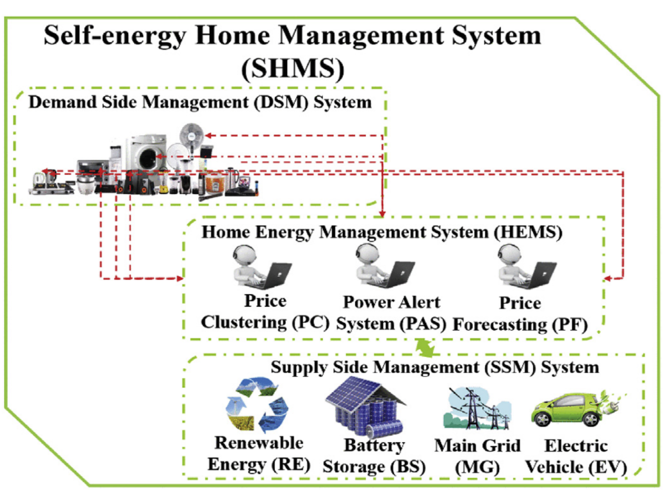


Fig. 14. Self-learning home management system architecture (Li et al., 2018).

The role of IoT supported smart meters was considered in the work (Mendes et al., 2020) to address different demand side management scenarios. The novel and adaptive compression mechanism was proposed in the same work to improve the communication infrastructure for the given case, i.e. complete controlling structure, Fig. 16. The proposed mechanism can reduce the quantity of data sent to utility companies and can automatize energy consumption management.

The proposed and tested control solution showed to be efficient with respect to the considered application, since compression rates were satisfactory and the proposed concept showed potential for other applications. The demand side management of a hybrid rooftop photovoltaic system was discussed in (Kalair et al., 2020) where the system was integrated in a smart Nano grid. The smart monitoring system was presented in detail for residential purposes, together with a developed experimental setup that contains specific electronic components, Fig. 17. The developed controller can automatically detect any frequency and voltage changes and link them with specific loading patterns. The proposed solution demonstrated efficiency since the power supply reliability was up to 97%. The proposed home management system could lead to the reduction of carbon footprints in the case of residential facilities.

A machine learning-based smart home energy system was investigated in (Machorro-Cano et al., 2020), using big data with the support of IoT. The home automatization system was coupled with IoT devices that enabled energy savings for the given purpose. A machine learning algorithm was used to study user behaviour and was later linked with energy consumption, i.e., with the proposed approach, specific user patterns were revealed. The developed monitoring system, Fig. 18 allowed specific recommendations to lead towards an improvement of energy efficiency in households, which were somehow personalized for the specific household. The system was successfully validated via the provided case study where the main strength of the conducted research was the personalized approach for the specific household. A step further could be to network and balance other households in the specific building facility. The importance of the BIM (Building Information Modelling) systems was discussed and analysed in the review

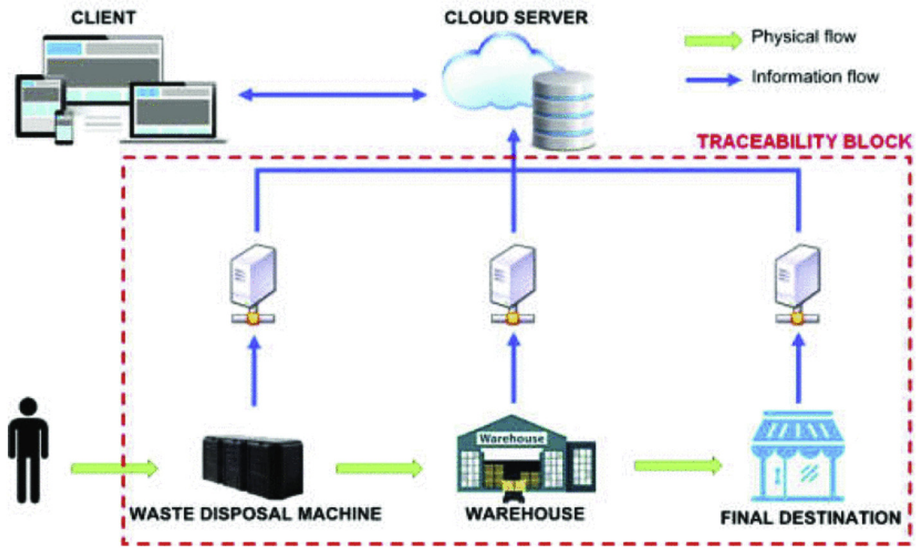


Fig. 15. Architecture of proposed identification and traceability system, (De Fazio et al., 2019).

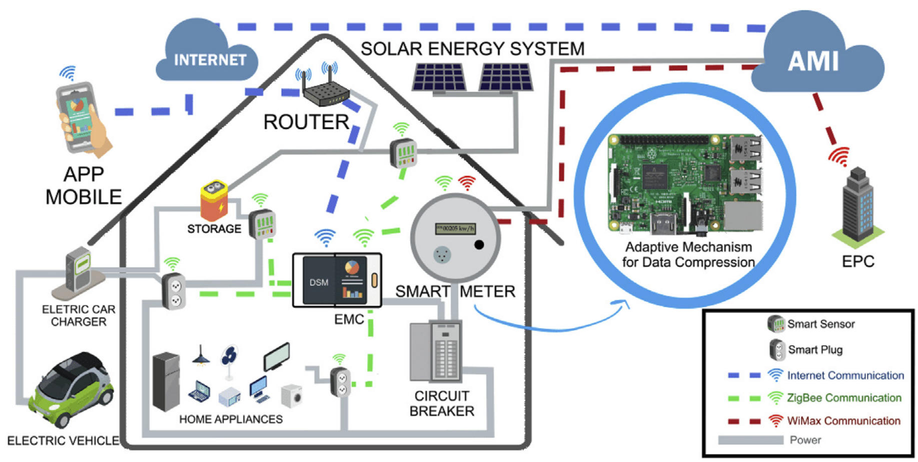


Fig. 16. Proposed general controlling structure (Mendes et al., 2020).

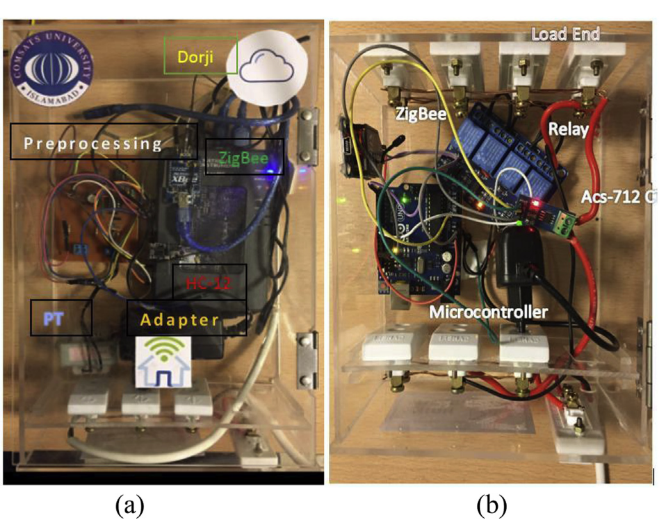


Fig. 17. Experimental setup with pre-processing unit (a) and smart controller (b) (Kalair et al., 2020).

paper (Pantelia et al., 2020). An overview of the recent works focused on the building smart operation was elaborated in detail with use of IoT technologies. In the same work the renovation projects were also tackled as well as interoperability problems caused by data sharing with respect to the BIM related applications.

An application of smart wearable sensors was reported in the study (Pivac et al., 2019) that were used for the monitoring of thermal comfort data as well as for the modelling of occupant metabolic response in office buildings. The smart and IoT supported monitoring system allowed the collection of useful data from the wearable sensors. The readings helped for the better understanding of thermal comfort issues in office buildings from a personalized thermal comfort point of the view. The experimental readings were compared with a subjective response from the occupants, where a successful modelling of personal metabolic responses was enabled with an accuracy of over 90%. Industrial facilities could also be improved with the implementation of IoT technologies as already briefly addressed in the introduction section. Legislation support is important to ensure smart electricity utilization in the households, especially from the perspective of the smart city concept. Study (Grycan, 2020) discussed legislative for electricity consumption for

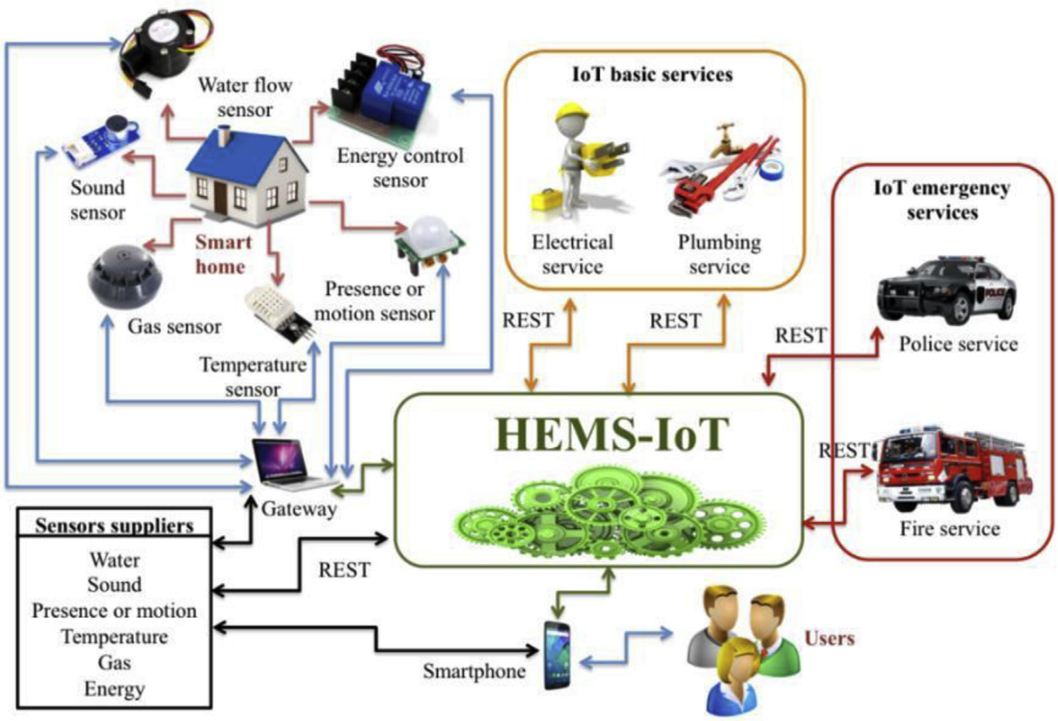


Fig. 18. Concept of proposed IoT supported smart home system (Machorro-Cano et al., 2020).

the case of the Polish residential sector. Lack of legislative was detected and mainly in the smart metering solutions that are slowing down development of the smart infrastructure. There is necessity for the new regulations to ensure adaptability to the novel desired goals towards smart cities. Development of the novel business models is important to ensure smart driven business in the energy sector. The case of the smart energy driven model was elaborated in (Chasin et al., 2020) as well as implications and necessary changes in the energy sector. Eight smart business models were discussed with introduction of desired changes. Presented knowledge and development business scenarios could be useful guideline for energy utility companies. The possibility of IoT based smart solutions was discussed in the review paper (Bagdadee et al., 2020), where the focus of the work was on IoT-based energy management systems in the industry. IoT based energy management systems were elaborated for industrial applications as well as for smart energy planning in industrial facilities. The energy management systems in factories were addressed from a perspective of energy demand and supply. The focus of IoT applications could also be used on a level of single or multiple devices or appliances. The scheduling and optimal power management of the transformers was analysed and discussed in (Sarajčev et al., 2020). The Bayesian approach was applied to detect an optimal controlling strategy to ensure benefits for power utility companies. The proposed and demonstrated model can predict the transformer health index with an accuracy of about 90%. The solution could be applied on the fleet of the power transformers where with the application of IoT technologies, further savings could be ensured for the specific application. The efficiency of the lighting system could also be improved with IoT devices. The work (Mukta et al., 2020) discussed and reviewed the possible application of IoT technologies for the energy efficiency improvement of highway lighting systems. The results of the conducted review revealed that the development of smart and IoT supported highway lighting systems lack a systematic approach, quality and comprehensiveness. Possible framework was proposed to bridge the mentioned gap and secure an efficient pathway for the improvement of energy efficiency in IoT based lighting smart and green highway systems. The necessity for the environmental suitability of the proposed smart lighting system was also raised in the same study and noted as an important factor that needs to be further investigated. Energy harvesting is also interesting topic and closely linked with the possible application of IoT technologies, especially since IoT devices require energy for their operation. An underwater piezoelectric energy harvesting system was discussed in (Kim et al., 2020) for the case of autonomous IoT sensor production. The proposed solution was fully designed and provided in the form of a prototype and demonstrated an autonomous energy source that could be further linked with IoT devices. The harvesting of waste energy could also be considered with the implementation of IoT devices. The possibility for waste energy harvesting supported by IoT was addressed and discussed in (Kausmally et al., 2020) for the case of an industrial chimney. The complete design procedure was reported, i.e. the conceptual approach for the waste heat recovery where the prototype was successfully developed and demonstrated. Energy storage systems are also interesting for the application of IoT technologies. A renewable energy storage system was analysed in (Sathishkumar and Karthikeyan, 2020), where a power management strategy was supported by IoT. The optimal design of a hybrid energy system coupled with energy storage was discussed based on solar and wind renewable energy resources.

The IoT approach allows successful monitoring and managing of complex energy systems. The main advantage of IoT for the considered application is the energy efficiency improvement, better synchronization of different energy systems and improvement of the economic aspect. A significant development of IoT products would lead to a rapid increase of big data that are usually processed by data centres. The energy load of data centres is increased, so efficiency improvements are necessary in the case of data centres to minimize load power as well as utilization of other limited resources. The issue related to data centres, power demands and the possible application of IoT technologies in order to reduce the mentioned unwanted impacts was discussed in (Kaur et al., 2020). The authors proposed a specific framework in the same work that is applicable for data centres and could lead to efficiency improvement of over 27% (proposed approach was based on empirical evaluations).

IoT technologies could also be successfully implemented in a circular economy concept as above already mentioned, especially in smart waste management systems and environment protection as already mentioned. The role of IoT technologies in e-waste was discussed in (Kang et al., 2020) for the case of the Malaysian recycling sector. A novel smart waste collection box was designed together with a user friendly mobile application, Fig. 19. The concept was successfully demonstrated. The developed solution could be further optimized and fitted for possible market implementation. A discussion of possible IoT framework, based on the developed IoT supported smart e-waste bin was elaborated for the Sunway city in Malaysia. The proposed approach could be a helpful guideline for other cities. The remaining issue with the proposed concept is its economic feasibility that should be further investigated via a detailed user survey, detecting user willingness for the acceptance of the proposed concept. The innovative IoT supported platform for the transformation of organic waste into inert and sterilized material was reported in (Ferrari et al., 2020). The specific Arduino-electronic platform was developed to control process parameters and link them with user responses and traceability. Novel

Fig. 19. Prototype of smart e-waste bin (Kang et al., 2020).

and low cost sensors were developed and successfully applied for the given purpose. The proposed prototype of the device was presented and was used for the mechanical treatment of waste. The developed IoT supported framework for the identification and traceability of products was presented in Fig. 20.

The implementation of IoT technologies in a circular supply chain framework was elaborated in (Garrido-Hidalgo et al., 2020) for the waste management of Li-ion battery packs from used electric vehicles. A novel and IoT supported supply chain framework was proposed, which is compatible with the information infrastructure. The approach could be further used for the recovery process of Li-ion batteries. Due to a planned increase in electric car fleets globally, intensive research was also directed for the potential usage of IoT technologies for the smart charging of electric vehicles. Real time IoT based forecasting applications were proposed in (Savari et al., 2020) for a more efficient charging process of electric vehicles. The application allowed better scheduling management where the waiting time was minimized, which improved the overall charging economy as well as charging time.

Environmental protection and sustainable behaviour could also be improved with the targeted application of IoT technologies. In the study (Irizar-Arrieta et al., 2020), long-term field investigation was presented with the main goal being to investigate how IoT technologies could help ensure the sustainable behaviour of users in office building facilities. The results of the conducted directed study could lead to the improvement of energy efficiency at workplaces with IoT utilization in different aspects. The impact of IoT technologies on a sustainable perspective and society was addressed in (Mahmood et al., 2020). The study was focused on addressing the impacts of home systems on the environment and sustainability in general. A survey was conducted for specific users and the investigation showed that the impact of home automatization on sustainability and environment is significant. However, the environmental effects should be discussed in more detail and quantified to get realistic indicators that would later be used for sustainable planning.

Besides the obvious potential impact of IoT technologies to the environment, IoT products could on the other side be used for environmental protection. The design and concept of a systematic framework for the massive deployment of IoT-based PM (Particulate Matter) sensing devices was elaborated in (Chen et al., 2020c). The proposed framework was applied for the monitoring of air quality. Compressed spatiotemporal data were used and that allowed for the efficiency improvement of air quality monitoring systems, energy savings and improved data saving ratio. In order to improve the interoperability between different sensor networks, as well as data sources, a novel IoT data framework was proposed in (Duy et al., 2019). The proposed analytical framework was used as a useful tool to improve the data management of environmental monitoring systems. The developed framework enabled a more efficient utilization of the gathered environmental data and improved knowledge extraction later. IoT platforms could also be used for environmental planning as it was demonstrated in the study (Wu et al., 2019). In the conducted research, a building information model was integrated successfully with IoT and used for environmental planning for environmental protection reasons. Moreover, the system was used for environmental protection in a specific construction project (tunnel utility). Different impacts to the environment were monitored during the construction project such as dust falling control, temperature monitoring, visual monitoring etc. The overall findings directed that the proposed IoT supported system showed to be effective for the considered application. The application of an IoT based data logger was presented in (Mishra et al., 2020), for the monitoring of equipment for environmental protection. The developed monitoring system

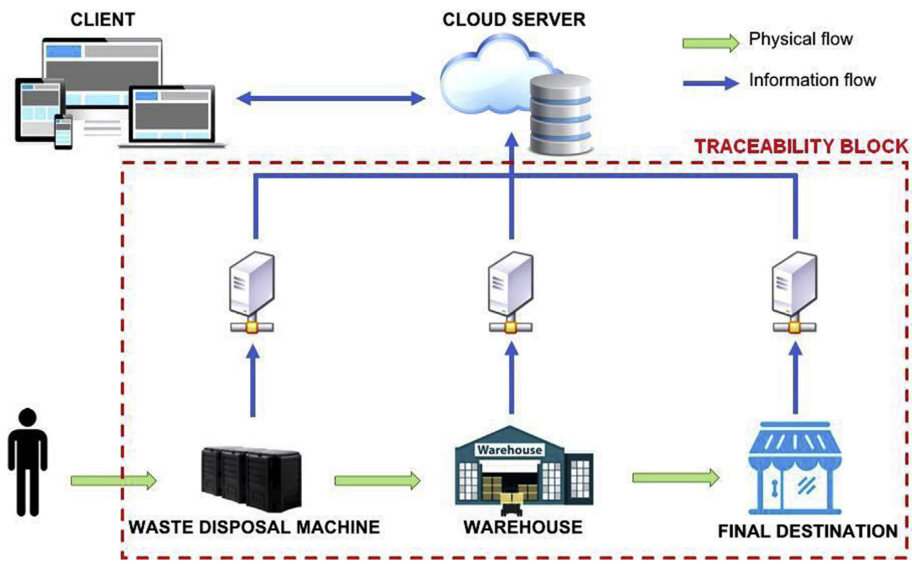


Fig. 20. Conceptual IoT supported framework for waste processing (Ferrari et al., 2020).

ensured accurate and reliable work of the equipment used for the environmental protection. Potential equipment faults were detected in advance (prevention of serious failure), the equipment energy consumption was rationalized and scheduled maintenance was enabled. The accurate prediction of particulate matter ($PM_{2.5}$) concentrations is very important, especially in urban areas. Usually, there is a network of sensors used for the monitoring of $PM_{2.5}$ concentrations but they are not well connected and harmonized in some situations, which is vital. An IoT framework was used, together with a fusion technique, to improve the data utilization from the PM measuring stations in the work (Lin et al., 2020). A novel multi-sensor space-time data fusion framework was proposed that ensured better accuracy, i.e. a more reliable model was ensured with a higher spatial-temporal resolution. Regarding the current progress of specific application areas in IoT devices for environmental protection, it can be conducted that the studies were mostly focused on air quality monitoring. Water-Energy-Carbon (WEC) nexus was analysed in detail for EU27 countries, in the recent work (Wang et al., 2020) by implementation of the Environmental Input-Output model (EIO). Study was important since contributed to the better understanding of the environmental performance in EU27 and could serve as important basis for future considerations or planning for policymakers.

Based on the previously conducted overview of latest research findings related to the application of IoT technologies in sustainable energy and environment, the further main findings could be highlighted:

- IoT technologies are intensively investigated from a perspective of smart monitoring in different devices or engineering components that are associated with energy applications. Better usage and networking of various collected data could lead to noticeable efficiency improvements, energy savings, improved safety, improved equipment maintenance and finally the general improved operation of devices in different engineering applications,
- The economic aspect associated with the application of IoT technologies was not addressed in most studies, which is a significant drawback,
- The environmental impacts associated with the implementation of IoT technologies for specific use were not addressed, which is serious and an important issue that should be carefully considered and investigated when discussing specific IoT concepts. Moreover, an integral techno-economic-environmental conceptual approach (TEE) should be applied when considering an IoT application for specific cases,
- The main advantages (benefits) of IoT technologies enable a personalized approach in specific engineering applications such as smart homes (level of single user), which lead to different possibilities for both energy and fund savings,
- There is significant potential in IoT technologies for environmental protection; however, rare studies have been conducted in that sense. More intense research efforts are needed in that direction to be able to utilize all the potential benefits of IoT technologies and improve the environmental suitability of IoT in one sense,
- The waste management and circular economy concept could be well supported with IoT technologies, where the main issue is the development of integral and conceptual smart waste management frameworks that would efficiently support the circular economy concept in different economies.

3. IoT enabled smart city

To enable the IoT-based smart city concept, Fig. 21, is described in the form of a tree that can be considered to further understand what the possible applications or functionalities the IoT-enabled Smart City can provide. The branches of the given tree are dedicated to applications, wherein the leaves of the given branch are dedicated to the functionalities that each application can have. As the more leaves a branch contains, the more functionalities it has. Fig. 16 represents the different functionalities of a smart parking system for instance. Further on, for example, smart homes can have many functionalities: smart metering (electricity, water consumption, gas monitoring), smart lock control, smart room temperature monitoring, smart kitchens and other appliances, etc. The root of the given tree (enabler and information source of these systems) is dedicated to the hardware whose system uses to accomplish any of the given possible functionalities. This section considers an overview of the most important hardware technologies, and software architectures that can enable and present functionalities for different applications in the smart city concept.

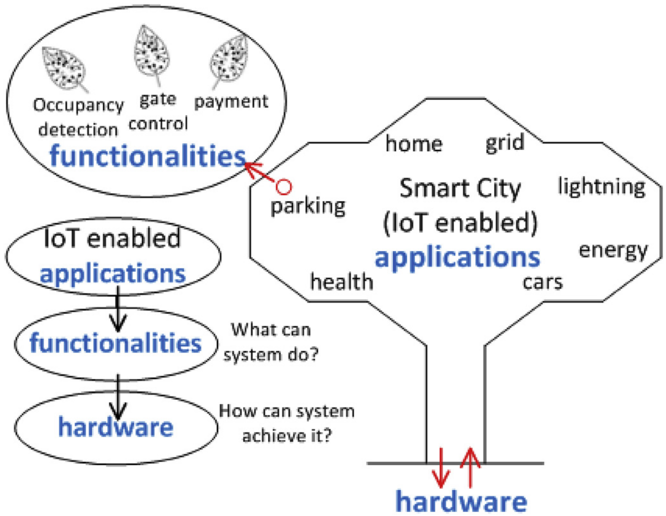


Fig. 21. Generalized concept of IoT enabled Smart City Architecture (Perković et al., 2020b).

3.1. Hardware overview and state-of-the-art

To enable Smart Cities, an infrastructure that uses sensing hardware acting as an information source is of crucial importance. As this sensing hardware is located in remote areas, often without access to an electrical network, an almost zero-energy use is needed and therefore can prolong battery lifetime and possibly enable self-powering through ambient power sources, e.g. solar cells. This is crucial for improving the usability of the whole system as a battery replacement in these circumstances is difficult, expensive and a time-consuming activity. To understand power consumption issues, an overview of state-of-the-art technologies to build the hardware is provided.

A standard sensing node, presented in Fig. 22 is consisted of a sensor component that delivers the sensed information to a microcontroller unit (MCU) for its further processing. To reduce power needs, the node is usually equipped with a related power management unit, while there is a given power source. Once the MCU acquires the data from the sensor, it gives data to a radio unit that uses an antenna to transmit the data over a wireless channel. In the next sections, the components are described in depth by referencing the relevant literature, while the specific original work was done in current technology investigations that can enable these functionalities.

Sensors vary in terms of design and functionalities. A good overview of sensing technologies, and its power consumption is given in Fig. 23. It can be noticed that each of them has its own power consumption pattern, where the more functionalities they have, the more consumption will appear. Using it in an optimal way is of the highest importance for reducing battery lifetime.

3.2. Efficient IoT radio units

To achieve data transmission, a critical part is to deliver the data in an efficient manner. For this, the major idea and enabler is to provide data links between sensing nodes and receiving stations for transmitted data. To satisfy different applications and related functionalities, it is important that these radios can timely transmit the data over larger distances while consuming less energy. The major competitors in this area are Low-Power Wide Area Networks (LPWAN) with their technology competitors: LoRa, NB-IoT and Sigfox. According to Fig. 24 LPWAN can satisfy long ranges wherein the data rate is sacrificed, just suitable for sensorial application. In these cases, sensor devices send several data packets containing only the sensed information.

When considering LPWANs, the competitive technologies are also orthogonal in terms of different application points of view. A good overview of these technologies is given in Fig. 25 and Fig. 26, also by providing the costs for each of them. In addition, Figs. 25 and 26 give the technological comparison between each of them, so the deployers can understand which technology better fits which need. These mostly refer to which kind of infrastructure is required to match needs, what distance can be covered, what the overall system latency is when considering the number of nodes, etc.

3.3. Power management

The basic mechanism that allows for the long lifetime of battery-operated devices (up to a couple of years) is to keep the device in low-power state during inactive periods. IoT devices, especially battery-operated ones, spend only a small fraction of time within active state, in which MCU performs sensor readings, and communicates data over wireless channels using a radio peripheral, while during inactive periods, the MCU along with other components is kept in deep-sleep state. Such a period between two active states, i.e. active - sleep - active is referred to as a duty cycle. Intuitively, to increase the lifetime of an IoT device, it is necessary to minimize its consumption during inactive periods. Logically, within inactive periods, it is necessary to place all active components into sleep. Some components, such as sensors, and radio modules, already come with libraries that support low-power consumption in sleep state (around 1uA per component or less). Using built-in functions, the MCU triggers external components to enter sleep once the sensor reading and radio transmission is done. On the other hand, the MCU also has to be kept in deep-sleep during the sleep period. However, to trigger the MCU waking from deep-sleep, some form of interrupt has to be sent to it. This is usually accomplished with some form of low-power timer. Depending on the MCU that is used in the implementation of an IoT device, there are many ways to accomplish this.

An MCU such as ATmega328P, found on Arduino boards, comes with a built-in Watchdog timer (WDT), with consumption up to couple of Ua, (ATmega328P, 2020). Some external timers, like TPL5010 come with Watchdog functionalities, however, with nA scale consumption (TPL5010, 2020). Unfortunately, the maximum time WDT can hold the MCU in low-power mode is around 8 s (Tutorial - Atmega328p, 2020). One way to increase sleep time using WDT would require a loop that periodically triggers the MCU waking up every 8 s, after which the MCU immediately enters deep-sleep. Within deep-sleep period, the consumption of MCU and WDT is only a few uA. To increase sleep time for ATmega328P, an external RTC clock could be employed, such as a cheap and precise RS3231 RTC clock, with ±2 ppm stability and 1uA of consumption (Datasheet - RTC3231, 2020). Other MCUs, such as STM32 or SAMD21, already come with built-in RTC clocks that can be used to trigger an alarm for waking up from deep sleep (Libraries - Arduino low-power, 2020), (STM32, 2020). All these components (MCU, sensor, RTC clock, radio peripheral, voltage regulators, capacitors, etc.), although in low-power mode, combined may consume tens to even couple of hundred of uA while being placed in deep-sleep. Moreover, it may happen that some boards equipped with components that adopt low-power modes have a hardware problem that prevent them from achieving low deep-sleep currents, such as found in MKRWAN1300 (Arduino LoRa with SAMD21) and (MKRWAN1300, 2020).

To reduce even more consumption regarding all components, it is suggested to use an external timer component that will

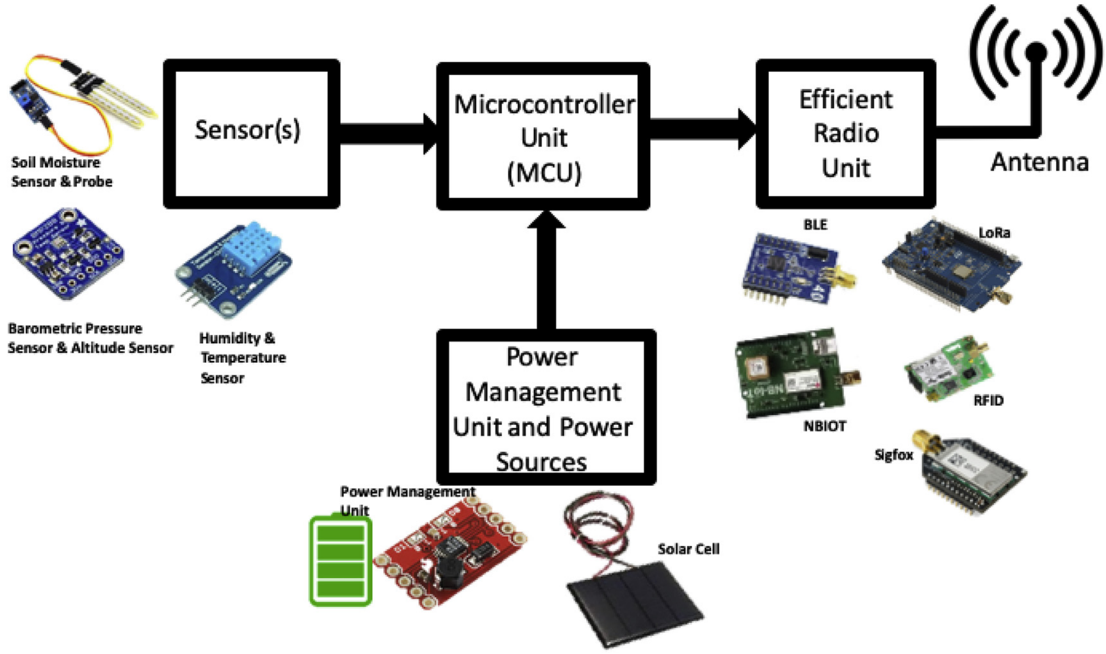


Fig. 22. Block scheme of standard sensing node architecture in IoT enabled Smart City.

Sensor type	Description	Voltage (V)	Cons. active	Cons. power-down
DHT11	Temp. Humidity	3.3, 5, 6	$1.5mA$	$50\mu A$
DHT22	Temp. Humidity	3, 5, 5.5	$2.5mA$	$150\mu A$
BME280	Temp. Humidity Pressure	1.71 - 3.6	$3.6\mu A$	$0.1\mu A$
BME680	Temp. Humidity Pressure Gas	1.71 - 3.6	$0.09–12mA$	$0.15\mu A$
BH1750	Light	2.4-2.6	$120\mu A$	$0.01\mu A$
UV SI1145	Proximity	1.71—3.6	$4.3mA$	-
TSL2561	Infrared	2.7-3.6	$0.24mA$	$3.2\mu A$
ADXL345	Accelerom.	3.3	$40\mu A$	$0.1\mu A$
MAX9812	Microphone	2.7-3.6	$230\mu A$	$100nA$
GY-MAX4466	Microphone	2.4-5.5	$24\mu A$	$5nA$
DS18B20	Thermometer	3.0-5.0	$1mA$	$750nA$
LMx93-N	Flame detect.	2.0-36	$0.4mA$	-
VL53L0X	Laser range	2.6-3.5	$5\mu A$	$16\mu A$
MAG3110	Magnetometer	1.95-3.6	$8.6 - 900\mu A$	$2\mu A$
HMC5883L	Compass	2.16-3.6	$100\mu A$	$2\mu A$

Fig. 23. Most popular sensors and their power requirements in active and power-down (i.e. sleep mode, Perković et al., 2020b).

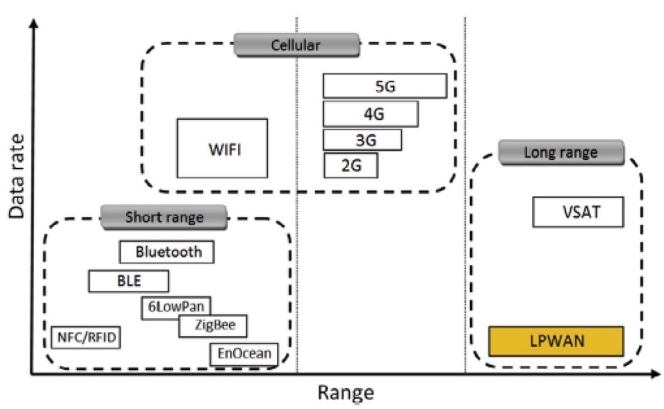


Fig. 24. Overview of technologies that can satisfy different usage scenarios (Mekki et al., 2019).

completely cut-off power for predefined periods. The TPL5110 is a low power timer where an alarm clock is regulated with resistors, allowing for the duration of sleep mode to be up to 2 h (TPL5110, 2020). Within the sleep period, the TPL5110 simply cuts-off power from other components leaving overall consumption to be equal to the consumption of the timer only. Since the TPL5110 is low power by nature, the overall consumption falls to only 50 nA. The drawback of such a solution is that the MCU is no longer in deep-sleep but is instead powered off, which means that possible variables that were held in volatile memory during deep-sleep will not be available to the MCU when it wakes up. For this reason, it is suggested to use EEPROM or flash memory to write the variables before cutting off power from the MCU. A Tega328P may use built-in EEPROM, while STM32 or SAMD21 can use flash memory or RTC backup RAM (Flash storage, 2020). The RS3231 RTC clock has an EEPROM that can be used for saving variables. The main drawback of EEPROM and flash memory is the limited number of writes (around 10,000), hence some external EEPROM or flash memory may be used with a larger number of writings, or either an external specialized chip like ATECC508A (ATECC508A, 2020) that supports secure storage (of key for example) (ATEC). It must be noted that when the MCU wakes from deep-sleep, the code runs from where it left off, which usually requires a couple of mS. On the other hand,

	Sigfox	LoRaWAN	NB-IoT
Modulation	BPSK	CSS	QPSK
Frequency	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Licensed LTE frequency bands
Bandwidth	100 Hz	250 kHz and 125 kHz	200 kHz
Maximum data rate	100 bps	50 kbps	200 kbps
Bidirectional	Limited / Half-duplex	Yes / Half-duplex	Yes / Half-duplex
Maximum messages/day	140 (UL), 4 (DL)	Unlimited	Unlimited
Maximum payload length	12 bytes (UL), 8 bytes (DL)	243 bytes	1600 bytes
Range	10 km (urban), 40 km (rural)	5 km (urban), 20 km (rural)	1 km (urban), 10 km (rural)
Interference immunity	Very high	Very high	Low
Authentication & encryption	Not supported	Yes (AES 128b)	Yes (LTE encryption)
Adaptive data rate	No	Yes	No
Handover	End-devices do not join a single base station	End-devices do not join a single base station	End-devices join a single base station
Localization	Yes (RSSI)	Yes (TDOA)	No (under specification)
Allow private network	No	Yes	No
Standardization	Sigfox company is collaborating with ETSI on the standardization of Sigfox-based network	LoRa-Alliance	3GPP

	Spectrum cost	Deployment cost	End-device cost
Sigfox	Free	> 4,000 € / base station	< 2 €
LoRa	Free	> 100 € / gateway > 1,000 € / base station	3-5 €
NB - IoT	> 500 M€ / MHz	> 15,000 € / base station	> 20 €

Fig. 25. Overview of performances and deployment costs for different LPWAN technologies (Mekki et al., 2019).

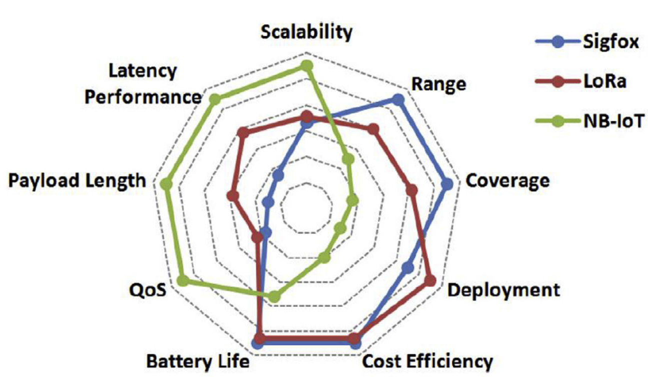


Fig. 26. Pros and cons for each of LPWAN competitors (Mekki et al., 2019).

powering the MCU with an external timer such as TPL5110 requires a fresh restart of code, which in some scenarios may indicate running the bootloader. For ATmega328P, by default it may take up to 2 s for the bootloader to start (Tutorial - Low-power nodes, 2020). Hence, to reduce consumption, it is suggested to either completely wipe out the bootloader or flash faster bootloader (Bootloader, 2020). It must be mentioned that battery capacity, along with its input voltage may vary during sensor lifetime or could be larger than the operating voltage of some components. A good quality voltage regulator that may deliver enough current to a sensor device while consuming itself small current is required. For example, MCP1700 (MCP1700, 2020) is a family of CMOS low dropout (LDO) voltage regulators that can deliver up to 250 mA of current while consuming only 1.6 μA, with input operating ranging from 2.3V to 6.0V, making it ideal for battery operated devices.

3.4. Microcontrollers for IoT: scouting and comparison

The Microcontroller (MCU hereafter) is the core of any Internet of Things (IoT) device and embedded system. Indeed, its role is to coordinate, according to a specific pre-programmed logic, all the peripherals of the IoT node thus providing sensing, actuation, and connectivity in an as low power mode as possible. In other words, the MCU sets the "smart-ability" of a certain object in relation with its cost, computational capability, power consumption, memory, communication interfaces and other features to accurately select during the design phase. It is worth highlighting that a "perfect" microcontroller does not exist, but just the most suitable one for the specific application. For this reason, the role of the designer in selecting the microcontroller for a specific IoT application is never simple. Some "universal" microcontroller key features are useful to drive the designer towards the right choice according to the requirements of the considered IoT application.

The proposed analysis aims at comparing some microcontrollers as potentially useful for the IoT by considering the following objective parameters.

- **Register Memory Bits**: This parameter refers to the number of internal register bits and buffer. The higher the number of MCU bits, the higher the number of operations that the MCU itself can sustain. This parameter sets different families of Microcontrollers.
- **Maximum Clock Frequency:** is the maximum frequency on the internal/external clock of the microcontroller. It is useful because it sets the number of operations of an MCU in a single time unit.

- **RAM**: RAM is the volatile memory of an MCU which is useful for performing quick operations, actions or data buffering. The absence of powering resets this kind of memory
- **Flash Type**: It is the static memory of an MCU that retains data in the absence of power. The quality of this memory in terms of writing operation figures and writing/reading speed determines a consistent part of the microcontroller cost.
- **Number and Type of GPIOs**: GPIO is the acronym of a general-purpose input/output interface. It is referred to as the presence of pins that can be configured to act as the analog or digital input/output of the MCU. The higher the number of MCU GPIOs, the higher the number of external devices (sensors, actuators, transceivers) that can be controlled.
- **Serial Bus**: Presence of an SPI/I2C bus for communication
- **Integrated Wireless Connectivity Interfaces:** This key feature is useful in the IoT to wirelessly connect the MCU by using Wi-Fi, Ethernet, or BLE interfaces.
- **Power Consumption:** Power Consumption is the most important aspect of IoT-oriented Microcontrollers. This parameter should be optimized by controlling the Active time and Sleeping time of the MCU according to the specific application.
- **Development board/Launchpad:** The availability of a development board is helpful during the design phase to test the targeted IoT solution before realizing a prototype. Providing this board is an added value for MCUs.
- **Arduino IDE Programming Interface:** Multi-brand MCUs implement an Arduino-compatible convergence programming language useful to simplify the programming operations and modular implementation of IoT applications.
- **Cost:** IoT applications are often cost-sensitive. In many cases, functionalities could not be implemented to maintain a low-cost IoT system design. Generally, both MCUs and the presence of specific sensors determine the cost of the whole solution.

In addition to the above-mentioned parameters, the computational capability of a microcontroller can be evaluated by considering the presence of an on-board Operating System. If supported, this feature helps in managing complex IoT embedded applications where several peripherals must be managed. In this regard, three different typologies of microcontrollers can be summarized:

- **No-Operating system:** The operating system is not present. In this case the microcontroller can be programmed in a "canonical" manner, by developing a code for low-level operations (Assembler of C are the main programming languages). A software-level connection cannot be implemented, however, the cost-effectiveness of these kinds of microcontrollers as well as reduced power consumption, make this MCU typology quite diffused.
- **RTOS**: namely "Real-Time Operating System". An RTOS Operating system enables a multi-task approach by introducing priority levels among the tasks running under the operating system. Moreover, this Operating System guarantees the correct timing of single events.
- **Linux/UNIX**: This feature allows high-level programming in a way similar to a canonical computer. Open source software can be run on the MCU thus enabling connectivity and port management. Real-time and low-power operations are never guaranteed so that this kind of MCU is often not compatible with IoT applications, except for hi-level management IoT node systems.

Underneath, selected multi-brand MCUs will be compared by using the above-mentioned metrics in order to have a quick perspective useful in selecting the right MCU for a specific IoT application. After a quick overview of the microcontrollers based on manufacturer descriptions, which is useful to understand the different categories, a table summarizing their main features will be provided. Being low-power, "No-Operating system" devices will be considered in this comparison, Fig. 27.

3.4.1. Texas instruments G series MSP430G2x13 and MSP430G2x53

The MSP430G2x13 and MSP430G2x53 series are ultra-low-power microcontrollers with built-in 16-bit timers, up to 24 I/O capacitive-touch enabled pins, a versatile analog comparator, and built-in communication capability using a universal serial communication interface. In addition, the MSP430G2x53 family members have a 10-bit analog-to-digital (A/D) converter. This is an entry-level microcontroller useful for general purpose low-power and low-cost IoT applications. The availability of a development board for the MSP43G2553 MCU, called "Launchpad", makes the design easy for simple IoT sensing nodes.

3.4.2. Texas instruments F series MSP430F552x

The MSP430F5529, MSP430F5527, MSP430F5525, and MSP430F5521 microcontrollers have an integrated USB and PHY supporting USB 2.0, four 16-bit timers, a high-performance 12-bit analog-to-digital converter (ADC), two USCIs, a hardware multiplier, DMA, an RTC module with alarm capabilities, and 63 I/O pins. The MSP430F5528, MSP430F5526, MSP430F5524, and MSP430F5522 microcontrollers include these peripherals but have 47 I/O pins. This MCU family is compatible with low-power hi-performance IoT applications where hi-speed communication, port availability, and USB connectivity is required. Also in this case, the availability of a "Launchpad", for the MSP430F5529 MCU makes the design easy for rather advanced and low-cost IoT smart nodes.

3.4.3. Texas instruments FR series MSP430FR572x and MSP430FR59xx

The TI MSP430FR572x and MSP430FR59xx families of ultra-low-power microcontrollers consist of multiple devices that feature an embedded FRAM nonvolatile memory, ultra-low-power 16-bit MSP430™ CPU, and different peripherals targeted for various applications. The architecture, FRAM, and peripherals, combined with seven low-power modes, are optimized to achieve extended battery life in portable and wireless sensing applications. FRAM is a new nonvolatile memory that combines the speed, flexibility, and endurance of SRAM with the stability and reliability of flash, all at lower total power consumption. Peripherals include a 10-bit ADC, a 16-channel comparator with voltage reference generation and hysteresis capabilities, three enhanced serial channels capable of I2C, SPI, or UART protocols, an internal DMA, a hardware multiplier, an RTC, five 16-bit timers, and digital I/Os.

3.4.4. Microchip PIC18F family PIC18F26K22

The PIC18 microcontroller family provides PICmicro® devices in 18-to 80-pin packages, that are both socket and software upwardly compatible to the PIC16 family. The PIC18 family includes all the popular peripherals, such as MSSP, ESCI, CCP, flexible 8- and 16-bit timers, PSP, 10-bit ADC, WDT, POR and CAN 2.0B Active for a maximum flexible solution. Most PIC18 devices will provide a FLASH program memory in sizes from 8 to 128 Kbytes and data RAM from 256 to 4 Kbytes; operating from 2.0 to 5.5 V, at speeds of DC to 40 MHz. Optimized for high-level languages like ANSI C, the PIC18 family offers a highly flexible solution for complex embedded applications.

3.4.5. Microchip PIC24F family PIC24F16KA102

The PIC24F is a cost-effective, low-power family of microcontrollers (MCUs) based on eXtreme Low Power (XLP) technology and 16-bit architecture. The flash memory ranges from 16 KB to

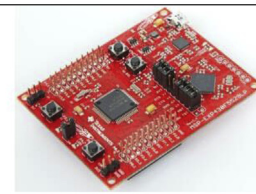
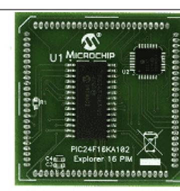
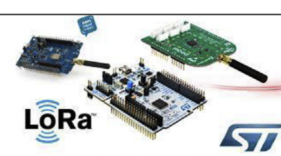
MCU	Reg. Mem. Bits	Max Clock Freq.	RAM	Flash Type	GPIO	BUS	Supply	Power (current) Cons.	Dev Board for IoT interfacing	Arduino IDE	Cost
Texas Instr. MSP430 G2553	16 bits	16MHz	SRAM <1KB	EPROM 16KB	20, 28 or 32 pins: Digital; ADC	UART IRDA SPI I2C	1.8 – 3.3 V	Active: 230 µA/ MHz. Standby: 0.5 µA	 ti.com/tool/MSP-EXP430G2	Energia Arduino IDE	From €0.82 to € 2.20
Texas Instr. MSP430 F5529	16 bits	25MHz	SRAM Up to 8KB	EPROM 128KB	80 pins: Digital; ADC	UART IRDA SPI I2C USCI USB	1.8 – 3.6 V	Active: 290 µA/ MHz. 150 µA/ MHz (code on RAM) Standby: 0.18 µA	 ti.com/tool/MSP-EXP430F5529LP	Energia Arduino IDE	€5.31
Texas Instr. MSP430 FR5729	16 bits	24MHz	SRAM Up to 1KB	Ultra low Power Ferromagnetic RAM (FRAM) 16KB	40 pins: Digital; ADC	UART eUSCI IRDA SPI I2C USCI USB	1.8 – 3.6 V	Active: 81.4µA/MHz; Standby: 6.3 µA; Real-TimeClock (RTC) WithCrystal): 1.5 µA Shutdown: 0.32µA	 ti.com/tool/MSP-EXP430FR5739	Energia Arduino IDE	€2.28
Microchip PIC18F26K22	16 bits	64MHz	SRAM Up to 1B	SRAM 64KB	40 pins: Digital; ADC	UART SPI I2C RS-232	1.8 – 3.6 V	Active: 290µA/MHz; Deep Sleep: 20nA	N/A	N/A	€1.74
Microchip PIC24F16 KA102	16 bits	32MHz	SRAM Up to 1.5KB	EEPROM 16K	28 pins: Digital; ADC	UART SPI I2C	1.8 – 3.6 V	Active: 195µA/MHz; Deep Sleep: 25nA	 mouser.it/ProductDetail/Microchip-Technology/MA240017?qs=sGAEpiMZZMtm36YkO3Igk2wJsmOnfSj2	N/A	€2.22
STMicroelectronics STM32L053 R8	32 bits	32MHz	SRAM Up to 64KB	EEPROM 2KB	64 pins: Digital; ADC	USART SPI I2C I2S USB 2.0	1.65 - 3.6 V	Active: 49µA/MHz; Sleep mode (full RAM): 340nA	 st.com/en/evaluation-tools/nucleo-l053r8.html	Yes NUCLEO EcoSystem	€2.99

Fig. 27. Comparison of microcontroller devices.

1 MB. The PIC24F family is a suitable solution for many space-constrained, low-power, cost-sensitive industrial, IoT and consumer applications.

3.4.6. STMicroelectronics STM32L0 family – STM32L053x8

The STM32L053x6/8 devices provide high power efficiency for a wide range of IoT applications. It is achieved with a large choice of internal and external clock sources, an internal voltage adaptation and several low-power modes. The STM32L053x6/8 devices offer several analog features, one 12-bit ADC with hardware oversampling, one DAC, two ultra-low-power comparators, several timers, one low-power timer (LPTIM), three general-purpose 16-bit timers and one basic timer, one RTC and SysTick which can be used as time bases. The MCU is provided with SPI, I2C, UART and USB 2.0 busses. This kind of MCU is studied for Ultra Low Power IoT applications and is provided with an effective development Arduino-compatible modular kit, called NUCLEO, allowing for easy interconnection with connectivity (BLE, Wi-Fi, Lo-Ra, etc) modules for IoT.

Taking into the account the above elaborated recent works, application scenarios and the enabling technology overview, following can be emphasized:

- all kinds of services that are used to enable smart cities highly depend on the deployed hardware sensing infrastructure. Less infrastructure implies limited functionalities for given application scenarios. On contrary, many different application scenarios can be considered but this increases implementation and maintenance costs,
- many different sensing techniques were proposed, and research community is intensively working to provide more reliable and cost-effective sensing technologies that can be easily implemented in IoT sensing nodes,
- to enable different functionalities of the given application scenarios it is important to have the technology which can deliver sensed data on a greater distance, while preserving the energy in order to improve battery lifetime. For their products, many vendors specify 2–10 years of lifetime for their products, and it can be concluded that the battery lifetime depends on how frequently data is sensed and sent to the receiving station. Two-years span can certainly be considered as not enough, ten years' horizon could be enough as by then, new technologies may arise and substitute currently implemented technologies. In any case, providing new technologies from any point of view: radios, MCUs, sensing techniques that can preserve battery lifetime is of crucial interest for both current and future IoT deployment,
- currently available radios can fulfil today's needs in terms of delivering data from remote areas in smart cities/villages. The NB-IoT, LoRa and Sigfox are overlapping in part, but can be considered as orthogonal for specific use-cases. Smart usage of given radios can further improve battery lifetime. However, it is always of the high interest to consume even less energy and provide larger communication distances and it provides the space for further analysis and technology improvements.

4. E-health – ambient assisted living systems

In recent years, the exploitation of new assisted living technologies has become necessary due to a rapidly aging society. In fact, it is estimated that 50% of the population in Europe will be over 60 years old in 2040, while in the USA it is estimated that one in every six citizens will be over 65 years old in 2020 (Corchado et al., 2008). In addition, in 75-year-olds, the risk of Mild Cognitive Impairment (MCI) and frailty increases and people over 85 years of age usually require continuous monitoring. This suggests that taking care of elderly people is a challenging and very important issue. People with limited mobility are increasingly looking for innovative services that can help their daily activities. Ambient Assisted Living (AAL) encompasses technological systems to support people in their daily routine to allow an independent and safe lifestyle as long as possible. AAL (or simply assisted living) solutions can provide a positive influence on health and quality of life, especially with the elderly. An AAL approach is the way to guarantee better life conditions for the aged and people with limited mobility, chronic diseases and in recovery status with the development of innovative technologies and services.

Modern assistive technologies constitute a wide range of technological solutions aimed at improving the well-being of the elderly, Fig. 28. These technologies are used for personalized medicine, smart health, health tracking, telehealth, health-as-a-service (HaaS), smart drugs and multiple other applications (Maskeliunas et al., 2019).

AAL technologies can also provide more safety for the elderly, offering emergency response mechanisms (Lin et al., 2013), fall detection solutions (Kong et al., 2018), and video surveillance systems (Meinel et al., 2014). Other AAL technologies were designed in order to provide support in daily life, by monitoring the activities of daily living (ADL) (Reena and Parameswari, 2019), by generating

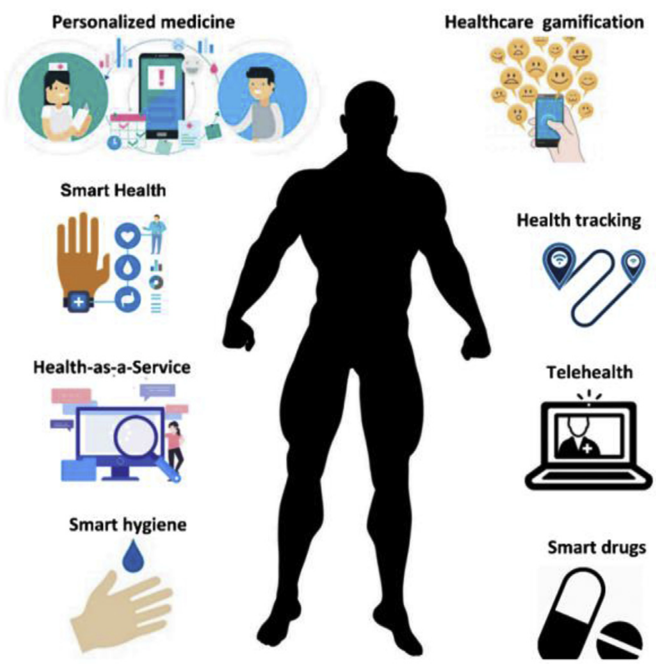


Fig. 28. IoT technology applications for AAL domain, (Maskeliunas et al., 2019).

reminders (Uribe et al., 2011), as well as by allowing older adults to connect with their families and medical staff. The recent advancements in mobile and wearable sensors helped the vision of AAL to become a reality. All novel mobile devices are equipped with different sensors such as accelerometers, gyroscopes, a Global Positioning System (GPS) and so on, which can be used for detecting user mobility. In the same way, recent advances in electronic and microelectromechanical sensor (MEMS) technology promise a new era of sensor technology for health (Vohnout et al., 2010). Researchers have already developed noninvasive sensors in the form of patches, small holter-type devices, wearable devices, and smart garments to monitor health signals. For example, blood glucose, blood pressure, and cardiac activity can be measured through wearable sensors using techniques such as infrared or optical sensing. User localization is another key concept in AAL systems because it allows tracking, monitoring, and providing fine-grained location-based services for the elderly. While GPS is the most widespread and reliable technology to deal with outdoor localization issues, in indoor scenarios it has a limited usage due to its limited accuracy due to the impact of obstacles on the received signals. The number of alternative indoor positioning systems have been proposed in the literature (Mainetti et al., 2014) that can be exploited in order to support AAL systems. Among all technologies, Bluetooth (BT) technology represents a valid alternative for indoor localization (Yapeng et al., 2013) or specifically in museums (Alletto et al., 2015). It is able to guarantee a low cost since it is integrated in most of daily used devices such as tablets and smart phones. The spread of the emerging Bluetooth Low Energy (BLE) technology makes the BT also energy-efficient, which is a key requirement in many indoor applications. An interesting investigation regarding the state-of-the-art and adaptive AAL platforms for older adult assistance was provided in (Duarte et al., 2018). The authors present an overview of AAL platforms, development patterns, and main challenges in this domain.

In recent years, a large number of solutions have been proposed in the literature in order to create smart environments and applications to support elderly people. The main purpose is to provide a level of independence at home and improve elderly quality of life. In (Dobre et al., 2018), an architecture which constitutes the base for the development of an integrated Internet of Things (IoT) platform to deliver non-intrusive monitoring and support for older adults to augment professional healthcare giving is presented, Fig. 29. The proposed architecture integrates proven open-data analytics technology with innovative user-driven IoT devices to assist caregivers and provide smart care for older adults at outpatients clinics and outdoors.

A solution for monitoring patients with specific diseases such as diabetes using mobile devices is discussed in (Villarreal et al., 2014). The proposed system provides continuous monitoring and real time services, collecting the information from healthcare and monitoring devices located in the home environment which are connected to BT mobile devices. The sensor data are transmitted to a central database for medical server evaluation and monitoring via 3G and Wi-Fi networks. An ad hoc application, installed on a mobile phone, allows the remote control of a patient's health status whilst the patient can receive any notifications from the health care professionals via the application running on her/his mobile phone, Fig. 30.

The work (Villarrubia et al., 2014) proposes a monitoring and tracking system for people with medical problems whose system architecture is shown in Fig. 31. The solution includes a system for performing biomedical measurements, locomotor activity monitoring through accelerometers and Wi-Fi networks. The interactive approach involves the user, through a smart TV. The locomotor activity of the elderly is deduced through the analysis of Received Signal Strength Indication (RSSI) measurements, i.e. through an algorithm, the received signal power from different access points located in the house is determined. Mobile accelerometers are used to analyze the movement of users and detect steps. Single board computers, such as Raspberry Pi, are used to collect data coming from the different sensors wirelessly connected to obtain real-time context-aware information such as gas, temperature, fire, etc. or to get information from biomedical sensors such as, oxygen meter, blood pressure, ECG, accelerometer, etc. The Raspberry Pi can be connected to a TV to transmit warnings or notifications coming from health care professionals.

The work (Mainetti et al., 2016) proposes an AAL system for elderly assistance applications able to provide both outdoor and indoor localization by using a single wearable device. A prototypal device has been developed exploiting GPS technology for outdoor localization and BLE technology for indoor localization. The proposed system is also able to collect all information coming from heterogeneous sensors and forward it towards a remote service that is able to trigger events (e.g., push notifications to families or caregivers and notifications to the same indoor environment that will change its status). In an enriched work (Mainetti et al., 2017), presents an architecture that exploits IoT technologies to capture personal data for automatically recognizing changes in the behaviour of elderly people in an unobtrusive, low-cost and low-power manner, Fig. 32. The system allows performing a behavioral analysis of elderly people to prevent the occurrence of MCI and frailty problems.

Based on the recent analysed research works on the use of IoT technologies in the e-health and for the creation of AAL systems, it is possible to draw the following general observations:

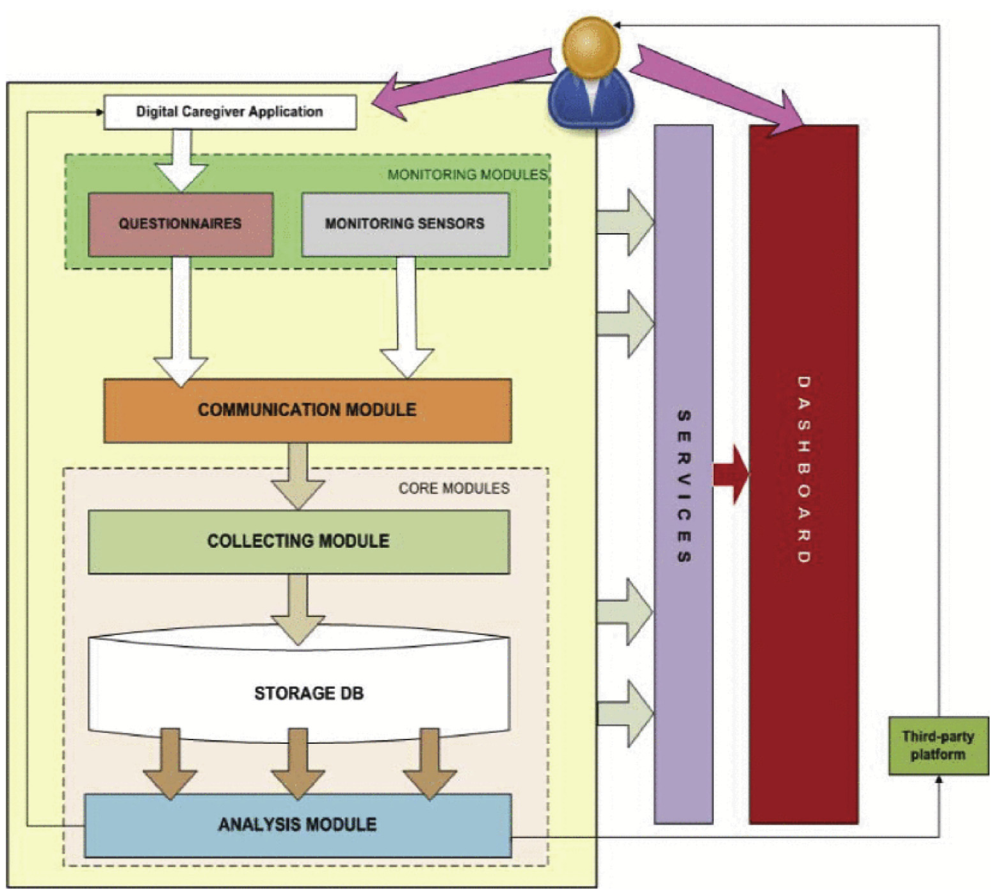


Fig. 29. Proposed modular architecture, (Dobre et al., 2018).

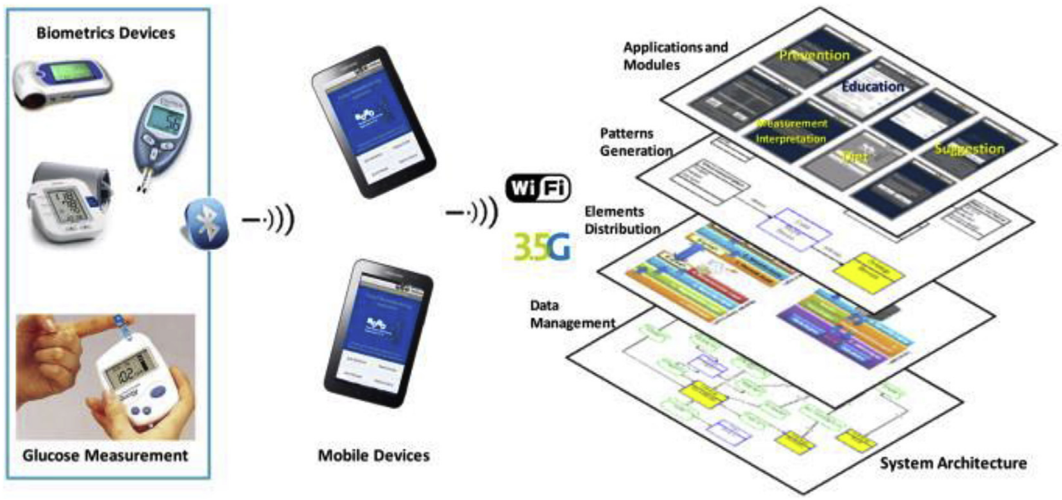


Fig. 30. Proposed system for continuous monitoring and real time services, (Villarreal et al., 2014).

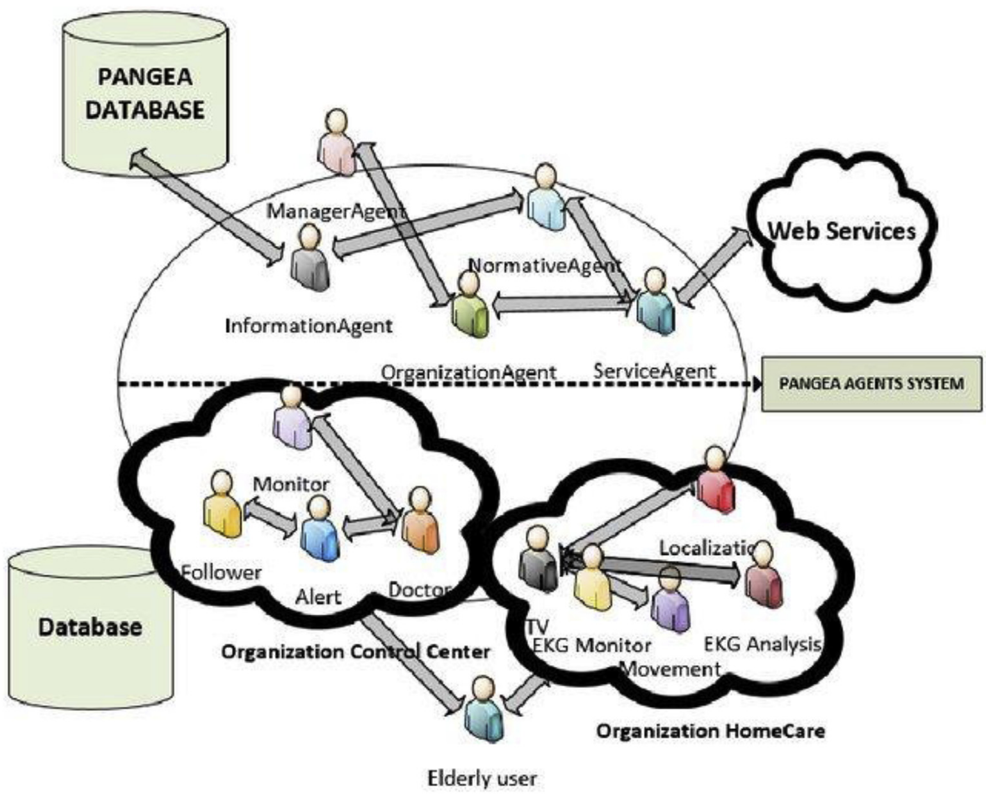


Fig. 31. Virtual organization of system, (Villarrubia et al., 2014).

- an extensive research is aimed at creating AAL systems intended primarily for the elderly or for people with physical or mental diseases,
- current challenges deal with the use of IoT technologies in order to capture the habits of the people monitored both in indoor and outdoor environments for behavioral analysis purposes. The behavioral analysis can be useful for monitoring people, scheduling interventions and providing notifications directly to the user,
- increasing efforts are needed in order to unobtrusively capture habits by favoring the use of wearable devices.

5. IoT technologies in Transportation and Low Carbon Products

The issue of security and traceability of goods is increasingly important in the logistics sector, with repercussions in terms of supply chain management and goods transport. In this case, information technologies and in particular the IoT can offer valuable support, increasing the degree of visibility and control over the entire supply chain. Transportation is a good example of how IoT technologies can bring value. In fact, this sector needs systems that on the one hand allow for the planning, management and

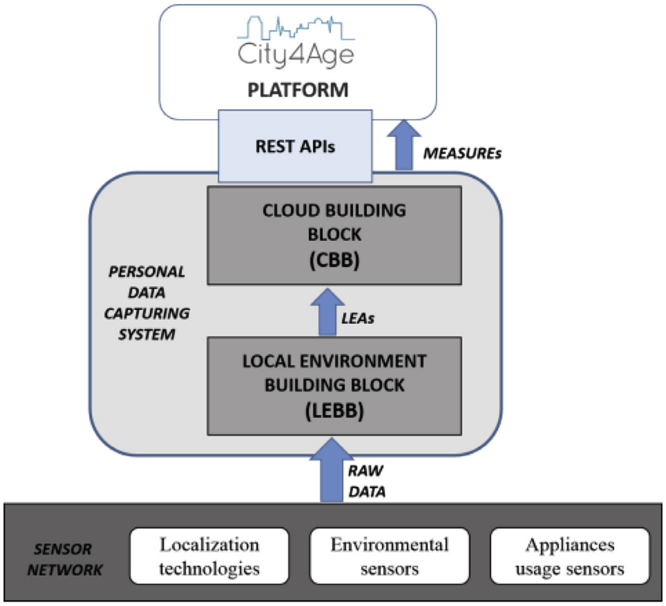


Fig. 32. Overall logical architecture (Mainetti et al., 2017).

optimization of flows (both along the supply chain and within complex logistics hubs such as intermodal ones) and, on the other hand, allow for the traceability of goods (products or containers) in real time along the entire supply chain. A further requirement concerns the check of goods integrity. In this context, it is clear how IoT technologies can contribute to the remote monitoring of flows and assets, providing a series of information useful for their management and optimization. This is possible through identification (e.g., via RFID or barcode), location (e.g., via GPS), monitoring of parameters and status variables of the assets (e.g., via sensors) and their transmission (e.g., via Wi-Fi or GSM/GPRS network).

The advent of IoT technologies allows to organize, automate and control processes remotely and from any device connected to the Internet. By definition, an efficient supply chain is responsible for delivering the goods, from the manufacturer to the end user, at the agreed time and under the specified conditions. Through the use of IoT technologies, it is possible to track the entire process in real time, promoting speed and efficiency in automated processes, reducing time and personnel costs. IoT technologies such as sensors, embedded and mobile devices, and cloud storage systems allow for the connection of "things" (warehouses, vehicles or goods) to the Internet so that the manufacturer, the logistics service provider and even the end user can thoroughly know at any time the status of products, their location and estimated delivery time.

Logistics can benefit from the use of IoT technologies in all the following sectors:

- efficient inventory and warehouse management
- automation of internal business processes
- fast and efficient delivery of products (e.g., route planning)
- conservation and quality of transported goods (e.g., monitoring of cold chain)
- location, monitoring and tracking of vehicle fleets
- interactive communication between vehicles and manufacturers/distributors of goods
- certification of both deliveries and transport phases

The basic principles of logistics always remain valid: transfer the right product, in the right quantity and condition, at the right time and right price, in the right place and to the right customer. As carrying out each of these tasks has become much more complicated in an increasingly globalized and interconnected world, the need for innovative solutions to achieve these objectives also increases. As mentioned above, the IoT is revolutionizing the logistics sector, offering many advantages and opportunities. Supply chain monitoring, vehicle tracking, inventory management, secure transport and process automation are the cornerstones of IoT applications as well as the main elements of interconnected logistics systems.

In the logistics sector, the IoT allows creating smart location management systems, which allow companies to easily monitor driver activities, vehicle location and delivery status, (Brincat et al., 2019). This solution is indispensable in the planning of deliveries and the organization of timetables and reservations. It is possible to detect any changes in real time and this is precisely the reason behind the success of the IoT: the ability to improve the management of good movement and therefore streamline business processes. Inventory and warehouse management is another important element of the connected logistics ecosystem. The positioning of small sensors allows companies to easily track items in warehouses, monitor their status, position and create a smart control system. In fact, with the help of IoT technology, employees will be able to successfully prevent any loss, ensure the safe storage of goods and efficiently locate the product needed. Even the minimization of human error becomes possible thanks to the IoT. In this scenario (Wang et al., 2015), proposes a layered architecture for the realization of an automation enterprise asset management system using IoT and RFID technologies, Fig. 33.

The sustainable and IoT supported business model was discussed in (Gao and Li, 2020) for the case of the bike-sharing services. Novel framework was developed that links sustainable indicators as well as social aspects of the business concept. The case studies for dockless bike-sharing services were discussed and presented for China and UK. Practical findings extended knowledge needed for improvement of the sharing economy to achieve sustainably goals through IoT enabled support. The work (Zhang et al., 2016) proposes an inventory management system for a warehousing company. The system adopts the concept of IoT using RFID technology to track the material and provide messages or warnings when incorrect behaviors are detected. In particular, it integrates RFID technology and a self-Adaptive distributed decision support model for inbound and outbound actives, inventory location suggestions and incident handling. In (Guptha et al., 2018), the authors design an IoT architecture for order picking processes in a warehouse that allows the inventory real time tracking and visibility into the reduction of warehouse operation costs, improved safety and reduced theft. IoT and RFID technologies are again exploited in (Valente et al., 2017) to improve productivity in the value chain of a steel mill. In this work, an existing RFID solution architecture based on the reference EPCGlobal/GS1 framework was modified in order to be extended to the IoT domain, Fig. 34.

The internet-connected devices collect large amounts of data which can be transmitted to a central system for further analysis. In this context, the integration between IoT and predictive analysis systems can help companies to create effective business development strategies, improve decision-making and manage risks. In the logistics sector, this integration finds application to plan routes and deliveries as well as identify various defects before something goes wrong. An integrated framework to track and monitor shipped packages, Fig. 29 was proposed in (Proto et al., 2020). Framework relies on a network of IoT-enabled devices, called REDTags, allowing courier employees to easily collect the status of package at each delivery step. The framework provides back-end functionalities for smart data transmission, management, storage, and analytics. A

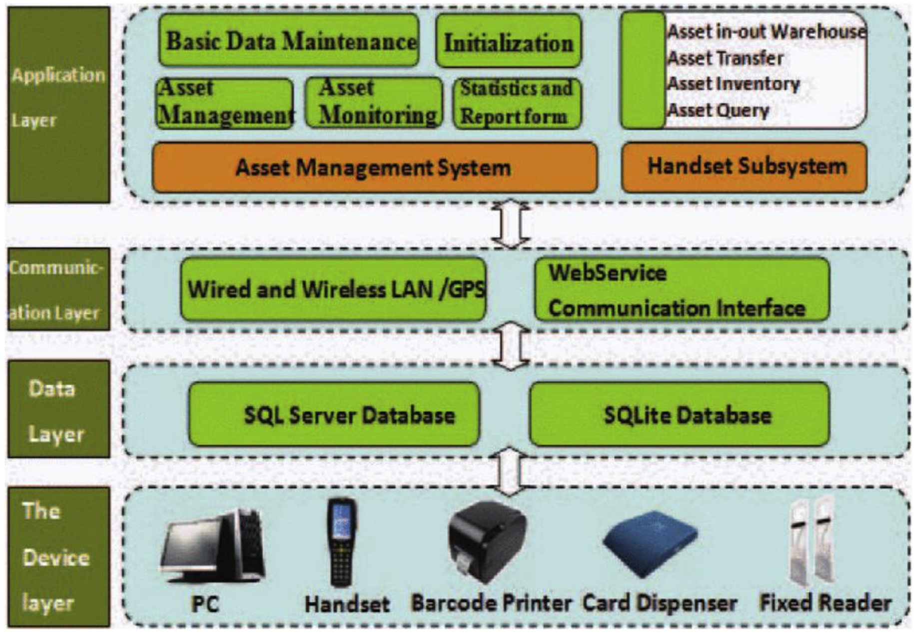


Fig. 33. Layered architecture of proposed automation enterprise asset management system (Wang et al., 2015).

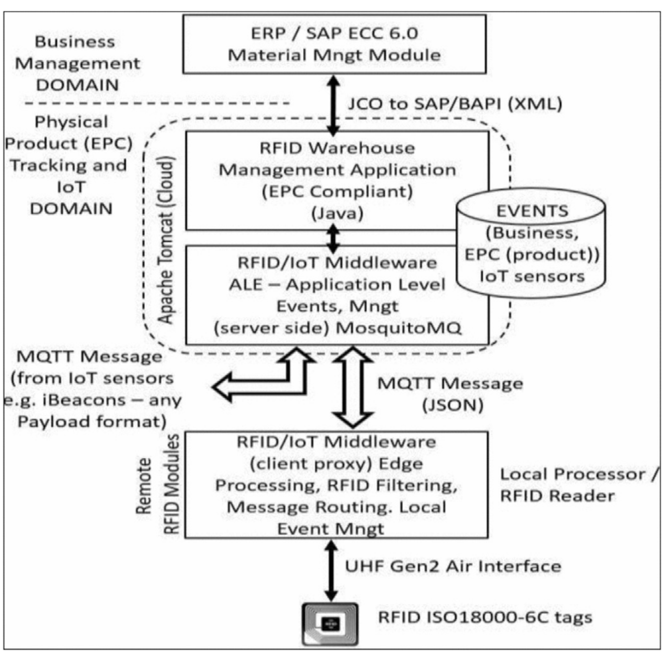


Fig. 34. RFID/IoT solution architecture for steel mill (Valente et al., 2017).

machine-learning process is included to promptly analyze the features describing event-related data to predict the potential breaks of goods in the packages (Fig. 35).

Ensuring product quality and integrity is an interesting challenge that in recent years has led to the creation of smart systems that integrate IoT solutions and block chain technology. The Blockchain technology associated with IoT sensors could allow the creation of a temporal “stamp” inside which a series of information is kept such as product delivery date, product characteristics and status, and origin of product. By positioning the sensors, for example, it is possible to monitor parameters such as product temperature and humidity, vehicle position and phases of the transport process and save this data in the block chain. Block chain infrastructure can also revolutionize company logistics in the field of document management (i.e., invoices, transport documents, etc.), traceability of goods (origin of products, monitoring of vehicle fleets, etc.), and play a substantial role in fighting counterfeiting. Imeri and Khadraoui (2018) showed a conceptual approach to the security and traceability of shared information in the process of dangerous goods transportation using block chain technology based on smart contracts. IoT and block chain technologies are exploited in (Arumugam et al., 2018) where a smart logistics solution encapsulating smart contracts, logistics planner and condition monitoring of the assets in the supply chain management area is presented, Fig. 36. Moreover, a prototype of the proposed solution is implemented.

The block chain-IoT-based food traceability system (BIFTS) to integrate the novel deployment of block chain, IoT technology, and fuzzy logic into a total traceability shelf life management system for the managing of perishable food, Fig. 37 was proposed in (Tsang et al., 2019). Challenges in the adoption of the proposed framework in the food industry are analysed and future research planned to improve the proposed work.

Taking into account above discusses recent research findings further main findings could be highlighted:

- The studies analysed previously show how the hardware and software technologies enabling the Internet of Things are leading to a digital transformation process that aims at an intelligent and advanced management of the entire logistics and transportation system.
- The main scientific challenges in this field aim to use sensors in order to monitor the status of the goods transported, to ensure traceability and above all to safely and reliably collect telemetry data and offer them to Artificial Intelligence modules for advanced processing.
- Furthermore, recently the interest has focused on the next generation of blockchain systems (the so-called blockchain 3.0) which aims to apply the benefits of the classic blockchain in typical scenarios of the Internet of Things, such as logistic and transportations.

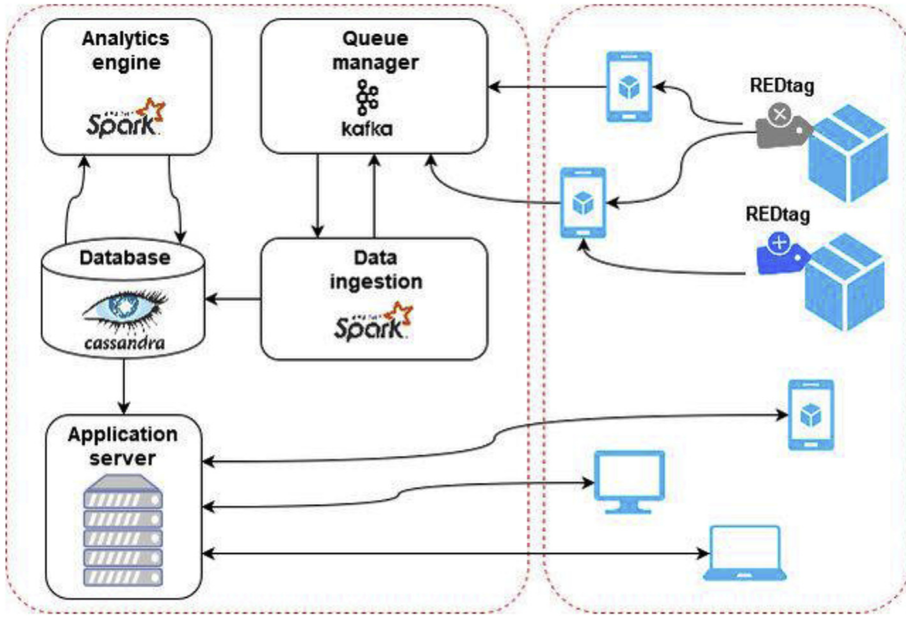


Fig. 35. Framework architecture, (Proto et al., 2020).

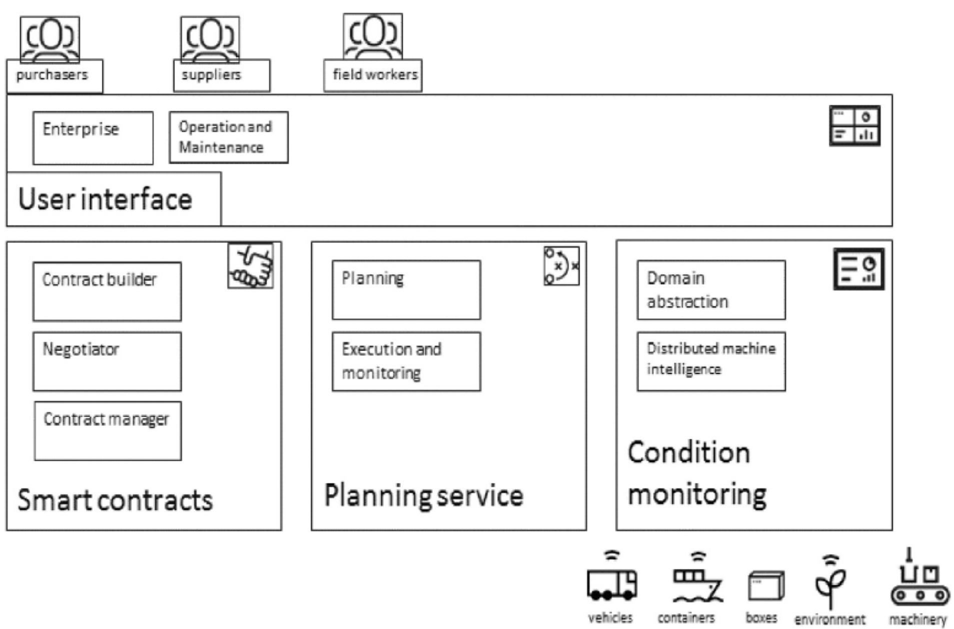


Fig. 36. High-level architecture of proposed solution, (Arumugam et al., 2018).

6. Concluding remarks and future directions in the field

This review paper discussed and presented latest research findings that were included within the JCELPRO VSI SpliTech2019 and dedicated to the 4th International Conference on Smart and Sustainable Technologies (SpliTech 2019). The contributions as well as herein presented knowledge is summarized and discussed in upcoming sections.

The Intense digitalization in recent years has allowed for different technological possibilities that have already gradually been changing the main economic sectors and societies in general. Digitalization in different economic sectors enabled various possibilities for advancements and for a more efficient utilization of limited resources, systems or processes. The main driver for an efficient digitalization in various sectors is information technology, i.e., IoT supported smart technologies. In the previous sense, the energy sector is one of the key sectors where "energy digitalization" has already been rapidly developing in various energy related fields. Currently, one of the most progressing implementation areas of IoT technologies is related to the energy sector. The developing solutions are focused on smart homes, i.e. advanced automatization of home energy systems, development of smart and adaptive micro-grids, or advancements in efficient demand-side management of power systems. A circular economy concept has also been intensively worked on where various concepts have been investigated, which can support smart waste management and help

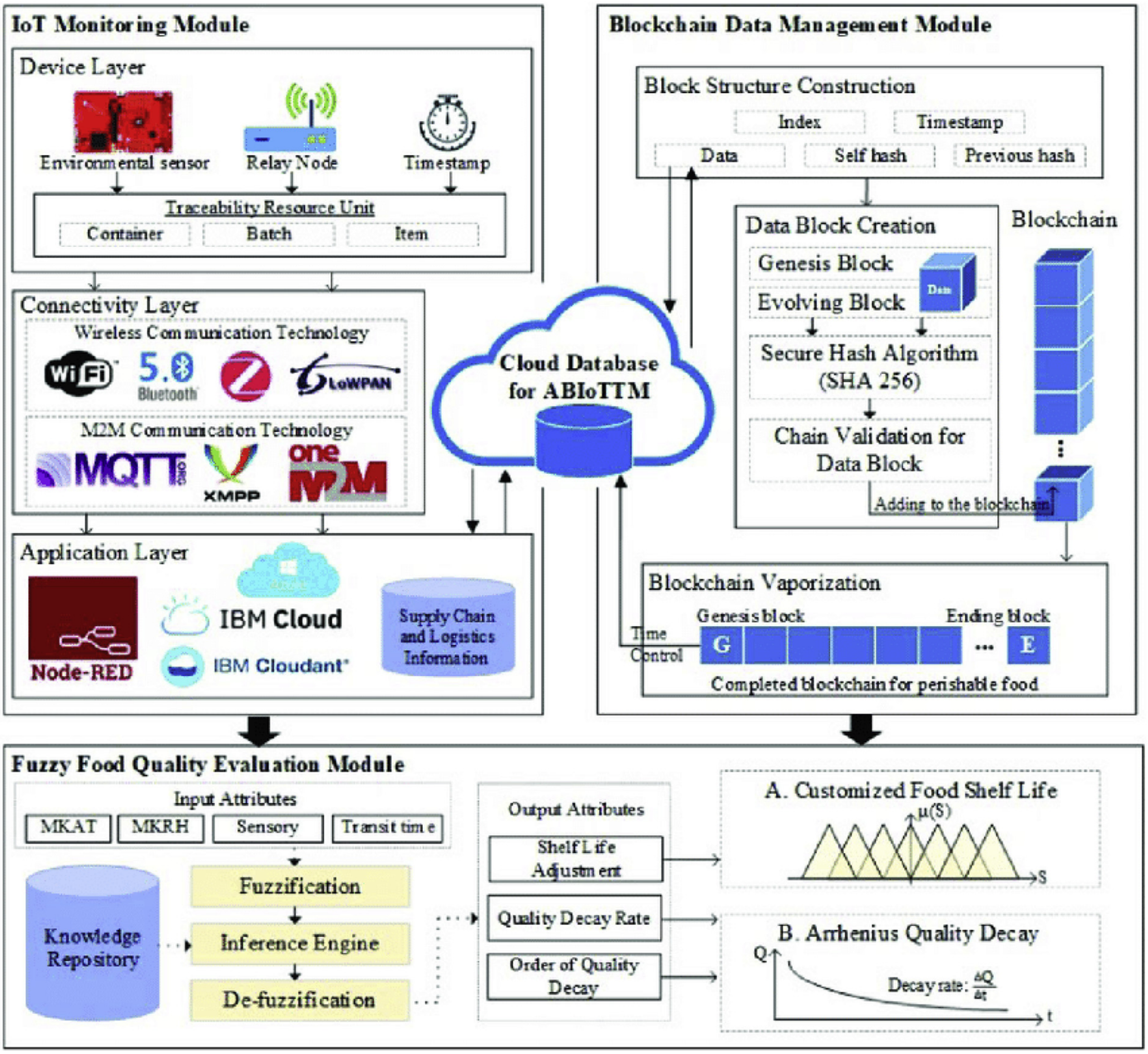


Fig. 37. Modular framework of BIFTS, (Tsang et al., 2019).

bridge one of the main challenges in society. Recently, different concepts have been tested where IoT technologies could be used for environmental protection, primarily for the monitoring of air quality, which is a big potential in that sense.

Healthcare systems can also be significantly improved with the application of IoT devices, i.e. via the E-health concept. An improved quality of services and patient safety could be enabled with an advanced IoT supported monitoring system. The prediction of life threatening states could be efficiently detected with a better treatment of patients, such as timely therapy decisions and qualitative rehabilitation. In general, large healthcare systems could also benefit from IoT, both in efficiency and from a cost aspect, which is important for hospitals. The current pandemic state with COVID-19 allowed for the consideration of different IoT applications or devices that could help in efficiently monitoring and controlling the pandemic, which proves the added value of IoT products.

The transportation sector is currently in gradual transition where a mix of transportation vehicle technologies is expected in upcoming decades with the involvement of electric vehicles primarily along with hybrid or hydrogen based vehicles. The main advancements of IoT in transportation are the support of the smart car concept where different vehicle operating parameters can be monitored in an efficient manner. The main advantage is early detection of severe failures, then regular maintenance, improved fuelling and finally improvement of safety and driving experience in general. The most challenging IoT application area is in the case of autonomous vehicles, where safety is the main goal and in that sense, significant research advancements are expected to occur in the near future.

The smart city concept is the most progressing IoT application area since cities have been vastly populated, which causes severe infrastructural issues. The main benefit of IoT technologies in the smart city concept is to bridge severe infrastructural challenges in highly populated cities. The improvement of life quality in cities is also expected thanks to the efficiency improvement of various convectional services in cities. The early detection of various and common daily problems in cities could be efficiently solved with IoT as with transportation issues, energy and water shortage supplies, security issues, etc. The biggest challenge in the smart city concept is directed to the efficient networking and operation of different sensing technologies, which must be followed with the proper education of the population.

Each technology that is rapidly progressing has got specific potential drawbacks that need to be carefully analysed and addressed. Since IoT devices are measured in billions, and with large potential impacts on the population, specific challenges need to be addressed, which were detected based on the herein conducted review. The main goal is to secure a sustainable and balanced development of IoT technologies. Therefore, further issues are briefly discussed below and should be carefully considered during the further development of IoT technologies:

- the rapid development of IoT technologies causes fast consumption of raw materials to produce different electronic devices where unfortunately some of raw materials are already rare or becoming,
- electronic devices are becoming more economically acceptable where a potentially large population would be affected. High production volumes are expected which can finally cause a rebound effect and a more rapid unwanted utilization of already limited resources,
- the sustainability aspect and long-term effects of IoT technologies are not clear and insufficiently investigated. A noticeable amount of energy would be needed to operate IoT devices and the electronic industry is leaving different unfavourable environmental footprints that also need to be carefully investigated,
- electronic waste will become one of the major issues caused with the planned rise of IoT products. Recycling rates must be improved and better e-waste management should be secured,
- IoT technologies can cause social impacts in specific industrial branches or businesses since working labour could be reduced and direct social contacts have also been reduced. In that sense, the application of IoT technologies should be carefully considered taking the raised issues into account,
- significant advancements in both specific electronic components as well as user-friendly software solutions are required,
- further development in sensing technologies and advanced data acquisition systems is also required,
- the minimization of energy consumption in IoT devices is a crucial target, i.e. reduction of energy supply.

From the herein addressed recent research findings within the VSI SpliTech 2019, it is obvious that developments in various IoT application sectors are promising but further advancements are expected and that are mainly focused on maximizing the efficiency of specific IoT supported processes or technologies, minimizing resource utilization (raw materials and energy) and environmental footprints. IoT technologies are an opportunity for humanity and can bring important as well as useful benefits to the population. The authors contributions within the JCLEPRO VSI SpliTech2019 provided quality discussion and presentation of the latest advancements in the field, and most important, they contributed to the better understanding of IoT application areas, technological possibilities, but also potential drawbacks and issues that should be carefully monitored in future terms. The crucial and important aspects are linked with sustainability where the rapid developments in IoT technologies must be carefully monitored from a resource and environmental point of view to ensure balanced and sustainable development of IoT products. Herein presented knowledge and published works in the Journal of Cleaner Production are serving as important foundations for researchers dealing with this challenging and dynamic research field.

CRediT authorship contribution statement

Sandro Nižetić: Conceptualization, Methodology, Supervision. **Petar Šolić:** Conceptualization, Methodology, Supervision. **Diego López-de-Ipiña González-de-Artaza:** Supervision. **Luigi Patrono:** Conceptualization, Methodology, Supervision.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication in Journal of Cleaner Production (**Internet of Things (IoT): Opportunities, issues and challenges towards a smart and sustainable future**) and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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