1 Introduction

This document intends to contribute to the *Consultation on Cloud Computing Research Innovation Challenges for WP 2018-2020* issued by the *European Commission (DG CONNECT, Unit "Cloud and Software")*. The document analyses and identifies gaps and research opportunities related to cloud computing, and is developed on top of a set of **Scenarios** and **Drivers** that, once mapped with the **State of the Art**, allow better understanding of the research **Gaps and Opportunities** that need to be fulfilled. The following concepts are defined to understand this proposal:

- **Scenarios**: futuristic viewpoints of different stakeholders, including industrial players, end-users, researchers, and regulators, for cloud computing, including security.
- **Drivers**: challenges that will act as drivers for the development of the cloud computing technologies and models needed to support the scenarios defined (e.g. standardization, open data).
- **Gaps:** aspects that prevent overcoming the driving challenges considering the current State of the art (SotA), and thus block the implementation of the scenarios.
- **Opportunities:** research opportunities related to cloud computing, including security, considering the gaps identified. Such opportunities are derived from the gaps and should take into account the EU-BR priorities.

2 Scenarios

Scenarios are futuristic viewpoints of different stakeholders for cloud computing, including industrial players, end-users, researchers, and regulators. Their purpose is to enable focusing onto the identification of drivers and gaps, and to support the future development of a research roadmap. To identify a preliminary set of scenarios, we started by analysing the Sustainable Development Goals (SDGs) from the United Nations, which include 17 goals to transform our world, ranging from *No Poverty and Zero Hunger* to *Good Health and Well-being*, among others. A detailed analysis and mapping of the Sustainable Development Goals (SDGs) from the United Nations with different *Circles of Sustainability*, highlighted several areas that seem to be of high priority in Europe. In the context of this work we restrain the scope to the most relevant and promising ones, that at the same time open a broad and representative set of research challenges. This way, with the lemma "*Cloud Computing for Sustainable Living*", we propose three main scenarios, as described next.

SC1. Environmental monitoring: Understanding climate changes, conserving and sustainably using marine resources, terrestrial ecosystems, forests, or combating desertification requires the collection and analysis of huge amounts of data (e.g. for planning and acting), that in turn require great storage and processing power, which are characteristics that fit the cloud computing paradigm. This will also strengthen a general "green" movement, encompassing for example, smart agriculture. In practice, environment monitoring infrastructures and services will be defined around very large, dynamic, environmental-friendly networks of sensors that gather data and must reliably provide it to cloud-supported actuators, to big data storage infrastructures, and to analytics tools for decision making. This implies reliable and fast, but energy-efficient, on-demand provisioning of services and infrastructures. The reliability and protection of the data and associated services, their physical location and use, as well as portability characteristics supported by adequate integration mechanisms, are aspects that need to be tackled.

SC2. Smart water and energy management: The population growth and concentration in large communities is making water and energy resources extremely valuable. Cities experiencing accelerated growth will be challenged to expand and operate sustainably and efficiency, while maintaining a high quality of life. Smart water and energy management are two key building blocks of a sustainable world and, in particular, of the smart cities of the future. Cloud computing (together with sensor networks, the Internet of Things, and big data analytics) will become a fundamental part of the cyber-physical infrastructure needed to manage energy and water resources, supporting control functions, dealing with the sensors and actuators, and collecting and converting the data to services for different stakeholders within the respective grids. This requires reliable and on-demand provisioning of services and infrastructures (sensors and actuators), which must be dynamically adapted to new demands and to the growth and changes in the grids. The data and associated services, their location and use, are aspects that need to be tackled. Cloud services will thus reach the very end systems interacting with the sensing and actuating devices, organized in different ways, within the context of the Internet of Things (IoT). In this context, there is a very large gap between the cloud computing and IoT paradigms that needs to be addressed.

SC3. Assisted health and well-being: Assisted Health and well-being is a key scenario for the application of cloud computing presenting demanding research challenges. In fact, cloud computing is a fundamental enabler for solving some key challenges in the area related to patient centred and mobility (national and trans-national) of health services. This includes the implementation of disruptive algorithms, protocols, mechanisms, and services to support the Big Data acquisition, storage and processing required for the implementation of personalized, precision and systems medicine solutions. Such solutions should support assisted health and well-being services tailored to individual patient needs, characteristics and contexts, but also support decision makers in defining regional, national and transnational policies (e.g. in public health). This way, aspects related to mandatory quality attributes like performance, reliability, security, privacy, scalability, and maintainability in the context of cloud computing, cloud services and cloud infrastructures, need to be researched.

3 Drivers

The **drivers** can be seen as challenges for the development of cloud computing technologies and models needed for implementing the scenarios defined in the previous section. Here, we discuss the main drivers for expanding research activities on cloud computing, considering three perspectives.

DR1. Cloud computing technologies are global and pervasive, raising new security and data privacy demands and requirements able to tackle emerging cyber-threats, and creating the need for data flow and portability:

> **DR1.1. Security and privacy:** Fully assuring data privacy, while allowing people to define fine-grained access control policies to their data, will be key challenges for the development of future cloud systems and services. Key aspects are the adequate definition and enforcement of access policies in the context of big data that allow keeping performance overhead at acceptable levels. Also, protecting large volumes of data during storage and processing against unauthorized and malicious accesses (attackers) will require disruptive approaches in the areas of data encryption, obfuscation and masking. Furthermore, the security must be assured in all layers of cloud infrastructures and services.
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> **DR1.2. Data flow:** One importance aspect regarding data flow is the need for moving large volumes of data across different cloud infrastructures distributed worldwide, in a way that allows nearly real-time access to data and resources. Another key aspect related to effective data flow is the need for assuring data quality, thus respecting regulations and quality of service agreements that have to be specified in advance. These aspects will require high-performance data communication channels and protocols, and raise new challenges related to data flow control, monitoring, logging, auditing, and analysis.
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> **DR1.3. Portability:** Data portability, the ability for moving data across interoperable systems, applications and cloud services, will only be possible by providing an essential basis for open access to data, driven by standards and regulations, and thus avoiding vendor lock-in. Another key aspect for data portability is data representation. In practice, achieving full data portability will require the definition of standard formats and advanced languages for defining semantics at the meta-level. A key constraint will be the need for maintaining backwards compatibility.

DR2. Socio-economic factors affect the cloud computing market, including demands created by national/regional regulations, and human factors, and other societal aspects demanding for new ways of deploying and providing innovative services for inclusive societies:

> **DR2.1. National/regional regulations:** Society will become increasingly dependent on large-scale cloud-based systems and services, as well as advanced cyber-physical systems, which in the event of major service failures

may cause not only significant economic loss, but also severe accidents or loss of vital government and public services. This dependence will increase the efforts to regulate many issues related to cloud computing.

DR2.2. Human factors: Human factors can take two perspectives: humans as part of complex sociotechnical systems and humans as drivers for the development of new systems and services. Complex systems rely to a large extent on human operators and their ability to handle failures and other critical events. While human reliability analysis has a long history, there is a striking lack of adequate techniques for assessing and modelling users and operators in complex roles, which will be an increasing demand for future cloud-based systems and services. Moreover, the design of future systems is expected to be fully human-driven, taking into account human and societal requirements and needs. This will require new approaches for modelling human-computer interactions and dependencies.

DR2.3. Innovative services: The cloud computing paradigm has the potential to democratize the access to information, resources, and advanced tools that were before only available to large companies and rich countries. This will stimulate entrepreneurship, innovation, information and knowledge. This, in turn, will raise the need to accelerate the development and deployment of new cloud computing supported services and business models, targeting the design and delivery of innovative Internet services by new players like small and medium-sized enterprises, communities and individuals.

DR3. Technological innovation creates new issues, such as green computing for a sustainable environment, access to open data for supporting advanced services and research, and standardization to support integration:

DR3.1. Green computing: Due to the expected growth of future cloud infrastructures, energy consumption will become a major issue that needs to be addressed. For this, new approaches for cloud infrastructures and services design will be needed, including low energy data storage and processing hardware, energy efficient software design and implementation, and energy-driven resource provisioning. In addition to green usage, there are other issues on green computing that also have to be considered: green design, green manufacturing, and green disposal.

DR3.2. Open data: The concept of open data is grounded in three key notions: availability and access, reuse and redistribution, and universal participation. Open data is of utmost importance for the scientific development community as it provides the means for testing and validating new techniques and tools. From a governmental perspective, open data can be used to support decision making and also for assuring transparency assurance. From a business perspective, open data allows defining new disruptive products or services for more innovative and inclusive societies. However, fully open data will bring specific challenges such as *anonymization* and *portability*.

DR3.3. Standardization: Standardization is a key aspect to maximize compatibility, interoperability, repeatability, and quality. In cloud computing, the idea of standardization can be seen as the solution for the coordination problem. Demands for standardization will be exacerbated by the need for sharing data across systems, countries, and continents. Also, standards will be needed for supporting reliable system communication and integration. Finally, standards will be essential for managing security and privacy aspects of big data, including enforcing application developers to handle personal data adequately, while allowing people to define fine-grained access control policies as mentioned in DR1.1.

4 Research Opportunities

The current State of the Art (SotA) has several gaps that prevent overcoming the driving challenges expressed above and thus block the implementation of the scenarios. Such gaps represent research innovation opportunities on cloud computing, that should be addressed in WP 2018-2020 .

4.1 OP1. Technological and legal framework for managing security and privacy

Gap 1.1 (G1.1): There are many differences across countries regarding the legal framework for privacy management. Also, priorities are not always aligned in terms of security/privacy/infrastructure needs.

G1.2: Current limitations in the technologies for secure processing may require rethinking big data programming models for building scalable and secure applications.

The following research innovation opportunities could address these gaps:

OppOP1.1: Develop a legal framework for assuring data privacy aspects in cloud computing, especially in the context of big data processing.

OP1.2: Design and develop a technological framework providing services for privacy-centred big data processing on the cloud (Privacy as a Service).

OP1.3: Develop guidelines for helping application developers to design and develop secure and privacy-friendly applications.

OP1.4: Provide techniques and tools for assuring the security of complex and dynamic cloud applications and services, including both design-time assurance and run-time assurance.

4.2 OP2. Cloud federation at cross-regional level

G2.1: Federation of cloud resources is the way forward to address data flow. However, the lack of computing resources aside with data stores and the difficulties in replicating and synchronizing reference data in due time, is preventing taking full advantage of cloud federation in many scenarios.

G2.2: The scientific community urges the development of public infrastructures that can be used to support their activities, especially in the context of Big Data processing.

The following research innovation opportunities could address these gaps:

OP2.1: Develop advanced solutions for supporting federation of data and resources in an effective way, addressing privacy, synchronization, portability, and fast data flow aspects.

OP2.2: Define a public, open cloud infrastructure that all scientific researchers can use in an integrated way, removing silos.

4.3 OP3. Cloud sustained cyber-physical systems and systems of systems

G3.1: The research and innovation challenges for the next generation of Cyber-Physical System-of-Systems (CPSoSes) ask for cloud based solutions to provide enhanced functionality with 365/24/7 availability, a high degree of adaptability, safety and security. New cloud computing protocols that address these aspects are needed.

G3.2: Usually, CPSoSes applications present a wide-scale (e.g. an urban environment). These applications require a relatively large amount of processing and storage at the server-side.

G3.3: CPSoSes environments are characterized by openness and dynamic executions. In order to provide a good integration among the applications on these environments standards are necessary.

The following research innovation opportunities could address these gaps:

OP3.1: Design and develop protocols and mechanisms that use the flexibility and elasticity of clouds to provide to CPSoSes Systems secure and self-adaptable services to support their characteristics, while reducing costs including the cost of development, ownership, and managing system evolution.

OP3.2: Definition of a model to integrate CPSoSes systems, cloud computing and big data protocols. This integration could follow some policies. For example, bring the processing of data closer to the data sources in order to improve performance and reduce communication costs.

OP3.3: Definition of a standard to represent and to store the data provided by the CPSoSes applications. Moreover, algorithms and protocols to efficiency store and retrieve data and needed, i.e., data should be stored in a way that facilitates its search.

4.4 OP4. Cloud to the edge

G4.1: Large and centralized clouds have been deployed and have shown how this paradigm can greatly improve performance and flexibility while reducing costs. There are, however, many issues requiring solutions that are user and context aware, dynamic, and with the capability to handle heterogeneous demands and systems.

G4.2: The Internet of Things (IoT) scenario strongly requires cloud-based solutions that can be dynamically located and managed, on demand and with self-organization capabilities, which are not available nowadays.

G4.3: Cloud to the edge has the potential to provide an enormous amount of resources, but it raises several research challenges related to the resilience, security, response time, data portability and usage, as well as energy consumption.

The following research innovation opportunities could address these gaps:

OP4.1: Innovative approaches to create, configure and manage time varying edge clouds need to be developed, up to the case where each Internet connected device is a cloud provider/member, going beyond the fog paradigm.

OP4.2: Explore self-* (adaptation, organization, healing, etc.) techniques and tools able to support the deployment of context aware, dynamic, and complex Cloud based systems.

OP4.3: Develop solutions for supporting and assessing resilience, security, response time, data portability and usage, as well as energy consumption of battery powered devices.

4.5 OP5. Cloud supported innovative and inclusive societies

G5.1: The access to information and computing resources in the cloud will stimulate entrepreneurship, innovation, information and knowledge, that will generate competitive advantages. In this scenario, there is a need to accelerate the development and deployment of new cloud computing supported services and business models.

The following research innovation opportunities could address these gaps:

OP5.1: Design and delivery of innovative Internet and cloud-based services. These services can include new SMEs or community services based on open data, big data, crowd services, e-governance, cultural content, inclusive activities and many other bottom up driven services and business models.

OP5.2: Design and delivery of cloud-based services that use the resources efficiently in order to reduce the costs related to their adoption, making it possible to be used by several communities.

OP5.3: Definition of new cloud business models addressed to all consumers and communities in order to bring more consumers to the cloud.

4.6 OP6. High Performance Computing (HPC) in Cloud environments

G6.1: The aggregated computational power of thousand processing cores of a conventional Cloud HW/SW infrastructure can be directly used for some HPC applications, however, for many parallel applications, the conventional Cloud's HW/SW limits the application performance scalability.

The following research innovation opportunities could address this gap:

OP6.1: Design and delivery of new Hardware and Software techniques, mainly in parallel process communication, scheduling and synchronization, in order to overlap the limitations imposed to HPC applications running on Cloud infrastructures.

OP6.2: Design and delivery of cloud-based communication protocols focused on decreasing the delay among HW/SW infrastructures and improve the work loading among the HPC architecture.

OP6.3: Design and delivery of cloud-based service that will provide HPC available for a broader academic and industrial community that currently cannot access very expensive HPC systems.

OP6.4: Design and delivery of cloud-based services and protocols focused on reducing the power consumption present in HPC infrastructure.