Viewpoint
Covid-19 digital test certificates and blockchain

1. Introduction

Since 2000, humanity has experienced pandemics like Severe Acute Respiratory Syndrome (SARS), Middle East Respiratory Syndrome (MERS), Ebola, Swine Flu, and coronavirus disease 2019 (COVID-19), with the latter being the most recent and the most severe compared to the rest. So far, COVID-19 has resulted in 72.8 million confirmed cases, including 1.62 million deaths globally. Compared to the Spanish flu in 1918 and HIV/AIDS in 1981, where 50 and 35 million people died, respectively, COVID-19 seems still far away, but its impact is predicted to be the most severe economic crisis since 1900. Additionally, the World Economic Forum (2020) estimates that the cost of prevention measures for COVID-19 in place could be 500 times less than the cost of managing the pandemic. Learning from the past would be beneficial for governments, instead of being a firefighter or responding reactively to the crisis. Perhaps, the COVID-19 impact on human, social and financial dimensions would be less severe if humanity learned its lesson.

Until now, governments have used different mitigation actions to minimize the virus's impact. These, range from social distance to work distance, movement restrictions, public health measures and other economic measures (OECD, 2020). Many countries imposed a first total lockdown in March 2020 and a second in Fall 2020, as the number of infected people increased. The lockdown's purpose was restricting mobility to keep low COVID-19 spread. While lockdown is an essential mitigation measure, it comes with very high associated costs potentially for a country's economy (Bausch, 2020). It also has a negative impact on psychological, social, domestic violence and other parameters. At the same time, most governments introduced the COVID-19 test to distinguish between healthy and unhealthy people and to increase the traceability of the incidents.

After the first wave of lockdowns, countries attempted to minimize their economic impact and work to return to normality. The concepts of immunity passport, vaccination certificates and negative test documentation are now on the agenda (Liew and Flaherty, 2020). However, these documentation types face many challenges, such as discrimination, violation of human or medical rights and personal data exposure that governments need to consider before implementing them. Recent examples demonstrated that there were several implications of COVID-19 test certificates of air travelers. The UK reports that the golden ticket was a negative COVID-19 test for some air travelers, but the absence of global detection and communication systems between countries allowed many fake certificates to be circulated (Kelleher, 2020) (News, 2020).

COVID-19 made public and private organizations to rethink the way of handling information. Numerous information and communication technologies (ICT) are valuable tools for enabling governments to improve their relations with citizens, organizations and other governments (Themistocleous and Sarikas, 2005). We live in an era where pieces of information are no longer generated and managed centrally, impacting organizations' information management systems. Information systems are now synonymous with the "value" generated to the organization and the various stakeholders involved (Ågerfalk *et al.*, 2020). COVID-19 raised many questions on how enterprises can improve or how information is managed for increasing value during pandemic times. Since the last decade, the combination of different information systems has always been challenging and costly for health-care organizations (Khoumbati *et al.*, 2006). Nowadays, the integration of heterogeneous systems is

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crucial for enterprise preparedness during a crisis. The appropriate involvement of different ICTs is vital for allowing effective communication of organizations interacting with the same network. According to (Kamal, 2006), organizations in order to increase their productivity and effectiveness need to improve their structure and process and implement appropriate information technology solutions. The selection of appropriate information technology solutions depends on the organization's internal and external environment while considering all associated threats and opportunities. Cutting-edge technologies (like blockchain) need to be explored further for identifying a new way of managing and communicating sensitive, immutable, auditable and transparent health information in the global ecosystem avoiding discrimination activities, considering human rights and protecting personal data.

Blockchain is a disruptive technology associated with the way information is stored, communicated and managed in an organization's internal and external environment. Blockchain records encrypted transactions in a distributed ledger validated through a decentralized network based on a consensus algorithm. In doing so, blockchain creates trust between unknown entities, increases security, records the transactions in chronological order, achieves transparency and immutability (Makridakis and Christodoulou, 2019). For many authors, blockchain is a new way of interacting within the digital world (Kakavand *et al.*, 2017) by avoiding the middleman. It also eliminates the conflicts and risks arising from several actors' interactions in a transaction. Blockchain is utilized in many areas like a land registry, public domain, supply chain, banking and finance, agriculture and healthcare.

Blockchain increases effectiveness, transparency, trust, and traceability data sharing and assists in the reform of governments' policies, health protocols, and procedures. Digital transformation offers a paradigm shift in the health-care industry and leads to improved diagnosis, treatment, prevention and increased quality of health service (Mantzana *et al.*, 2010). The increased demand for COVID-19 tests as a prevention measure to avoid contamination leads to the increasing need for a new decentralized global health-care system (Christodoulou *et al.*, 2020). This will allow all authorized entities in a worldwide network to append transparent, immutable, hashed transactions that refer to medical data. The availability of these health certificates will enhance people's mobility and will improve its economic impact.

The advantage of issuing certificates directly on a blockchain is that the certificates themselves are valid rather than just proof. Their signing becomes immutable, transparent, trustworthy (Lemieux, 2016) and permanent (Dubovitskaya *et al.*, 2017; Zheng *et al.*, 2017) in a chronological order (Puthal *et al.*, 2018). The trustworthiness of records derives from establishing the reliability of data from an unauthorized alteration and authenticity, which refers to registration, the source and evidence that indicate the information content, and any changes from their creation. This makes every transaction a verifiable true record and can only be updated by a consensus, and data are immutable, which means that once entered, it cannot be modified (Themistocleous, 2018). Blockchain allows every part of the data to be always 24/7/365 available and secure using hashing encryption methods. The system's uniqueness is that it provides trust between the unknown parties with the middleman's absence and with lower transaction costs (Cunha *et al.*, 2020).

The remaining paper is structured as follows: Section two investigates the normative literature using machine learning and bibliometric techniques. This goal is to explore the application of blockchain in healthcare further and especially its application in COVID-19. Section 3 is a closer investigation of the background concepts and demonstrates how mobility can enhance blockchain technology with local and international cooperation. It also presents essential blockchain platforms like Hyperledger and Ethereum that can be used for the development of COVID-19 test certificates. The paper closes with conclusions and recommendations for further work.

2. Background research

The purpose of this section is to employ a systematic review to better understand the literature and its gaps by focusing on the keyword "Blockchain AND COVID-19". We developed a machine-learning algorithm to search the Scopus database for journal and conference articles that meet the abovementioned criterion, and we identified 59 papers for further study. We thoroughly checked these 59 articles to identify inconsistencies, and we used the novel bibliometric procedure developed by Plevris *et al.* (2017) to analyze the results. This method will allow us to understand the critical concepts used alongside Blockchain and COVID-19 and their inter-associations.

Figure 1 depicts a bibliometric map, which is based on the analysis of those 59 papers. Each keyword in Figure 1 is placed on the map and analyzed to measure the co-occurrence strengths. Each keyword's importance can be recognized by the size of each circle located next to it. The size of each circle is related to the number of occurrences of a specific keyword. The co-occurrences are linked through a line for understanding the similarity (link strength) between the objects (Papadaki *et al.*, 2019). Figure 1 reveals that the keywords Blockchain and COVID-19 are positively associated mainly with artificial intelligence (AI), machine learning (ML), big data (BD) and Internet of Things (IoT). It appears that the authors of these 59 papers believe that the interplay of those technologies can support the fight against the pandemic and minimize the economic impact and infection rates.

In terms of COVID-19 traceability, blockchain and COVID-19 are related more to healthcare, transmission stages, big data, Ethereum and smart contracts. Social distancing is also being explored in association with big data, AI, blockchain, smart contracts and healthcare. Health-care records distribution and access are becoming extremely important after this recent crisis. The analysis of the normative literature indicates that there is a gap in verified health-care records. This makes health-care information difficult and costly to exchange. The efficient management of health-care information can reduce costs and improve health-care organization processes (Yang and Yang, 2017). However, to do this, some technical barriers need to be overcome, such as confidentiality, privacy, interoperability and

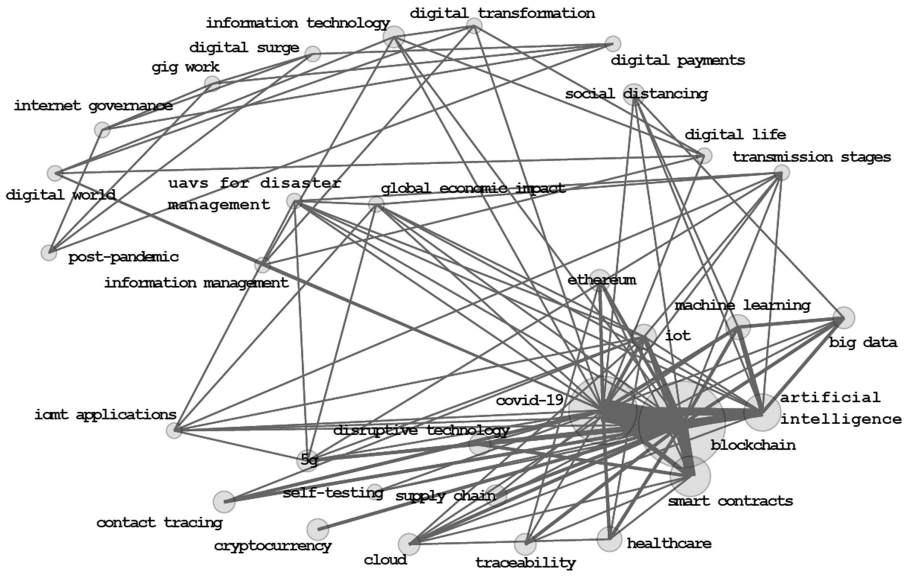


Figure 1.
Bibliometric map of the relation between COVID-19 and Blockchain Keywords

integrity (Yang and Yang, 2017). Looking into the bibliometric map, it is identified that AI and blockchain are closely linked to the literature. Mainly blockchain seems like a storage platform, while AI is related to the data stored and is used to create intelligence. Therefore, it is enhancing the participants' decision process. IoT also provides a great potential in the health-care sector by utilizing multi-sensors that can generate raw digital data (Choi *et al.*, 2017), while big data analytics can be used for data processing (Din and Paul, 2019).

Further the involvement of smart contracts in the research is done for the improvement of automated transactions and securing of information exchange. Smart contracts provide a secure distributed and shared ledger of all transactions (Karamitsos *et al.*, 2018), allowing efficient validation among the participants to avoid the middleman. Smart contracts applications are also looked at through the literature on raising funds for assisting the local government in obtaining additional resources (Uddin *et al.*, 2018). Through the bibliometric map, it is revealed that COVID-19 is positively associated with smart contracts. Moreover, it seems that the post-pandemic is positively related to governance, digital transformation and payments.

In order to assist the readers to better understand our study, we provide a summary of the six most cited papers that examine blockchain and COVID-19 (Table 1). The most cited paper is from Ting *et al.* (2020), published just three months after the pandemic outbreak. Their work concentrated on the importance of enchanting public health with digital technologies in general and, more specifically, how blockchain technology can be used as a collaborating system between different participants, hospitals, pharmacists and patients for timely delivery of medication with accurate tracking (Ting *et al.*, 2020). The second article on the list is by Chamola *et al.* (2020), which focuses on the use of different innovative technologies such as blockchain and AI to minimize the pandemic's impact. Chamola *et al.* (2020) investigate mobile apps that have emerged due to the pandemic for storing data in immutable records. These apps attempt to overcome the lack of integration of verified data sources where blockchain's advantages enable the validation of continuously changing data. Their work focuses on CIVITAS and MiPasa applications. The first one utilizes blockchain as storage for

Table 1.

Authors	Title	Year	Source title	Cited by
Ting D.S.W., Carin L., Dzau V., Wong T.Y.	Digital technology and COVID-19	2020	Nature Medicine	91
Chamola V., Hassija V., Gupta V., Guizani M.	A Comprehensive Review of the COVID-19 Pandemic and the Role of IoT, Drones, AI, Blockchain, and 5G in Managing its Impact	2020	IEEE Access	18
Mashamba-Thompson T.P., Crayton E.D.	Blockchain and artificial intelligence technology for novel coronavirus disease-19 self-testing	2020	Diagnostics	14
De' R., Pandey N., Pal A.	Impact of digital surge during Covid-19 pandemic: A viewpoint on research and practice	2020	International Journal of Information Management	10
Chang M.C., Park D.	How Can Blockchain Help People in the Event of Pandemics Such as the COVID-19?	2020	Journal of Medical Systems	7
Vaishya R., Haleem A., Vaish A., Javaid M.	Emerging Technologies to Combat the COVID-19 Pandemic	2020	Journal of Clinical and Experimental Hepatology	6

capturing citizen's ID information in relation to their health-care records, for allowing the local authorities to provide permission to individuals to leave their homes or give hospital discharge of patients (Chamola *et al.*, 2020). This application also has built-in functionality to track patient symptoms and communicate back to health-care authorities. The second one, MiPasa, is an open data hub or a shared platform designed in Hyperledger Fabric to verify patient information among different participants. As it was described, there is a lack of verified patient data, and this platform will allow secure exchange of verified information. The paper by Mashamba-Thompson and Crayton (2020) proposed a tracking system for emerging infectious diseases utilizing both blockchain and AI. They design the system with a geographic information system (GIS) embedded in mobile phones enabling positive-tested people tracking. The fourth paper on the list, written by De' *et al.* (2020), argues that there is a need for design apps that balance privacy versus public health. Chang and Park (2020) look at the importance of blockchain technology in detecting accurate diagnosis, allowing transparent donations and preventing the spread of inaccurate information about the disease. Vaishya *et al.'s* (2020) work concentrated on emerging technologies that can be utilized to fight with COVID-19; among those, they are considering to draw benefits of real-time information and the traceability aspects blockchain possesses.

In summary, most of the studies indicate that blockchain provides an excellent technology for securely communicating verified patient information (Chamola *et al.*, 2020; Ting *et al.*, 2020), (Chang and Park, 2020; Mashamba-Thompson and Crayton, 2020). Blockchain technology allows tamper-proof and authenticated data to be stored in a decentralized system. However, several challenges need to be investigated further to utilize blockchain technology, such as legal frameworks and government regulations, the shortage of skills and awareness of the low engagement.

From the analysis of all 59 papers, it appears that the main focus is on the presentation of the benefits of utilizing blockchain technology. On the contrary, there is limited work published on blockchain, COVID-19 and global mobility. Also, there is little work available that discusses the practical implementations of blockchain COVID-19 test certificates. From the abovementioned investigation, we identified a couple of research gaps. As a result, we propose a new practical approach to enhance mobility and knowledge, considering the impact of health pandemics and applying it to the future as a prevention measure system mitigating risks from similar epidemics.

3. Blockchain and coronavirus disease 2019 (COVID-19) test certificates

In the case of digital health certifications, a blockchain may hold a list of each certificate's issuer and receiver, along with the document signature (hash) in a database-ledger (the blockchain), which is stored on computers that are part of the blockchain network. The use of a Blockchain platform to generate certificates provides the following advantages:

(1) COVID-19 certificates are immutable. Therefore, it is almost impossible to be altered by external parties.

(2) COVID-19 certificate can only be verified by any party who has access to the blockchain using open-source software. There is no need for intermediaries or centralized entities.

(3) COVID-19 certificate can also be validated as no third parties are needed to validate the certificate.

Figure 2 demonstrates how blockchain technology can enhance mobility with local and international cooperation. The issuing country's health institution performs a COVID-19 test and produces a digital certificate using a security mechanism which is added to the issuing country's

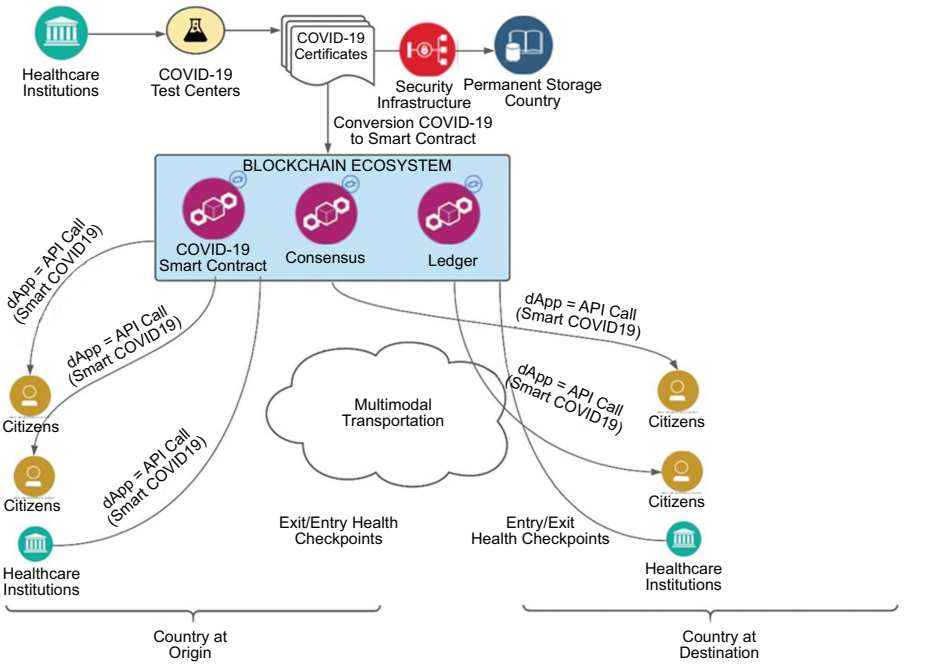


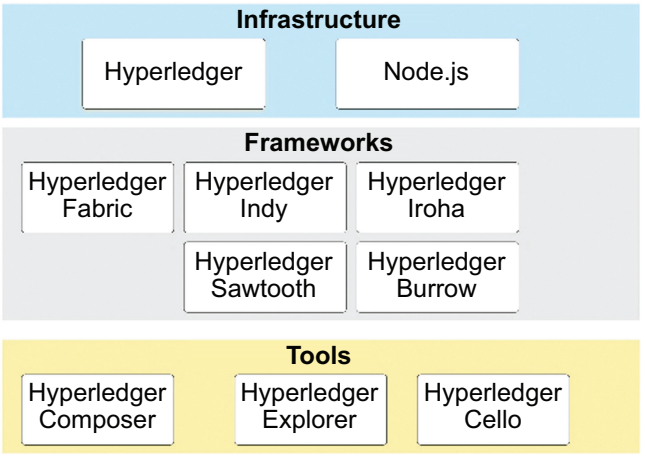
Figure 2.
COVID-19 digital certification overview

health care repository. The different stakeholders and participants are approved government health-care institutions, citizens and entry/exit checkpoints. Blockchain allows all participants in the blockchain ecosystem to obtain a digital copy through an application programming interface (API) call from a blockchain system. This copy is anonymous and encrypted to protect sensitive health-care data of the citizens following the Health Insurance Portability and Accountability Act (HIPAA) standard. When people want to travel from the country of origin to the destination, they could present the digital COVID-19 certificate at the entry and exit checkpoints. In this way, we minimize the risks of privacy and violation of human rights.

Various blockchain platforms can be used to implement COVID-19 digital test certificates. For the purpose of this paper, we will refer to Hyperledger (Linux Foundation, 2020) and Ethereum (Buterin, 2015) as they are two of the most common blockchain platforms used. Each of them follows a different approach on how to implement COVID-19 digital test certificates, and it has its own advantages and disadvantages.

3.1 Hyperledger platform

Hyperledger is an open-source platform developed by the Linux Foundation, and it is a permission distributed ledger that allows only authorized participants to read and write transactions. It is one of the most popular platforms nowadays that does not require validation of the transaction through the mining process. Figure 3 depicts Hyperledger's layers, tools and frameworks. The first layer is concerning the infrastructure or the hardware assets, which are the Hyperledger and Node.js. The second layer is compromised by the available frameworks used to structure blockchain among different participants or enterprises. There are five available frameworks (Figure 3) and from these Fabric and Burrow frameworks are more suitable for COVID-19 certificates (e.g. both support smart contracts). The third layer tier is comprised of tools that assist businesses in deploying



Source(s): Linux Foundation, 2020s

Figure 3.
Hyperledger platform

blockchain as a service (Hyperledger Cello), visualizing operations (Hyperledger Explorer), and constructing a network.

3.2 Ethereum platform

In 1997, Nick Szabo (1997) introduced the smart contract concept which refers to a digital form of a traditional contract, and like it, it allows a digital legal binding among concerned parties. Ethereum is an open-source blockchain platform used to execute smart contracts and trade cryptocurrencies (Marr, 2018). It is a platform that is a cryptographically backed, transaction-based state machine (Wood, 2019). The smart contract design and development is the basic building block for the implementation of COVID-19 digital certificates in the Ethereum platform.

3.3 Advantages

The advantages of utilizing a Blockchain platform for health-care pandemics can be summarized as below and among others include

(1) Accessibility: The results will be available 24/7/365 and accessible in a chronological order.

(2) Mobility: The development of blockchain certificates will result in immutable, secure, transparent and value data that will improve citizens' mobility at the local and international level.

(3) Immutability and reduced fraud risk: COVID-19 test certificates are stored in distributed ledgers and are impossible to falsify. That means the immutability of the data is achieved.

(4) Security and privacy: Blockchains are considered more resilient and less vulnerable to malicious attackers since the database ledger is encrypted and decentralized. Digital fingerprints of the COVID-19 tests will be stored in blockchain, and thus, personal data are protected.

4. Conclusions

This paper investigates a very timely issue related to the application of blockchain technology in assisting overcoming COVID-19. In doing so, we contacted a systematic literature review and identified 59 articles that focus on this topic and were published during the first ten months of 2020 in academic journals and conferences. To better understand the literature, we developed and used a machine learning algorithm that helped us to create a bibliometric map. The map assisted us in defining correlations among different keywords and areas and we analyzed the results using the method proposed by Plevris *et al.* (2017). The analysis of the normative literature indicates that there is a research gap in verifiable health-care records issued on blockchain. Also, there is limited work, in the use of blockchain certificates for COVID-19 tests. In addition, there is lack of research on practical implementations of blockchain COVID-19 test certificates. Based on these findings, we described how technology can be used to issue and validate COVID-19 test certificates on blockchain. According to our literature review, it was revealed that smart contracts play an important role in the development of such applications. Based on these but also on our blockchain experience, we report that blockchain platforms like Ethereum or Hyperledger are appropriate for the implementation of such solutions. The design and development of smart contracts provides the foundation for implementing COVID-19 digital certificates on the Ethereum platform. applications that will record COVID-19 tests will increase mobility at the local and international level, and help reduce the widespread implications of the pandemic. From a practical point of view, such solutions can be used for other healthcare-related data too.

Future work needs to assess the impact of the different health-care protocols applied in countries and identify a way of exchanging cross-country information. Finally, future works need to be done on identifying synergies among different innovation technologies for developing solutions that can be globally implemented.

Maria Papadaki
British University in Dubai, Dubai, BUiD/ Dubai Center for Risk and Innovation (DCRI), UAE and Department of Mechanical Aerospace and Civil Engineering, The University of Manchester, Manchester, UK

Ioannis Karamitsos
Rochester Institute of Technology, Rochester, New York, USA, and

Marinos Themistocleous
Management and MIS, School of Business, University of Nicosia, Nicosia, Cyprus and Digital Systems, University of Piraeus, Piraeus, Greece

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About the authors

Dr. Maria Papadaki is an assistant professor at the British University in Dubai (BUiD) and a managing director for the BUiD_Centre for Risk and Innovation (DCRI). She has over ten years of experience in risk management from both academia and industry, with numerous years in the implementation, development, improvement and management of risk frameworks, tools and techniques in the aerospace industry. Maria worked previously in Rolls-Royce plc and the University of Manchester, leading different enterprise risk management, project management, and supply chain risk roles. In 2015, she initiated the idea and led the development of the first innovation Hub (H2B) in Crete, Greece, on behalf of the Heraklion Chamber of Commerce. She then joined the BUiD in 2016 as an assistant professor/director for the Center of Risk and Innovation (BUID_DCRI) and led the development of digital

certificates for BUiD's graduates, which made the university 1st in the Middle East and 3rd in the world implementing blockchain technology in education. In 2018, Maria was appointed to the Institute of Risk Management's (IRM) in London as a board of directors. Under this profile, she leads the global education and training standards strategy for the UK's institute (IRM). Maria also holds a position as a visiting lecturer at The University of Manchester. Her research interests include enterprise risk management interface with disruptive technologies such as blockchain, artificial intelligence, and IoT.

Ioannis Karamitsos (B.Sc., M.Sc., Ph.D.) has vast research academic and industry experience over 30 years as an executive manager who worked within the private and public sectors and is experienced with European, Middle East and Chinese companies. From 2020 to present, Ioannis is an assistant professor of data analytics at the Rochester Institute of Technology-Dubai Campus. In 2016, he had joined Department of Electrical Engineering as an adjunct professor at the Rochester Institute of Technology, Dubai. From 2010 to 2020, Ioannis was a digital transformation technologist at Orange Business Services, with ten years of consulting experience working with clients to develop and deliver their strategies and transform their organizations into smart and digital cities. Ioannis is a member of DSOA-Dubai Innovation Advisory Board. He is particularly interested in applying blockchain, cryptography, machine learning, IoT and data mining techniques to emerging problems related to large-scale decentralized cyber-physical systems and critical infrastructures as well as energy, healthcare and other domains of major economic and social impact. Ioannis received his PhD in Computer Science from the University of Sunderland, UK, a master's degree in telematics management from the University of Danube Krems, Austria, and bachelor's degree (Laurea) in electronic engineering from the University of Rome "La Sapienza", Italy. He also has executive certificates from Oxford University (Blockchain Strategy), MIT (Tackling the challenge of Big Data) and from Columbia Business School (Driving Strategic Impact Program).

Professor Marinos Themistocleous is the associate dean of the School of Business, director at the Institute For Future (IFF) and the scientific coordinator of the world leading blockchain and digital currency MSc programme at the University of Nicosia. He is a member of the Parallel Parliament of Cyprus and president of the Digital Economy and Digital Government Committee of the Parallel Parliament. Marinos has collaborated with many organizations including the Greek Ministry of Finance, Bank of Greece, Greek Standardization body, Greek Federation of SMEs, ORACLE UK, B3-Blockchain Business Board UK, Intelen US, BTO Italy and Cyprus National Betting Authority. He retains close relationships with the industry and serves as consultant in the areas of blockchain, e-business, e-health, e-governement and information systems integration. He has authored more than 175 refereed journal and conference articles, several teaching textbooks and has received citations and awards of excellence. His research has attracted funding from various organizations. Marinos is on the editorial board of academic journals as well as on the board of prestigious international conferences. In the past, he served as the managing editor of the European Journal of Information Systems (EJIS).