Next Generation Software Technologies Empowering the Digital Transformation of Europe

Recommendations on Software Technology Research for Horizon Europe

Executive Summary

This paper, published by NESSI (http://www.nessi-europe.com/), the European Technology Platform dedicated to software, data and services, emphasizes the fundamental role software is playing in the digitalisation of society and economy.

Software is having real impact on the economy, society and every individual. Currently, the software industry generates directly and indirectly more than 5% of the jobs in Europe and is contributing with 7.4% of the total European GDP[1]. R&D intensive companies across all sectors allocating 25% and more of their R&D budget to software offerings experienced a faster revenue growth than their competitors with lower allocations[2].

The paper identifies important research challenges in software technologies to be addressed in Horizon Europe in order to feed and sustain the innovation and solution deployment pipeline for digital products, services and business models and thus to secure and strengthen the European innovation capabilities in a digital world. In particular, research is required to deliver the next generation of software technologies that exploit the following emerging digital enablers:

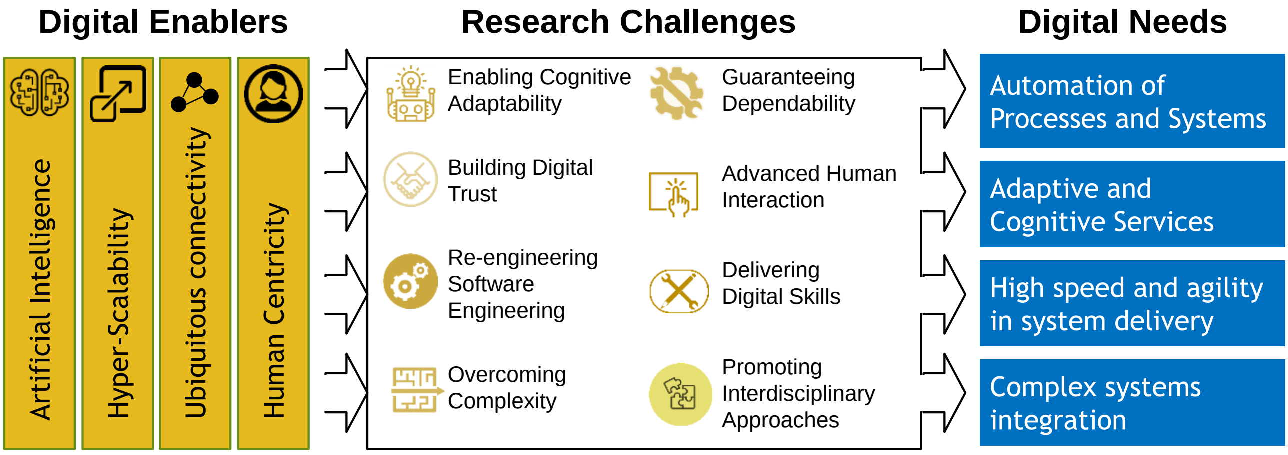
- **Artificial Intelligence** (AI) delivers unprecedented machine-based analysis, cognition and decision making based on advanced machine learning (ML) technologies and big data assets. Thereby, AI enables novel, cognitive software systems, as well as new means to support the software development and construction process.
- **Hyper-Scalability** exploits the whole continuum of compute capabilities (device, fog, edge and cloud) in order to scale out software systems based on demand and user needs. Thereby, hyper-scalability achieves new levels of resource efficiency and cost-optimal deployment of systems, facilitating the delivery of systems at a much larger scale than possible today.
- **Ubiquitous connectivity**, driven by the new generation of mobile networks and the emerging Next Generation Internet (NGI), allows large-scale, high-bandwidth and almost instantaneous interactions between computers and devices, among users, communities and autonomous agents, as well as between data, media and knowledge actors. Thereby, ubiquitous connectivity allows dynamic federation, integration and communication within multi-stakeholder and multi-service systems.
- **Human-centricity** means that software is intuitive and trustworthy, facilitating transparent and fluent interaction between users and digital systems. Thereby, human-centricity empowers more and more people to use, interact and adapt software systems to their needs and situation.

This next generation of software technologies will empower Europe to meet fundamental needs of digitalisation:

- **Automation** of processes and entire systems, thereby increasing productivity and delivering new digital business models;
- Implementation of **adaptive and cognitive services** to better meet customer demands and prevent run-time failures, thereby increasing customer satisfaction and adoption of digital services;

- **High speed and agility** in providing new system functionality, thereby being able to exploit market opportunities, technology trends and the ever-increasing data availability quickly;
- Integration of systems into even more **complex systems of systems**, thereby achieving scalability and economies of scale.

Acknowledging the aforementioned emerging digital enablers, this paper identifies key research challenges to be addressed in order to meet the needs fundamental to enabling the digital transformation across Europe (see figure below). Meeting these research challenges will allow the implementation of Europe's Next Generation Internet vision leading to an Internet, which supports citizens and businesses to push further the frontiers of technology, an Internet which retains people's trust in the online environment as well as their Internet engagement, which is more human-centric, and which offers the same fair opportunities to everyone. To this end, dedicated research activities on software technologies that are capable of exploiting Artificial Intelligence, Hyper-Scalability, Ubiquitous connectivity and Human-centricity should be included as main pillars in the upcoming Horizon Europe Research & Innovation Programme.



Software Drives and Accelerates Digitalisation

Software is one of the corner stones of digital technologies along with hardware, networking and data. Being one of these fundamental digital technologies, software is the transformative power behind all the developments of digitalisation in every field of modern life and will continue to be one of the forces behind technology enhancements and evolutions. Therefore, Europe must be a forerunner in software research and innovation as new applications emerge in industry, transportation, telecommunications, smart and sustainable cities and even in space technologies.

This transformative power is grounded in the capabilities of software technologies to meet the fundamental needs of digitalisation:

- Automation of processes and entire systems;
- Implementation of adaptive and cognitive services;
- Speed and agility in providing new functionality;
- Integration of systems into even more complex systems of systems.

The impact of software advances can be observed in:

- **Smart Devices:** The number of smartphone users worldwide has reached 2.3 billion. Software is playing a key role helping to turn the smartphone into more than a mobile telephone. The smartphone has long been the multipurpose device used for purposes ranging from entertainment, staying connected with friends, to shopping, doing business, or even staying healthy[3]. In addition to smartphones, various other and new media platforms have appeared, e.g. tablets, smart tv's, and more will follow in the form of augmented and virtual reality platforms.

- **Automotive and avionics**: As cars become more software than hardware, the cost of the electronics and software in the average vehicle has risen from 20% in 2004 (e.g. air-bags, engine controllers, antilock brake controllers) to well over 40% today (e.g. assisted and autonomous driving, infotainment). Today a premium class car on average contains 100 microprocessors and runs on 100 million lines of software code[4, 5]. New automotive solutions are deeply intertwined with software development and intelligence. This effect is also observed in avionics. 50% of the cost of developing a new aircraft, i.e. several billion Euros, is related to embedded software and electronics subsystems such as guidance systems, flight control hardware/software and other integrated systems[6].

- **Smart homes and buildings**: Homes are becoming proliferated with IoT devices targeting assisted-living and home automation, e.g. smart-meters, entertainment, security, home care and alert systems, etc. The home automation system market was valued at USD 39.93 billion in 2016 and is expected to reach USD 79.57 billion by 2022[7]. Moreover, with new advances in software smart buildings are becoming more self-aware, sustainable and connected. For example, advances in software interoperability, cyber-physical systems, and cloud computing are enabling the software defined smart home, allowing virtualisation, automation, centralisation and intelligent decision systems as well as the creation of new business models, such as new energy market places.

- **Health**: The popularity in personal fitness and well-being apps and devices is readily observable and increasingly there is the promises of chronic and acute electronic healthcare management systems including telemedicine services. The global healthcare sector is estimated to invest nearly USD 410 billion in IoT devices, software and services in 2022, a rise of almost 600% when compared to a market of USD 58.9 billion in 2014. Examples include health and wellbeing monitoring using wearables integrated to backend systems, nutrition data combined with other life improving information such as fitness apps, and cognitive software providing personal wellness coaching. Software and systems accounted for the majority of share in the "IoT in healthcare" market[8].

- **Manufacturing**: The worldwide smart manufacturing market was valued at USD 67 billion in 2016 and is expected to reach USD 152 billion by 2022. AI and related software advances are vital for the growth of this market. Industry 4.0 will rely on these technologies to develop complex cooperative systems with increased data sharing and analytics capabilities. One example of this evolution is the advancement towards Industrial Data Spaces (e.g. www.industrialdataspace.org/en/).

- **Telecommunications**: 5G networks are software-driven and programmable, based on a new distributed network architecture integrating cloud, virtualization, and software defined networking technologies and augmented with cognitive capabilities making use of data analytics and ML. The software defined design is a key step in enabling the new concept of network slicing or in providing a highly flexible spectrum management. "5G will enable the support of new types of applications connecting devices and objects and versatility, by way of software virtualization, allowing innovative business models across multiple sectors."[9]

- **IoT**: On average, 40% of the value that IoT applications can generate is achieved through the interoperability of IoT systems.[10] Interoperability plays a role especially in IoT settings such as smart cities, smart mobility, or in eHealth where systems have to be interconnected across multiple sectors and ecosystems (energy, logistics, public transportation, environment, water and waste management, etc.). Software-based solutions also address the challenges of ease of integration, managing the resulting system complexity, or building trust in using and operating these complex systems.

Examples such as these demonstrate our world is becoming increasingly software defined, where software plays a central role in the betterment of organizations and our daily life. Software is the glue that makes the digital services, devices, systems, ships, vehicles or spacecraft work intelligently by themselves and in collaboration with each other and other systems.

Software is Generating Significant Economic and Social Impact

In the era of digitalisation, enterprises, administrations and professionals are applying software beyond simple automation of workflows and processes; i.e. beyond increasing productivity and reducing cost. In fact, software technologies and software-based solutions are also being used to promote better customer understanding and individualized experiences, to accelerate innovations for competitive advantages, and access new business models for increased revenue such as the servitisation[11] of products. Software is having significant impact on the economy, society and every individual. For example:

- **Software triggers economic growth and job creation**. It is estimated that a "fully functional Digital Single Market could contribute EUR 415 billion per year to the EU's economy and create hundreds of thousands of new jobs."[12] Currently, the software industry generates more than 5% of the jobs in Europe (~11.6 million jobs are depending on software). [13]
- **Software is a significant contributor to European GDP**. In 2014, the EU28 GDP of the software industry was EUR 249 billion. However, if the indirect and induced impact of the software industry is included, a further EUR 661 billion can be added for 2014, resulting into a total value-added GDP of software activities of EUR 910 billion - which corresponds to 7.4% of the total European GDP.[14] Furthermore, Software is a market sector with accelerating growth, with a yearly growth rate between 2009 and 2015 averaging 1.5% and forecasted to accelerate up to 2.9% until 2020.[15]
- **Software R&D spending catalyses wider innovation across all sectors.**[16] An analysis of the 1,000 companies around the world with the largest R&D spending showed that in 2010 those companies allocated 17% of their total R&D budget in software offerings. In 2015, these companies spent 21% of their R&D budget for software and it was predicted that this share will be close to 25% in 2020. The same report indicated that companies allocating 25% and more of their R&D budget to software offerings experienced a faster revenue growth than their competitors with lower allocations. The significance of software R&D investments creates a catalyst that underpins innovation and generates far-reaching economic, societal and personal value.

Digital Needs, Disciplines & Capabilities

Despite the significant impacts stated previously, Europe is still at an early stage in achieving the true potential of digitalisation. For example, only 20% of the companies in the EU-28 are considered highly digitised and there are still many technological opportunities to be exploited especially by SMEs.[17] Furthermore, over the past 10 years, R&D investments of European software companies grew only by 5%, whereas the R&D spending of US software companies grew faster at a rate of 8.2%.[18] Additionally, 373,000 ICT specialists were lacking in 2015 across the EU and it is expected that this number will grow up to 500,000 by 2020. Europe is missing opportunities offered by the digitalisation not only because of the shortage of ICT experts, but also because the European workforce and the population at large does not have the right digital skills as required to benefit from the digital transformation. For example, most jobs require a basic level of digital skills, however in 2016, 37% of EU-28 labour force had insufficient level of digital skills and 11% no digital skills. Especially advanced software skills are most urgently needed, because they are becoming increasingly critical to access the job market. However, in 2016, 28% of European internet users had no software-related skills at all. [19]

The importance and the impact of software will further increase with the emergence of AI. For the first time, software implementing AI algorithms will be able to closely imitate and augment human thoughts and behaviour as well as to model complex organizations and entire societies. Software will not be any more a tool for automating workflows and systems, but it will grow into the novel role of implementing highly complex systems that intimately interact with people in hybrid digital/virtual and physical ecosystems. By that, software and software developers will be increasingly confronted with social and ethical issues and the call for human-centric software will become louder.

Considering the actual impact software has had and will have on Europe's digital future, there is an urgent need to boost European innovation in software domains to make Europe a global digital leader. Software research and innovation addressing the fundamental needs of the digitalisation – a) automation of processes and entire systems, b) implementation of adaptive and cognitive services, c) speed and agility in providing new functionality and d) integration of systems into even more complex systems of systems – provides the best leverage. NESSI asserts that excellence in the following disciplines will be instrumental for continuing to address the digital needs:

1. **Artificial Intelligence (AI):** In the era of AI, NESSI expects that there will be a new generation of software systems with embedded AI capabilities providing self-awareness, meaning systems will be self-organized, self-optimized, self-protected, self-healing and beyond. AI will be more readily embedded within software, mastering the complexity of future systems and improving the productivity of the software engineering process itself. These next generation programs are not programmed, rather they learn from every interaction and the surrounding context. These programs are built by using novel ML and deep learning techniques, which have significantly different characteristics when compared to today's programming tools and algorithms.
2. **Hyper-Scalability**: Software is required to interact, in a seamless way, with a vast array of other software components, devices, sensors and people to achieve shared goals - even though they were not designed to work together originally and are likely to be independently managed. NESSI foresees the emergence of ever-more complex systems, ranging from small systems to large interconnected systems of systems e.g. transport, telecommunications, financial markets, energy grids, healthcare, manufacturing, cities, etc. These complex systems will be software and hardware compositions of heterogeneous and autonomous components and compute capabilities that are decentralised (e.g. non-hierarchical, independently/locally-managed), distributed (e.g. multi-locational) and dynamic (e.g. continuously evolving).
3. **Ubiquitous connectivity**: Basic prerequisite for allowing hyper-scalability is a ubiquitous connectivity infrastructure enabling dynamic federation, integration and communication among multiple stakeholders and within multi-service systems. This infrastructure will be increasingly complex and has to meet heterogeneous requirements in terms of data rates, latency, coverage, mobility, energy efficiency as well as security and resilience. It will be the task of software and AI to master this complexity and to provide the flexible capabilities as required by the software-based services and systems relying on and built on top of ubiquitous connectivity.
4. **Human Centricity**: Intuitive software is essential for fluent interaction with digital systems and data, enabling real time interoperability between systems and with the user or services. Additionally, our trust in software will increasingly depend on not only its security and privacy, but also its behaviour and transparency. NESSI identifies that human-centric software will usher in new levels of intelligent adaptation. Systems will automatically follow regulations, policies and intentions and provide new levels of controls over not only the behavior of systems but also the way they interact with humans.

New levels of transparency and security will emerge, in conjunction with new regulatory frameworks, especially when sensitive and/or personal data are being processed.

NESSI envisions that interdisciplinary research in the aforementioned disciplines will provide the opportunity to deliver new technical capabilities for building advanced software*,* which includes:

a) Enabling cognitive adaptability. Anticipating all relevant situations in which software has to operate is often not possible due to the uncertainty of what changes a software system may face at run-time. Examples for such changes include cyber-physical or IoT systems operating in ever changing environments, such as smart cities, or digital business processes that face unpredictable usage patterns. An emerging solution to address this uncertainty is to furnish software systems with self-adapting cognitive capabilities. These systems are not programmed, rather they are self-adaptive and learn from interacting with the surrounding context. Breakthroughs in deep learning and learning paradigms, such as reinforcement learning, provide new opportunities for embedding cognitive adaptability within software and systems. This will allow a software system to self-adapt and self-improve based on context awareness of its environment, its goals and its constraints. Primary research challenges include ensuring:

- **Governance of self-adapting software*:*** Anticipating the possible changes that a self-adaptive system may encounter at run time requires defining which situations the system should be able to handle by means of self-adaptation. However, anticipating all relevant situations at design time is challenging, due to incomplete knowledge and uncertainty about the system environment. As a result, a self-adaptive system may encounter situations that have not been fully understood or anticipated, which in turn may lead to ineffective adaptations. AI-based cognitive intelligence allows a self-adaptive software system to self-improve its adaptation mechanisms. Underpinning this will be a need to guarantee the predictability and governability of self-adapting software system and architectures.
- **Transparency of machine learning algorithms:** Cognitive adaptability will handle situations at run-time that have not been fully understood or anticipated during design-time by software developers – thereby mastering the complexity, dynamicity and uncertainty of future systems. However, this can create difficulty when developing, debugging and testing such software systems that can self-adapt e.g. determining causality and liability for autonomous actions and decisions. The lack of transparency about how a system works and who or what is responsible for the resulting output can raise concerns. Algorithmic transparency should allow verification, even by non-experts, and can contribute to discovering errors or biases that otherwise would have been left unnoticed. A main challenge in achieving this is the cognitive overhead required when trying to explicate complex processes. Effective clues and safeguards are topics of research to uncover and characterize possible unwanted effects of algorithms, and the circumstances under which they may occur e.g. preventing adversarial attacks on ML algorithms. Limitations to the observability of all inputs and outputs of an algorithm, for security or legal reasons, is another challenge.
- **Quality datasets:** AI shines with labelled data but currently labelling in many circumstances can be expensive or practically impossible. Therefore, establishing effective techniques for generating labelled training datasets will remove a significant bottleneck to producing high quality ML systems. Additionally, algorithms may be so widespread that they even come to regulate individuals or society as a whole; e.g. on an individual level, they may be affecting health decisions, on an interpersonal level intervening in human relations, while on a broader level they may even impact legislation and the delivery of justice. Possible biases hidden in the datasets that train algorithms need to be more readily discoverable and addressable to maintain/enhance fairness and preserving human values and principles.

Cognitive adaptation offers these systems the ability to continuously adapt and evolve to meet the needs of their new context - becoming ever more efficient and effective. For example, cognitive adaptability can be a key enabler of 'citizen software', allowing users to describe their needs in terms of "intents" or "system goals" and thus to customize, orchestrate or even create software services and removing the burden of software optimization, configuration, quality assurance, repair, evolution and adaptation from the person developing the software.

b) Building digital trust. In digital systems, the notion of trust is traditionally connected with the idea of authentication and authorization, i.e. verifying the identity of an entity and what that identity is authorized to do in the system. As digital systems evolve into dynamic ones, where different human and machine agents interact with each other and the outcomes of their interaction are not known a-priori, the notion of 'behavioural trust' comes into play, i.e. the need to monitor and manage the behaviour of an artificial entity to establish its trustworthiness. If software is to assume greater responsibility, then trust is crucial for its acceptance and adoption. Primary research challenges include the following:

- **Availability of trusted data:** The impact of generating and spreading misleading information is been a recurrent issue in the news and social platforms. Reputation of individuals or brands can be vastly affected, decisions of huge importance can be greatly influenced, and people's lives can be endangered. The speed of detection is a main factor, as false information can have negative effects in a short time, even when a posteriori proven as false. There is a challenge, and opportunity, for intelligent software methods to help detect false information to protect society and software systems from manipulation and deceit. This will require significant advances in information processing, together with novel combinations of human and machine output to promptly detect false information and counter-act its proliferation.
- **Evolution of blockchain-like technologies and smart contracts***:* Software components and services should "behave" in compliance with data protection rules and software license agreements. Those rules and agreements should be easy to understand by the users of software services. Models formalizing the aspects of data usage and processing as well as systems and services able to explain their behaviour, including the identification of actors and the traceability of transactions, could improve this situation by providing transparency and allowing automated auditing and enforcement of rules. In consequence, new ways of building systems and services have to be investigated, able to integrate all related aspects including technology, usability, trust, and regulation. Blockchain technologies and smart contracts might provide the new types of formal contracts to be used for digital services. Resolving challenges such as transaction speed, the verification process, resiliency and data limits, or the need to reverse transactions in case of erroneous and wrong entries will be crucial in making distributed models, such as blockchain, widely applicable.
- **Verifiability complementing security, safety and privacy:** Mistrust can occur because software entities can be maliciously programmed to deceive and manipulate, but also because of algorithmic errors and poor-quality datasets, causing a system not to have desired behaviour. That means digital trust in software components and services increasingly depends not only on its security, safety and privacy features, but also on its behaviour, transparency and verifiability. Novel approaches are needed that will provide verifiable trust solutions in addition to security, safety and privacy.

Building Digital trust can boost the sharing economy and promote direct interactions between people; for example, simplifying transactions and reducing bureaucracy and making processes more democratic, transparent and efficient. Such solutions are expected to contribute to new reputation systems built and maintained by communities rather than central authorities.

c) **Re-engineering software engineering.** Software engineering methods will have to support the construction and operation of self-adapting complex systems, which span across multiple sectors and integrate technologies and know-how from multiple disciplines. Therefore, there is need for advanced and radically new approaches to improve productivity, quality, and security in developing software. These approaches have to be powerful enough to address the wide range of engineering processes and requirements of new digital systems; from life-critical, highly dependable systems deployed in transportation, health, defence or energy sectors to the agile and ubiquitous solutions that continuously adapt to users' and societies' needs. The approaches have also to sustain the open ecosystems allowing multiple actors to develop jointly high-quality and innovative software including open source communities, third party developers complementing large software suites and solutions, and cloud-based services ecosystems leveraging powerful APIs and platforms. Primary challenges include ensuring:

- **Software composability:** Traditional software is built using a decomposition process. The system is broken into sub-systems, which are then broken into sub-components and so on until the lowest object in the hierarchy is defined. Under the traditional software engineering, the setting of each component provides a deterministic interface with a well-defined semantic. The interface semantic of each component in the hierarchy is assumed to remain constant until the system is changed due to bug fixes or feature requests. AI systems introduce ML components to this decomposition. As a result, some of the system components become, by design, non-deterministic. Composing non-deterministic components will need to be addressed for example by the application of statistical testing.
- **Quality assurance and debug-ability methods:** The increased dependencies on ML based software systems introduce a host of new quality assurance and security challenges (e.g. it is expected that KI/ML components will introduce vulnerabilities that cybercriminals can exploit in new ways). The fact that learning may be computation intensive makes the debugging cycles much longer, compounding the challenge further. This new situation is likely to require a new programming paradigm that will enable the smooth integration of many non-deterministic ML components and interfaces in a readable and debug-able manner. In addition, the data pipeline development approach represents efficiency hazards. Under current practice, it is hard to anticipate upfront if the pipeline will produce high quality models, thus requiring repeated iterations through the data resulting in major inefficiencies (e.g. resampling of data and manual labelling). These iterative cycles need addressing through novel tooling and methodologies. Furthermore, development frameworks let developers install functionality more easily from reusable code libraries/pieces. Therefore, software components increasingly have to interact with other independently designed software components within ultra-large-scale software-intense systems. AI/ML techniques could support software development with new validation and verification methods, thus creating high-quality, less vulnerable and more secure code.
- **Automated software development/delivery/maintenance:** ML components are dependent on data. As a result, system changes to code, data and models are interdependent and are likely to require new type of source control. In addition, there is high-degree of freedom in the choice of ML model's parameters. During system development, choices are made to optimize the ML component performance based on the current data. As the number of possible hyper-parameters is exponential, difficulties may arise in maintenance and updates. AI-based techniques to support software development, delivery and maintenance are necessary to overcome many of these challenges.

The ability to develop ultra-reliable and efficient AI software systems with well-defined boundaries of applicability and performance is key to the creation a thriving AI-based economy.

d) **Overcoming Complexity.** Software and systems complexity is increasing along its different dimensions such as the number of lines of code, the diversity of programming languages and development tools available and required for implementing a system, the heterogeneous use cases software has to support, or the different ways how data is stored, accessed and processed. Furthermore, software engineering has increasingly to deal with unprecedented problems related to extreme scalability, dynamicity, heterogeneity, and distribution – both at design and runtime. Therefore, software assembly and operation require a paradigm shift to open new opportunities for safe and quality-guaranteed composition and integration of distributed software systems and services and to master the increasing complexity. Primary research challenges include:

- **Designing and running industry-grade dynamic and non-deterministic systems at scale***:* Self-adaptive and autonomously working devices and software components are required to build intelligent industry-grade systems such as smart cities. These systems can carry out intelligent tasks through the collaboration and the machine to machine interworking of devices and software components. Large-scale smart systems will represent even human actors in many contexts. Additionally, crucial elements for large-scale smart industry-grade systems include the ability to guarantee non-functional requirements such as business continuity in case of system failures - see also the following item e) about guaranteeing dependability. Traditional software engineering methodologies were developed to build deterministic systems and therefore are not adequate to enable the highest degree of autonomy and expressiveness and to cope with the complexity and non-determinism of those systems. Therefore, new methodologies for designing and running those systems are required making use of AI and involving for example digital-twin based simulations for cyber physical systems.
- **Robust and efficient distributed design patterns and algorithms:** Distributed software systems must be reconsidered from a holistic point of view taking into account that the overall system behaviour is an emergent feature resulting from the interaction of many sub-systems. These sub-systems may involve personal devices, high performance information systems, localized and virtualized edge resources, or cloud containers with global visibility. Additionally, users and organisations connected to and interacting with these systems influence strongly the overall system behaviour as well. There is the need for novel tools and methodologies to control and predict behaviours in complex systems that are built up from a compute continuum ranging from simple sensors/actuators operating in a locality, edge devices and fog nodes, up to virtually endless resources over a global cloud. This continuum will encompass also network infrastructures that are becoming increasingly software-driven.
- **Frictionless optimisation across cloud, fog and edge platforms:** Data is expected to be under a producer's / owner's control but is inherently dispersed over computing and storage devices. Furthermore, services that rely on this data will be distributed across multiple different "business and computational" boundaries, spanning from individuals' devices and local mobile edge computing nodes to fog-oriented gateways and multi-provider cloud compositions. Therefore, there is a need to ensure optimal experiences – whether human or agent based - across this compute continuum by optimising the location of compute workload execution to respect latency and data requirements. This optimisation has to consider for example the adequate distribution of intelligence at the edge and the centre and approaches such as serverless computing and NoOps in which case a cloud provider manages the allocation of machine resources in a fully automated way.
- **Virtualization of fine-grained computing resources:** The growing number of connected physical resources will entail the definition of novel abstractions to virtualize the access to distributed, collaborating, heterogeneous, and self-organizing resources which are geographically dispersed. This is a form of reverse virtualization, in which physical entities are physically/logically grouped together under a single virtual interface, for better reliability, increased quality of information, and better elasticity. This scenario calls for novel solutions addressing new technical challenges,

especially when coupled with industry-grade quality requirements in open, dynamic, and extreme-scale execution environments.

Software can and will be a powerful enabler for hyper-scale, non-deterministic and complex systems natively designed to help people and virtual agents to collaborate in a dynamic and flexible manner.

e) Guaranteeing dependability. The scale of future systems gives rise to great opportunities but also many challenges where – owing to scale and complexity - failures are likely to occur and cyberattacks may reach unprecedented dimensions. It becomes highly uncertain the possibility to define a priori complex system interactions (i.e. emergent properties[20]) as there will be billions of loosely connected software components, devices, sensors, and people. This places unprecedented demands on ensuring overall dependability (e.g. proof of correctness) of such systems to realise the synergies, opportunities and benefits. Primary research challenges include ensuring:

- **System predictability:** Interaction between components (i.e. networks, data, hardware and software) of large-scale software intense systems ultimately lead to unanticipated behaviour. Developments will need to comprehend possible reactions to initial actions and orchestrate component and system level behaviour to achieve predictability of local and system-wide goals. Therefore, this will need new forms of modelling and monitoring including models that can represent a wide range of component properties for an ultra-large-scale system. New exploitation methods able to deal with complex system interactions are required to facilitate, for example, system reasoning between dynamic component properties and feedback loops. Additionally, new techniques are also needed for the synchronisation of these models in real-time with actual system behaviour, to maintain accurate feedback loops between modelling, actions, monitoring and effects.
- **System autonomy:** Such systems need to adapt to unpredictable (at design time) run-time changes in their environments, e.g. self-management behaviours including self-configuration, self-optimizing, and self-healing. Software needs to support system evolution during run-time, in reaction to (unanticipated) changes taking place e.g. can adapt to different circumstances with limited, or even without, human intervention - but still within human control. For example, each system component should be able to internalise a global system goal and comprehend how it can be achieved through means of cooperation with other system components. Therefore, system components should be able to learn from each other and learn as a community. However, guarantees also need to be provided about software and system behaviour and goals, such as minimal requirements or quality of service. Nevertheless, symbiotic and fail-safe human-in-the-loop mechanisms should be part of the design of such systems.
- **System fluidity:** System dependability needs to be maintained in the face of ongoing system fluidity e.g. resolving sub-system conflicts, scaling demand, ongoing failures, and/or attacks, and whenever a system is adapted there will be the need for system dependability checks. Because of the scale of such systems, novel techniques are needed to identify, predict, and control key indicators of the system's dependability at run-time in a timely manner.
- **System scalability:** These systems need trusted dependability at scale whilst tolerating varied dependability across its constituent components and subsystems. That is, an ultra-large system must behave as expected (i.e. can be trusted) despite: a) software design and implementation errors; b) failures of the execution infrastructure; c) interaction with potential users including erroneous actions and threats; and d) interaction with the physical environment including disturbances and unpredictable events. For example, autonomous driving and vehicle-to-everything (V2X) systems require a minimum level of trusted dependability across an array of connected systems (and systems of systems). A key challenge will be to understand how

dependability of individual components can be trusted within a dynamically composable system, how dependability aggregates, and how it can be enhanced.

- **System optimisation:** Improving system dependability entails non-optimised use of resources and, conversely, system resource optimisation may jeopardise dependability. For example, if resource utilisation is pushed to the limits, deadlocks may occur and enhancing dependability by massive redundancy costs extra resources. One key software research challenge is ensuring system dependability without disregarding system optimisation.

Ensuring dependability of such systems can significantly boost economic activity in emerging innovations whilst also preventing unintended negative consequences against society, especially for critical systems in high value-at-risk contexts and emerging innovations such as autonomous transport, industry 4.0, energy grids, healthcare, telecoms, or finance.

f) Advancing human interactions*:* Rising user expectations and the increasing importance of customer-centricity puts a demand on advances in the augmentation of human experience, senses and intelligence. Software lifecycles have to be short enough to allow for rapid adaptations and fine customizations and to easily benefit from advances in the foundations of the Next Generation Internet. Primary research challenges include:

- **Design and development of software for smart materials:** New intelligent devices and interfaces will be build and emerge from new materials, nature or bio-inspired solutions, and polymer-based composites. They will be more responsive, adaptable and active. The intelligence required for this smart behaviour is not limited by the computing capabilities of these materials but is provided by software and AI components being distributed and executed anywhere in the cloud or at the edge these devices are connected to. Software engineering approaches for designing and developing these distributed software systems for smart materials will need to cope with the challenging environment of diversity in materials, application domains and disciplines.
- **Advanced user interfaces:** Technological advances in user interfaces are emerging such as 3D, Augmented and Virtual Reality or haptic feedback. They will provide new ways of augmenting user experience and human intelligence, will allow to "feel" the virtual environment around us, and will transform today's 2D Internet into a spatial web of the Next Generation Internet. Software engineering, designing and developing software and services making use of these advanced user interfaces, will have to deal with diverse requirements such as usability, user experience and acceptance, trust, security, and privacy and has to be aware of the benefits provided by the communication technologies offered by the Next Generation Internet.

Increased human synergy with complex cooperative software systems via intelligent user interfaces will enable new dimensions of innovation and productivity. For example, safe learning experiences based on simulations in interactive augmented virtual environments can provide new opportunities in sports, transportation, security, manufacturing, or healthcare. Or real-time human factor computing can offer new ways to explore dangerous environments such as space, seabed, nuclear facilities, and mining. Software is essential in building the required functionality to augment human activities and sense and in maintaining the trust in digital systems.

While the previous sections refer to technical capabilities, NESSI advocates that non-technical capabilities also have to be addressed, in order to meet the fundamental needs of the digitalisation.

g) Delivering digital skills: The EU estimates 500,000 vacancies for ICT professionals not covered by 2020. Additionally, 10% of the workers in the OECD area are in jobs at risk of being replaced by digital technologies and 25% are working in jobs where 50-70% of the tasks might be taken over by technology[21]. While only a few occupations will be automated entirely, most jobs will become increasingly augmented by digital technologies requiring that workers adapt and extend their skills accordingly[22, 23, 24]. The following challenges and/or shortcomings should be addressed:

- **“Simplification” of developing software:** Software technologies can help combat the widening skills gap by making software itself easier to both develop and use.
- **Access to up-to-date curricula:** Removing barriers to digital upskilling and access to relevant education will be key, as well as keeping curricula in-synch with rapidly evolving technology areas.
- **Non-traditional forms of learning:** A new generation of personalized learning software will be necessary that benefits from the multimodal ways of interactions, more readily facilitating life-long learning.

Ensuring the proliferation of software skills (both technical and user based) will allow enterprises and individuals benefit from the advantages of digitalisation. The increased number of experts and workers with good software skills will have positive impacts on employment, productivity, innovation and societal well-being.

h) **Promoting interdisciplinary approaches**. Digitalisation and digital transformation are increasingly directed towards the generation of digital value networks that span many diverse stakeholders as it is the case in Smart Cities and Industry 4.0 scenarios. Software development therefore increasingly needs to transverse cross-sectorial boundaries and deal with growing multidisciplinary issues and domains. Primary research challenges include:

- **Multidisciplinary software development methods:** New software development technologies and methodologies must be conceived and used, and software professionals must master domains such as ML algorithms and applications, Al software development, human interaction design, 3D design, content engineering, and data fluency, to stay ahead with the increasingly cross-sectorial scope and the multi-disciplinarity of the digital era interventions.
- **New paradigms for exploring software usage:** To realise the full potential of software possibilities, development teams must empathize with the user before any development begins by adopting approaches such as design thinking. This may not necessary require expertise in the customers’ field, but it does require critical thinking, to empathize and sympathetically define the user’s needs, ideate them and lastly prototype and test the final solutions. Further developing these user-centered problem-solving approaches for designing software systems and services will be essential for the human-centricity of the Next Generation Internet and will result into digital systems that allow for intuitive interaction and meet users’ needs.

New interdisciplinary approaches for software development will allow the use of software systems in many different, not even currently anticipated contexts, generating novel services and markets with gains in terms of new jobs, productivity and economic growth.

These technical and non-technical capabilities support the Next Generation Internet vision for permission-free innovation, openness and interoperability, more specifically:

- **Foster diversity and decentralisation**, and grow the potential for disruptive innovation; e.g. be a global common, rising above international politics and competition
- **Achieve a highly adaptive, resilient and sustainably open environment** for our cultures and economies by guaranteeing the safety of citizens, and strengthening the health and autonomy of markets and societies; e.g. whenever companies or parts of the network go down by some natural or other disaster, the effects on the rest of the infrastructure should be close to zero

- **Support a transparent technological environment** that is trustworthy and avoids any bias or systematic abuse of global trust; e.g. the architecture, governance and policies structure how entire societies and economies interact and protect free speech, private enterprises and much more.

Recommendations for European Research Programme Horizon Europe

Hardware, networking, data, and software technologies are the fundamental pillars of digital technologies, and the driving force behind digitalisation. H2020 has provided substantial research funding in the areas of hardware, networking, and data technologies such as Future Internet (incl. 5G), micro-nano-electronic technologies, security (incl. cybersecurity) or content technologies and information management (incl. Big Data). Software technologies were used and investigated in all these areas, but a European software agenda was missing as pointed out by the report "*Software Technologies - The missing Key Enabling Technologies*"[25].

Considering the impact software will play in our digital future, there is an urgent need to boost know-how in software, and correspondingly software research activities, to make Europe a digital leader globally. Advancements in digital technologies such as software will be key to re-inventing the internet to reach the full human potential, for all generations. The European Next Generation Internet initiative aims to take up this challenge and to drive a technological revolution in resiliency and trustworthiness while promoting openness, inclusivity, transparency, privacy, cooperation, and protection of data.

NESSI is recommending the inclusion of Artificial Intelligence, Hyper-Scalability, Ubiquitous Connectivity and Software-Human Centricity as main pillars of a focus area on advanced software in the upcoming European Research Programme Horizon Europe, with dedicated research funds for progressing their underlying research challenges and applications.

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