Research and Education Towards Smart and Sustainable World

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Abstract—We propose a vision for directing research and education in the ICT field. Our Smart and Sustainable World vision targets at prosperity for the people and the planet through better awareness and control of both human-made and natural environment. The needs of the society, individuals, and industries are fulfilled with intelligent systems that sense their environment, make proactive decisions on actions advancing their goals, and perform the actions on the environment. We emphasize artificial intelligence, feedback loops, human acceptance and control, intelligent use of basic resources, performance parameters, mission-oriented interdisciplinary research, and a holistic systems view complementing the conventional analytical reductive view as a research paradigm especially for complex problems. To serve a broad audience, we explain these concepts and list the essential literature. We suggest planning research and education by specifying, in a step-wise manner, scenarios, performance criteria, system models, research problems and education content, resulting in common goals and a coherent project portfolio as well as education curricula. Research and education produce feedback to support evolutionary development and encourage creativity in research. Finally, we propose concrete actions for realizing this approach.

Index Terms—smart world vision, sustainable development goals, Internet of Things (IoT), artificial intelligence (AI), computational intelligence (CI), reductive view, systems view, emergence, experimental-inductive method, hypothetico-deductive method, functionality, basic resources, performance, energy efficiency, dependability, availability, reliability, safety, security, constraints, optimization, decision making, hierarchy, open-loop control, closed-loop feedback control, degree of centralization, distributed systems, education, integrative learning, research, innovation, history.

1 INTRODUCTION

We are convinced that common research paradigms and goals including shared visions and research problems promote teamwork and result in coherent project portfolios as suggested in [1], [2] and hence accelerate research and development. Our selection for the core goal is to provide prosperity for the people and the planet through better awareness and control of the environment, both natural and human-made. We base the goal on the United Nations 2030 sustainable development agenda [3] and its 17 Sustainable Development Goals (SDGs). The goal is in line with the European Unions strategic agenda 2019-2024 and its main priority “building a climate-neutral, green, fair and social Europe” [4], leading to the European Green Deal [5]. A pioneer in promoting sustainable development has been the Club of Rome founded in 1968 as a discussion forum by Aurelio Peccei and Alexander King, leading to the report Limits of Growth in 1972, later updated [2]. The Earth overshoot day is an alarming evidence of the problems in global development [6]. We agree that exponential economical growth cannot continue because of finite resources. Instead, the focus has to move from quantitative to qualitative improvement.

Starting from the core goal, we formulate a vision for guiding research and education in the field of information and communications technologies (ICT). We select the Smart World vision [7], [8] as the basis due to its general nature. This vision is originally based on Mark Weisers idea of ubiquitous or pervasive computing [9], which was preceded by the ideas of distributed systems and mobile computing [10]. The term Smart World has been used in the literature for decades, but it was first linked to Weisers vision in [11], [7]. Moreover, our formulation is inspired by the Smarter Planet vision [12], the world will be instrumented using sensors and actuators, interconnected using communications, and intelligent using traditional optimization, artificial intelligence (AI), and computational intelligence (CI). We often use the term AI to correspond to any of those intelligent methods.

We define the Smart and Sustainable World vision as follows: Prosperity for the people and the planet is achieved with intelligent systems that sense their environment, make proactive decisions on actions advancing their goals, and perform the actions on the environment. Sustainable development is emphasized in decision making and system performance is optimized to save basic resources. Humans observe the autonomous operation through user interfaces and, when needed, revise the operation or control the systems manually.

The term Smart and Sustainable World has been used earlier, for example, in [13], but has not been defined as above. Our vision is empowered by advances in technology that introduce ICT devices and intelligent systems everywhere. As an example, miniaturization, wireless technologies, and energy harvesting enable self-powered sensors and user interfaces to be embedded in everyday objects. This technology and its increasing intelligence need to fulfill the needs of society, individuals, and industries but also optimize resource usage as intelligent use of the limited

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basic resources will be crucial to realize sustainability. This apparent requirement is recognized in [13] and [14], for example. The role of intelligent systems (i.e., artificial intelligence) in achieving SDGs is recognized in the EU White Paper on AI as well [15]. Technology acceptance and human control are essential to realize the vision. Moreover, the intelligent systems must act according to the cultural values, norms, and laws of our society. Intelligent systems and human beings are discussed in Section 2.4.

The vision leads to truly complex systems of systems [16], a large number of interconnected devices provide a distributed platform for numerous co-existing intelligent systems that share the platforms limited resources. We argue that managing the complexity calls for studying system-level research problems - and this requires complementing the conventional atomistic reductive view for conducting research with a holistic systems view [17], [18], [19].

In reductive thinking, also called analytical thinking, the idea is to start from conceptual analysis, reduce research problems to simpler problems, then perform experiments, generalize the results to a theory by induction, abduction, or formation of hypothesis, and finally derive result to the original problem from the theory by deduction. A system is assumed to be the sum of its parts. However, this is valid only in linear systems. In complex systems nonlinear relationships between system parts cause a phenomenon called emergence or even chaos. Nonlinear systems should be avoided but when this is not possible, systems thinking [2] and systems engineering [20] are called for. The growing need for systems thinking to solve complex problems is inline with the general progress of science from simple to complex. For example, the short history of mathematics of the last century included in [21] shows this development in mathematics.

In systems thinking, reductive thinking is accompanied by intuition, interdisciplinary discussions, generalizations, structural analogies, and existing system models that are known to work. A system model is an intentionally simplified description of regularities in a system, usually mathematical [22]. An old but useful classification of general linear and nonlinear system models is included in [23]. When deriving the result in complex systems, deduction can be replaced with some more general nonlinear inference. Moreover, simulations and experiments with system models as the key concepts to consider when specifying intelligent systems. The disciplines related to the Smart and Sustainable World vision have similar system ideas such as optimization, decision-making, open-loop and closed-loop (feedback) control, hierarchy, and degree of centralization [36], [37]. Specifically feedback loops formed of sensors, decision blocks, actuators, and controlled processes are crucial for intelligent behavior. The subsidiarity principle guides in organizing a system into hierarchical and relatively autonomous subsystems. These topics are discussed in Section 2.4.

We identify scenarios, system requirements, performance parameters, basic resources, system ideas, and system models as the key concepts to consider when specifying intelligent systems. The disciplines related to the Smart and Sustainable World vision have similar system ideas such as optimization, decision-making, open-loop and closed-loop (feedback) control, hierarchy, and degree of centralization [36], [37]. Specifically feedback loops formed of sensors, decision blocks, actuators, and controlled processes are crucial for intelligent behavior. The subsidiarity principle guides in organizing a system into hierarchical and relatively autonomous subsystems. These topics are discussed in Section 2.4.

We suggest a systematic approach for planning research and education based on the Smart and Sustainable World vision. This approach supports setting system-level research problems and applying systems thinking to solve them. We sketch steps starting from the vision and proceeding through scenarios and requirements to system specification, and finally to research problems and education content. These steps result in a preliminary system model, a set of research problems, and content for the education curricula. The research problems form a basis for a coherent project portfolio. The curricula, in turn, lay a basis for educating researchers with the required general knowledge to contribute towards the vision. We present the steps in Section 3. In Section 4 we suggest actions to start aligning research and education with the vision. Section 5 presents the conclusions.

To serve a broad audience, we explain in each section the essential concepts and list key literature. As the literature on these topics is quite fragmented, this survey can help interested readers to locate relevant research, avoid work already done and to apply the latest knowledge in their research.

2 INTELLIGENT SYSTEMS AND HUMAN BEINGS

2.1 Intelligence

Increasing the intelligence of human-made systems is in the core of the Smart and Sustainable World vision. In standard language, intelligence implies human-level self-consciousness that indicates having or showing awareness of ones own existence, actions, etc.” [38]. Human beings have the unique property of reflective consciousness [39]. They are aware of their own sensations and their environment in a wide sense, know history, and plan and anticipate the effects of their own actions.

As our focus is on intelligent human-made systems, we follow the definition of intelligence in general engineering terms [40], [41]: the ability of a system to act appropriately in an uncertain environment, where appropriate action is that which increases the probability of success, and success is the achievement
of behavioral subgoals that support the systems ultimate goal. Both the criteria of success and the systems ultimate goal are defined external to the intelligent system. The goal of an intelligent system may correspond to some human need. Uncertainty means lack of precise knowledge. Intelligence can also be defined as a ratio, or quotient, of the ability of a system to control its environment versus the tendency of the system to be controlled by the environment. This is a useful definition for our vision, as it emphasizes controlling.

Performing appropriate actions in an uncertain environment is central for intelligence and leads to the need of control systems and feedback. Feedback is a central concept in several well-known models such as the sense, act, and plan paradigm, the cognitive cycle, the observe, orient, decide, and act (OODA) loop and the monitor, analyze, plan, execute, and knowledge (MAPE-K) loop. Control systems have been expanded to achieve intelligence and manage uncertainty by applying traditional optimization, AI, and CI to learn from and make decisions based on the state of the environment observed via sensors and by changing the state of the environment based on the decisions via actuators.

Traditional optimization methods include exhaustive search, local search, linear programming, dynamic programming, divide and conquer, scalarization, cybernetics (feedback), and game theory. However, the global optimum is usually not easy to find because of many variables, dynamic environment, nonlinearity of the problem, local optima, and limited observability and controllability of the environment or process to be controlled. Complex nonlinear problems require nonlinear solutions.

Artificial intelligence is sometimes called machine intelligence. AI is based on symbol manipulation, conventional hard computing methods using binary deductive logic, and statistical methods. CI is using pattern recognition and soft computing methods. AI includes expert systems, case-based learning, statistical learning and multiagent systems using game theory. CI includes statistical and structural methods, neural networks, fuzzy systems, and evolutionary computing. Pattern recognition is a general principle that integrates various other principles. Information can be defined as patterns or structures, and information transmission is in principle transmission of patterns. The state of a system as a set of system properties can also be seen as a pattern. Human brain is a large neural network that is based on pattern recognition, a complement to deductive logic not as sensitive to errors. Evolution, self-organization, and genetic algorithms are basically formation of patterns. Pattern recognition has produced such fields as data mining and big data. Many principles can be seen as special cases of pattern recognition, for example data detection and channel estimation in communications, feature detectors in radio signal classification and interception, and formation of situation awareness. When pattern recognition (analysis) and formation (synthesis) are combined with feedback they form a decision block of an intelligent (in fact, learning) system.

Rational agents are central in AI, defined as any device that perceives its environment and takes actions that maximize its chance of success at some goal. A recent definition of AI resembles closely the definition of intelligence above: "Artificial intelligence (AI) refers to systems that display intelligent behaviour by analysing their environment and taking actions with some degree of autonomy to achieve specific goals." Edge AI, that is, distributing AI to the edge of the network, near the data sources, humans, and controlled processes, widens the application area of AI by shortening latency, enhancing privacy, and improving performance.

2.2 Human acceptance and control

When intelligent systems become more common, humans use them to an increasing amount to contribute to the society and to consume the services they need. In addition to intelligent systems operating in the physical environment (vehicles, factories, service robots, and household appliances, for example), a large number of intelligent systems operate as embedded systems and control the information infrastructure and the services. These systems decide and learn where to locate computations and how to share the communication resources to maintain smooth user experience for social media, for example. In addition, these systems decide the content that services show for humans and also use services on behalf of humans.

Introducing such pervasive decision power for intelligent systems requires considering how humans accept these systems and stay in control. Broadly, these systems can be accepted when they are useful, easy to use, and ethical. Useful services fulfill the needs of humans and services are easy to use when they have high usability. Regarding ethics, the systems have to behave according to the cultural values, norms, and laws of our society, including safety, security, cooperation, trust, justice, integrity, respect, and privacy. Perceived usefulness and perceived ease of use are considered to be central factors in technology acceptance, but additional factors have been listed as well. Of these, we emphasize trust due to the significant role that intelligent systems have in the Smart and Sustainable World.

Transparency supports building trust by presenting the grounds of the decisions and the use of data to humans. Explainable or interpretable AI, that is, AI capable of justifying its decisions, tackles these challenges. The EU’s Ethics Guidelines for Trustworthy AI lists explicability as one of the four ethical principles for AI systems. The other three are respect for human autonomy, prevention of harm, and fairness. EU’s White Paper on Artificial Intelligence also emphasizes trust, values, and fundamental rights such as human dignity and privacy protection. As data are central for intelligent systems, handling data needs to be considered with care as well. This issue is discussed in more detail in the European strategy for data, but is outside the scope of this paper. On building sustainability and guiding AI research and development, we have selected reports mainly from EU as it has been recently quite active in these fields.

We highlight the respect for human autonomy, that is: "Humans interacting with AI systems must be able to keep full and effective self-determination over themselves." This principle is related with the principle of meaningful human
control, stating humans not computers and their algorithms should ultimately remain in control [69]. Such human authority is essential, humans must have power over human-made intelligent systems. Systems providing meaningful human control are responsible to the human moral reasons and their operation is traceable to one or more relevant persons with proper moral understanding; these are called the tracking and tracking conditions [66]. Tracking ensures human authority.

The possibility to revise the operation of an intelligent system or control a system manually is important also because an autonomous system can generate chaotic behavior if some parts fail and not enough redundancy is used, sensor data are contradictory, or the system does not have a clearly defined goal. Human intervention might be needed also when a system is behaving as designed, but the design or behavior learnt by the system has flaws. Even without flaws, automation and autonomy may sometimes create danger or surprising situations. Furthermore, variations in the available resources might require manual control, for example, when an autonomous vehicle loses connectivity to the infrastructure.

Acceptance and human control set requirements for the system, specifying, for example, sufficient cyber security to prevent unauthorized access and deliberative malfunctions, consent management to determine the operations humans allow for intelligent systems, or user interfaces to monitor and control intelligent systems. We discuss requirements in more detail in Section 4.1. This type of requirements in automatic decision-making are already recognized in the General Data Protection Regulation (GDPR) and also considered to some extent in some EU Member States laws [67] though the emphasis is generally on services using data instead of intelligent systems performing actions in the environment.

2.3 Human awareness

The vision implies greater awareness for humans. They gain situation awareness based on the information delivered by the intelligent systems and command the systems to advance the goals they have set for themselves. When sensors measure also humans, they get insight on their own condition. Understanding how their decisions affect their own and their environments well-being can lead to adjusting the goals. In this way, intelligent systems can persuade humans to take sustainable actions.

This awareness can in the future be expanded in the form of telepresence where all the senses (for example, sight, hearing, and sense of touch) come into use. The delays are minimized so that the interactions with the environment look almost instantaneous, and humans feel physically present at the remote site. Combining telepresence and autonomous operation produces systems that make decisions autonomously and control environment based on these decisions but are observed by remote humans that can also give high-level goals for the systems.

Fig. 1. Structure of science in reductive thinking consisting of the real world in the bottom, the theory world on top, and scenarios in the middle. The structure describes the inductive and deductive parts of both research and learning. The problem is reduced into simpler problems before the inductive and deductive parts. The diagram includes the idea of feedback from the real world to the theory world. The deductive part corresponds to systems thinking but only in mathematically tractable problems.

3 Reductive and systems approaches for conducting research

We argue that managing complexity requires complementing the conventional atomistic reductive view for conducting research with a holistic systems view [17], [24], [18], [19]. This combination helps to avoid the tendency towards fragmentation as well, instead generating coherent scientific knowledge using unified terminology over disciplines.

3.1 Reductive thinking

Analysis and synthesis are common methods in science and engineering. Deduction corresponds to analysis and induction, abduction, and formation of hypotheses correspond to synthesis. Abduction means inference to the best explanation [69]. In practice, abduction is implemented by strong inference using many competing hypotheses [70].

Reductive thinking, also called analytical thinking, is the basis for the success of the western culture [43], [18]. In reductive thinking, we first start from conceptual analysis, reduce a research problem to subproblems, then study the subproblems by performing experiments in the real world, generalize results to the theory world by induction, and finally derive a result to the original problem by deduction (from the theory world to the real world), see Figure 1. The figure was inspired by [71], [69], [72], but in [72] the figure is upside down in a simplified form. Our figure is hierarchical so that the abstract concepts are at the top and concrete things are at the bottom as in [69].

In science, a hypothesis, theory, or model is verified with the hypothetico-deductive method by deriving results deductively and comparing them with real measurements [22]. In engineering design, we do not initially have any object to be verified, only requirements that do not exist in sciences [23], [24], [25], [20], [76], [77]. Verification of the system model is done by comparing the analytical or simulation results with the requirements.

When a complete system is being studied, the research problem corresponds to system requirements, and conceptual analysis produces system specifications, a system
model, and finally a system prototype. This is the hypothesis in various phases. Results to subproblems refine the hypothesis. Deduction produces predictions about the subsystems. When the whole system can be constructed based on the hypothesis, a full prototype can be first verified with respect to the requirements and then validated in a real environment, i.e., verified whether the system fulfills the needs.

In reductive thinking, a whole is assumed to be the sum of its parts, which is valid in linear systems. In complex systems this assumption cannot always be made because of possible nonlinear relationships between the parts causing a phenomenon called emergence or even chaos. Emergence implies occurrence of properties at a higher hierarchy level of the system which are not predictable from properties at lower levels. Thus when systems are complex, reductive thinking is not possible without oversimplification, and systems thinking is hence called for.

3.2 Systems thinking

In systems thinking, reductive thinking is accompanied by intuition, interdisciplinary discussions, generalizations, structural analogies, and existing system models that are known to work. These tools facilitate using transferable knowledge useful in new situations and different disciplines, thus improving our creativity (Epstein 2017). Reductive thinking is a special case of systems thinking since the latter is also sometimes using analysis.

Intuition is largely based on experience. The system ideas presented in Section 4.2 are applied in the proven system models, for example, to organize a system into loosely coupled relatively autonomous subsystems. Thus, these models help to decrease the number of relationships between the parts of the system with subsidiarity (also discussed in Section 4.2). Interdisciplinary discussions provide knowledge from other disciplines and structural analogies information on possible solutions. When deriving the result, deduction can be replaced with some more general nonlinear inference which may be called systems thinking. Moreover, simulations and experiments with system prototypes provide insight on higher hierarchy level properties. They replace the mathematical analysis in cases where the analysis is not possible. Deduction corresponds to systems thinking only in mathematically tractable problems.

As a summary, in the combined reductive and systems thinking bottom-up reductive experimental-inductive research is followed by top-down hypothetico-deductive and systems research. This research paradigm supports studying complex systems by starting from system-level research problems, reducing them into subproblems, generalizing their results, and achieving a result to the original problem based on the resulting theory. Intelligent systems call for studying system-level research problems and systems view to meet their strict performance requirements in the presence of resource constraints, specifically when they form large-scale systems of systems. Sustainability sets further requirements to resource usage.

Good books on systems thinking include those by Boulding about hierarchical and evolutionary view of the world as a total system, Meadows about various practical applications of systems thinking, and Kossiakoff about systems engineering, and Checkland and Richardson about the history of systems thinking since ancient times, and Bossel about modeling of complex systems. Avizienis et al. presented an excellent conceptual analysis on dependability and security that have become essential elements in system design, in addition to conventional functionality, performance, and cost. We describe systems view in more detail in Section 4.2. On the other hand, more experienced researchers using the systems approach can focus the efforts by setting common goals and participate to other research activities as well, for example, to defining the research problems and setting the hypotheses. Forecasting is important to have time to adapt to the expected changes. Generalists can be better than specialists in forecasting even in the specialists own disciplines, as they have the general knowledge and broad understanding about the history to identify relevant future problems.

Systems thinking cannot be based only on the reductive multidisciplinary view that is an additive view without notable interaction between disciplines. This approach produces new knowledge in separate disciplines and stays within their boundaries. An example is an encyclopedia: experts from different disciplines write articles independently with some guidance from the editor-in-chief. Interdisciplinary view is a more advanced, interactive view that analyzes, synthesizes, and harmonizes links between disciplines into a coordinated and coherent whole, producing, for example, a unified report or book on a given research problem. The third and most advanced view is the transdisciplinary view: disciplines are integrated to general knowledge in a societal context and their traditional boundaries are transcended. The final goal is the unity of science. In natural sciences and engineering, the interdisciplinary and transdisciplinary views are applied in systems thinking, i.e., in general system theory and systems engineering.

3.3 Systems thinking in mission-oriented research and education

The United Nations sustainable development agenda and the European Unions strategic agenda lead to the need of mission-oriented approach which also calls for the systems approach to determine the vision and the common goals and to solve complex problems where the solution can be found only by using results of many disciplines. Moreover, the impact of research can be found by using the systems approach rather than the reductive approach. Research platforms are gaining popularity as a mission-oriented approach to organize research. Research platforms
are research programs for interdisciplinary research projects [24], [87] that address large societal and global problems (e.g., related to SDGs) which can only be studied from an interdisciplinary perspective.

Systems approach is needed in education as well (Section 5.5). Learning is essentially a bottom-up inductive process, but top-down deduction can be used to strengthen the learning [71]. Learning by doing corresponds to the reductive approach if the problem is initially reduced to a simpler problem following by induction using the bottom up approach. Integrative learning, in turn, uses final top down analysis and hence matches with the systems approach. Proper education curriculum can act as an external force guiding researchers towards systems thinking and to reduce fragmentation.

4 DESIGNING INTELLIGENT SYSTEMS
4.1 Scenarios, system requirements and resources
4.1.1 Scenarios and system requirements
Scenarios and use cases are effective means to discover user needs and define functional and nonfunctional requirements [88], [89], [90]. Scenarios have been used as a representation of system requirements to improve communication between developers and users. Scenarios offer a down-to-earth middle-level abstraction between models and reality [89], see Figure 1. We consider use cases to form a special case of scenarios and focus on the type of scenarios that describe the interaction of a system with its environment and users, as well as interaction among its parts.

A requirement is a general statement about user needs. Functional requirements define a system or its components, the functions that the system or the components must perform, whereas nonfunctional requirements are performance requirements that are related to the use of basic resources. The requirements need to concern human acceptance and control as well, for example to support building trust and providing meaningful human control, as discussed in in Section 2.2.

We emphasize performance requirements as we expect intelligent use of basic resources to be a central condition for realizing the Smart and Sustainable World vision since all the resources are scarce [19], [14], [36]. The world is essentially a closed system regarding materials, and thus their usage should be minimized and they should be recycled for sustainability [91]. Resource regulation is needed as common and free resources are otherwise used wastefully; this is known as the tragedy of the commons [2]. For example, climate change is caused by wasteful use of the atmosphere.

4.1.2 Performance and resources
Performance is one of the fundamental properties that characterize systems, the others being functionality, dependability, security, and cost [82]. Also stability, scalability, and efficiency are important properties [92]. Performance and constraints are system level challenges as can be seen already in the definition of intelligence [40], thus they are highly relevant for the vision. Intelligent systems must meet the performance requirements as they will operate in our everyday environment, in close contact with humans, and they will control various processes crucial for the industry and the society. Sustainable development, on the other hand, places constraints on the use of basic resources and can thus lead to challenging performance requirements.

The six basic resources are: materials, energy, information (data, control, and knowledge), time (delay), frequency (bandwidth), and space (size) [53], [93], [36]. The first three basic resources are the most important and well known in general system theory where an open system exchanges them with its environment through its boundaries [94], [17], [53], [54], [19], and the last three are well known for example in communication theory [95].

Performance often varies in time, frequency, and space, and we are interested in the variations. Efficiency is a performance parameter that is usually measured using the ratio of benefits and expenditures [54] where the benefits may be, for example, data bits or operations, and expenditures are usually consumption of basic resources. The general additional performance parameters are dependability and security [52], [96], [77], [98], see Figure 2. Means of achieving dependability include error tolerance, fault tolerance, and robustness. We identify efficiency, availability, reliability, safety, and security as the essential performance parameters of future systems. These parameters are emphasized when the technology serves humans, as discussed in Section 2.

Specific constraints include fundamental limits of nature [83], [99], [100]. The continuing development of technology and the ever more stringent requirements of new applications (e.g. millisecond-level latency and ultra-low energy consumption) approach these fundamental limits. Thus, understanding system requirements and optimizing resource usage is becoming even more important. Otherwise the planned services will become expensive, or even infeasible to implement. As an example, Moores exponential prediction of the development silicon electronics has had problems already since 2004 and will not continue after 2021 [101], [102].

4.2 Transdisciplinary system ideas
4.2.1 Closed-loop feedback
The closed-loop feedback concept is the basis of most intelligent systems including intelligent agents in AI systems [81], [43], [103], [2], [44], see Figure 3.

Feedback includes in general four blocks, namely the plant, process, or environment to be controlled, sensing, decision making, and acting. Feedback may be positive (reinforcing) or negative (balancing) [81], [103]. Positive feedback may result in exponential growth; it is therefore inherently
Thus after optimization, a decision must be made with a not unique but a set of optima called Pareto optima. In multiobjective optimization, there may be many conflicting and incommensurate objectives. According to Firby in 1989, decision making or competitive. According to proactive architec- but also proactive and in a social environment cooperative.

The decision block has the optimization task and it can be hierarchical and distributed. In control engineering, the decision block is called the controller. In social sciences, the decision block is called an actor. In computer science, the decision block is called an agent.

The goal and the performance criteria are given externally to the decision block. The performance requirements are described numerically using performance criteria. The goal is in general the desired state of the process to be controlled, for example performance or location. The process is transferred from the present state to the desired state, usually iteratively.

We expect the concepts introduced in this section to be crucial when intelligent resource-efficient systems are developed.

4.2.2 Intelligent decisions

For intelligent behavior, analyzing, planning, and optimized decisions are needed. The decision block usually includes a more general planning phase. Using historical information, the decision block imagines alternative futures and selects the best. Thus, an intelligent generalized decision block combines analysis (deductive logic or pattern recognition) and synthesis (pattern formation, decisions), finally producing control data for the act block. The decision block includes also a model of the process containing the needed memory for historical information.

The decision block should ideally be not only reactive but also proactive and in a social environment cooperative or competitive. According to proactive architectures were first studied by Firby in 1989. Decision making can be challenging when several local optima exist instead of a single global optimum. In multiobjective optimization, there may be many conflicting and incommensurate objectives or criteria. In this case the global optimum is not unique but a set of optima called Pareto optima. Thus after optimization, a decision must be made with a subjective preference that is usually equity. We discuss the decision block in more detail in.

4.2.3 Hierarchical systems

In a hierarchical system, sensing results proceed upwards and actions proceed downwards. The feedback loops at the upper hierarchy levels are much slower than those at the lower levels. The actions can be understood to form a goal hierarchy so that the upper level actions set goals to the nearest lower levels in the hierarchy. Each level has the priority to set goals to the next lower level to avoid deadlock situations.

A system may be centralized without any subsystem autonomy or decentralized implying complete autonomy of the subsystems. However, some central control is needed to avoid disorder. The system may be also distributed. In this case the subsystems share sensing information with at least their nearest neighbors using either a shared global memory or message passing through a control channel.

Communications between the levels should be restricted to the essential. This general principle is known as subsidiarity, which is the best and most efficient way to organize hierarchy.

4.2.4 Hierarchy of systems

We can classify systems into the general hierarchy shown in Figure formed by combining the results in. A more comprehensive hierarchy is presented in combining hierarchy and evolution. Similar general hierarchies are included in. A hierarchical and distributed version of the system model (Figure 3) is valid for all these systems, but in some cases open-loop control without sensory may be needed to support fast enough although rough responses.

A simplified hierarchy includes automatic, autonomous, self-organizing, and manually-controlled (often remote-controlled) systems, from bottom up. In large systems, several of these systems might be combined to manage complexity. Automatic systems do not need any manual intervention but may receive some external control information such as a set-point value, reference signal, or route to a given goal. Automatic systems include control systems, adaptive systems, and some learning systems that use external control signals. Autonomous systems are learning systems that do not need any external control during operation except for the initially given goal.

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In manually-controlled systems the decision block is replaced by a human being. The human setting the goals is in the loop, and therefore these are the most intelligent of all systems and as a whole belong to self-conscious systems.
Modern system models in different disciplines include system ideas, they give concrete goals for the research, concretize the vision; together with the scenarios, and System model through self-reproduction. Consciousness is a product of evolution, made possible for control, adaptation, learning, or self-organization. Self-reproductive systems do not use any set-point values or reference signals from robots and other artifacts. For example, natural systems and adaptive systems and morphogenesis corresponds to choice is needed to provide goals for a machine. Generally, some sort of conative structure or freedom of choice is needed to provide goals for a machine.

In natural systems homeostasis corresponds to control and adaptive systems and morphogenesis corresponds to learning and self-organizing systems. Only natural systems are self-reproductive, self-conscious, and social. Natural systems differ in many respects from human-made systems, from robots and other artifacts. For example, natural systems do not use any set-point values or reference signals for control, adaptation, learning, or self-organization. Self-consciousness is a product of evolution, made possible through self-reproduction.

### 4.3 System models

**System model, system architecture, and system platform** concretize the vision; together with the scenarios, and system ideas, they give concrete goals for the research. Modern system models in different disciplines include:

- networked control systems (NCS) and autonomous, cooperative, and self-organizing robots in control theory
- distributed and autonomic computing mobile agents and multiagent systems (MAS) in computer science and software-defined networks (SDN) and self-organizing networks (SON) and cloud and edge servers in communication theory

These disciplines have similar trends towards hierarchical distributed systems, and finally to autonomous or cooperating, autonomous, and self-organizing systems, but the disciplines are using different terminology. Similar situations can be observed between other disciplines as well.

Hence, there is a clear need for interdisciplinary discussions, surveys, and vocabularies so that researchers can locate other fields results, use common, earlier coined terms, and avoid work already done.

A system architecture defines how intelligent systems are divided into parts, and a platform is an execution environment for the software of these systems.

### 5 From Vision to Research and Education

#### 5.1 Planning research and education

Scientific inquiry has been successfully carried out in a compartmentalized manner in specialized disciplines, by selecting at every step the most beneficial research topics, which are so called hot topics. Focus on citations in research evaluation has resulted in stagnation and incremental research. Exploratory research leading to breakthroughs has been widely ignored and therefore new ideas are harder to find. Furthermore, the reactive greedy approach does not always return optimal or even good solutions especially in cases where the problem is complex with various nonlinear interactions.

Rather than chasing citations, authors would need persistence, a focused research program, good methodology and publishing in relevant journals. Funding organizations should encourage such steps by considering innovative new multivariate assessments of research productivity, including assessing social impact. A good approach is to act proactively and contribute to the selection of research topics as was done for example by Weiser.

We suggest five steps for planning research and education to support realizing the Smart and Sustainable World vision. These steps focus on research. When compared with the general system life cycle, our suggestion can be located at the concept development stage, though activities similar to the engineering development stage are performed during the actual research when building prototypes.

Planning proceeds from top down, but feedback from bottom up is also essential. The key concepts related to these steps were described in the previous sections. Vertical industries, research environment, enabling technologies, research problems, and education, are discussed in more detail below. The planning starts by refining the vision, if necessary, and continues by writing scenarios on how intelligent systems provide services for their users. The scenarios are hence closely related to user needs and goals.

When services are defined, the most important vertical industries can be considered (Section 5.2), as well as the local industries needs and the core competences of the university. Further information source are European Commission’s missions for Horizon Europe, the twelve megatrends, ten megatrends for the 2020s, Gartner hype cycle, and other technology trends. Foresight tools provide yet one more possibility to consider research that can be expected to have a significant impact. In addition to writing scenarios, this information can be used to estimate the technology that will mature soon, and to recognize open problems as well.

Scenario writing should be guided by the Sustainable Development Goals and their Key Performance Indicators.
TABLE 1
Steps to plan research and education

| Steps to research and education | Description |
|--------------------------------|-------------|
| 1. Smart and Sustainable World vision | Prosperity for the people and the planet is achieved with intelligent systems that sense their environment, make proactive decisions on actions advancing their goals, and perform the actions on the environment. Sustainable development is emphasized in decision making and system performance is optimized to save basic resources. Humans observe the autonomous operation through user interfaces and, when needed, revise the operation or control the systems manually. |
| 2. Scenarios and use cases | Operation and interaction of intelligent systems with their environment to achieve the given goals. |
| 3. System requirements | Functionality, dependability and security: availability, reliability, safety, confidentiality, integrity, maintainability; performance: efficiency of the use of basic resources: materials, energy, information, time, frequency, and space, constraints and fundamental limits; and cost. |
| 4. System specification | System ideas: optimization, decision-making, open- and closed-loop control, hierarchy, and degree of centralization. System models: Networked control system (NCS), automatic, autonomous, and self-organizing systems, multiagent systems, autonomic computing, software-defined networks. Enabling technologies: artificial intelligence (AI), computational intelligence (CI), Internet of Things (IoT), cyber-physical system (CPS), high-performance computing (HPC), big data and mobile cloud computing, cybersecurity, smart devices, ultra-densification, energy harvesting, software-defined network (SDN), network function virtualization (NFV), network function virtualization (DN2D), radio access technology (RAT), massive multiple-input multiple-output (MIMO), millimeter wave (mmW) and THz communications, wireless charging, optical and satellite communications, green communications. Research environment: resources and services to conduct research. |
| 5. Research problems and education content | General research problems: Massive scaling, architecture and dependencies, creating knowledge and big data, robustness, openness, security, privacy, and humans in the loop, emergent behavior. Knowledge and skills: Autonomous systems, decision theory, network and traffic theory, nonlinear system theory, systems thinking. |

(KPIs) [142], as sustainability is central in the vision. The White Paper on 6G and UN SDGs [143] proposes how the achievement of SDGs can be supported with research on 6G systems. This information is directly applicable, as the future intelligent systems will be 6G systems. Moreover, human needs, acceptance and control need to be emphasized. The resulting scenarios can be used to draft the impact whether scientific, societal, economic, cultural, or environmental. Further, they are tools for discovering goals and goal hierarchies for the intelligent systems.

The next step, specifying system requirements, is based on the scenarios. Here, performance parameters, basic resources and the fundamental limits of nature play an important role. The performance requirements can be met with a system specification by applying system ideas and selecting suitable system models. Decisions on organizing the intelligent systems into hierarchical levels and relatively autonomous subsystems are made, for example. These decisions lead to identifying the required functionality in more detail, to architecture considerations, and to considering the needed research environment and enabling technologies (Section 5.3).

The last step is to determine the focus of the research by specifying the research problems and to specify the education topics. Requirements lead to research problems when the required functionality or performance cannot be achieved without new solutions. The open problems listed in Section 5.4 can be considered as well. However, a random component and scientific curiosity should always be allowed to support the evolutionary approach and encourage creativity in research. The education topics provide the required general knowledge to study system-level problems and apply systems thinking (Section 5.5).

These steps produce a plan for contributing to the vision by generating new knowledge and educating experts. The plan contains the ingredients that are needed to start the actual research as described in Section 3. The conceptual analysis is performed during the first four steps. The system specification represents a hypothesis about the system. The general research problem is reduced to subproblems during the fifth step. Moreover, the research environment provides resources and services for experiments and education content refines education.

5.2 Vertical industries

The most important vertical industries in Europe include factories of the future, automotive and mobility, healthcare, energy, and media and entertainment [144]. Services and products are developed mainly for the vertical industries. As these verticals are also globally significant and they can all contribute to sustainable development, we focus on them. However, we add agriculture in this list as it is responsible of over 11% of global greenhouse gas emissions [145].

A vertical market is a group of companies that serve each others specialized needs and do not serve a broader market [146]. A vertical market is tightly focused on meeting the needs of one specific industry (i.e., application area). As the term implies, in the systems view, the vertical market includes all abstraction levels from physical implementation to services although the markets are named according to the application areas. In contrast, a traditional horizontal market sells its goods and services in more than one industry and, therefore, targets a range of business segments.

The fourth industrial revolution introduces IoT and CPS to realize efficient and flexible factories of the future [139]. 5G systems provide a reliable and fast communication channel for connecting all the devices into a single system, combining fiber and wireless including satellite connectivity. Process optimization inside factories will be crucial [147]. Such optimization is an obvious application for intelligent systems.

The key trends in automotive industry are connecting vehicles to the Internet and to each other, and advancing
towards higher automation levels. Vehicles collect data with their sensors, change information with other vehicles, and use the road infrastructure as well [148]. Intelligent systems will play a central role in increasing the automation, and also in realizing cooperative vehicles.

Electronic health (e-health) and mobile health (m-health) offer ICT to healthcare, to transfer health resources and healthcare by electronic means, and to support the medical and public health practice by wireless devices like mobile phones and patient monitoring devices [149]. Although these developments will change healthcare significantly, larger changes will be triggered by introducing IoT, more systematic data collection and sensing, and intelligent systems using the collected data and AI to control the various healthcare related processes.

Reliability is emphasized in the energy sector, as device installations are expected to last 20 years and the controlled processes are critical for the society and the other vertical industries. Grid protection and control and smart metering are examples of the ongoing trends. Distributed generation and storage of power and micro-grids will change the energy sector considerably in the long run [150]. Similar to other verticals, intelligent and autonomous systems enable low latencies in decision making, managing complex processes, and optimizing resource usage.

The key trend in media and entertainment is the change of user habits and expectations. Media is consumed more on-demand and on-the-move [151]. A major need for intelligent systems will be optimizing network usage, for example, to minimize overall bandwidth usage and server loads for a large number of mobile users by caching media on edge servers.

In agriculture, smart farming introduces new ICT solutions to support efficient production processes [152]. The relevant technologies include satellite imagery, agricultural robots, sensor networks and unmanned aerial vehicles. Data collection and analysis provides sensor data for intelligent systems controlling the processes.

5.3 Research environment and enabling technologies

*Research environments* also called research infrastructures, are needed for experiments (Figure 1), in testing hypotheses and prototypes as well as in complex systems to bring out interactions, emergent properties, and end-to-end performance. Research infrastructures are facilities that provide resources and services for research communities to conduct research and foster innovation [153]. They may be single-sited, distributed, or virtual. They include major scientific equipment or sets of instruments; collections, archives or scientific data; computing systems and communication networks; and any other research and innovation infrastructure of a unique nature which is open to external users [153]. For research on Smart and Sustainable World, the research environment should contain a platform for intelligent systems and resources for simulations.

*Enabling technologies* are used in the research environments and prototypes, to provide the functionality for which mature technologies are available. Research is a combination of theory, simulations, technologies, research environments, experiments, and big data [154]. Inter- and transdisciplinary mission-oriented research needs to be accompanied with a large selection of technologies, as listed in Table 1. This list includes the ten key enabling technologies for 5G systems [155] that will play an important role in realizing the Smart and Sustainable World vision. We add artificial intelligence, cyber security and high-performance computing (HPC, or super-computing) among the enablers [156]. We list also Cyber-Physical Systems (CPSs), integrations of computation and physical processes, combining control, computing, and communications [117], as an enabling technology as CPS is a rather generic system model.

Furthermore, data representations, identifiers, naming rules, protocols, and interfaces between subsystems or modules are crucial for the targeted large-scale systems. Technologies of World Wide Web Consortium (W3C) and Semantic Web support efficient use of data in such systems and codifying semantics [157]. Many future systems will be open. Openness means that the system is available to everybody, using open data and involving competition for common resources, and thus leading to privacy, security, and safety problems due to possible internal faults and physical or cyber attacks [82]. Sufficient safety and security is crucial and establishing trust among users as well. Private isolated Internet may sometimes be needed to guarantee cyber security.

Computing and control may be distributed. In communication networks, the whole signal path from sensors to the decision block and to the actuators must fulfill the reliability and real-time requirements. To avoid delays, processing and communications are often close to the user as in multi-access edge computing (MEC) servers and device-to-device (D2D) communications. Many implementations will be based on software and virtualization.

Internet of Things (IoT) is an essential enabling technology to connect sensors, actuators, user interfaces and other components to the Internet. Current IoT platforms offer a varying set of services for data storage, data access control, data analysis, resource discovery, etc. The number of available platforms is large, for example the authors in [158] survey 39 platforms and in [159] 40 leading IoT solutions. IoT will have a significant role in all vertical industries, as IoT systems will be pervasive - the number of IoT devices is expected to exceed 75 billion worldwide by 2025 [160]. The market size of IoT has been estimated to grow, from 100 billion U.S. dollars market revenue in 2017, to 212 billion by the end of 2019 and to around 1.6 trillion by 2025 [161].

Miniaturization is leading to Internet of Nano-Things where the power consumption is reduced by orders of magnitude to the order of microwatts, nanowatts, and picowatts [162], resulting in smaller devices and new applications. Internet of Nano-Things, and miniaturization generally, support developing devices that are embedded in the environment and harvest energy for their operation [163]. However, fundamental limitations of electronics challenge this trend, and smaller power implies also smaller computation rate and need for simpler processing. 5G and 6G systems will also be important enablers and research topics, as they bring very short latencies in the order of 1 ms and reliable communication, which enables wider use of wireless communications in all vertical industries, for example, to connect with each other the devices forming
the feedback control loop.

5.4 Open problems

When selecting the research problems, the open problems presented in this section can be considered as concrete goals that have an important role in guiding the research [60], [1], [2]. The open problems listed in literature often have broad scope and need to be narrowed. An example of a general problem related to the Smart and Sustainable World vision is the intractability of multiple causal feedback loops, leading to the need of higher-order cybernetics [17], [164]. A famous example on the intractability of the many connected feedback loops is the three-body problem in physics, creating an emergent problem because of the nonlinear interactions between the bodies [17].

Table 2 presents examples of open problems. In artificial intelligence, one of the most difficult open problems is the frame problem: the inability of machines to understand semantics, that is, relationships between abstract symbols and reality [168]. No theory exists for this problem and therefore no machine understands semantics [43], [55], [169]. Understanding of semantics is an important part of self-consciousness as well as cognition. For example, cognitive radios are in fact learning radios. Russel et al. [167] list open problems requiring solutions to guarantee artificial intelligence that is beneficial for the society and robust (i.e., behaves as intended). Robust AI includes meaningful human control discussed in Section 2.2 and is closely related to technology acceptance as well.

The open problems for IoT systems [8] overlap partially with the technology enablers for 5G systems. Research problems related to IoT, specifically to intelligent use of IoT resources, will be crucial due to the expected large number of IoT devices in the verticals. Additional open problems in communications can be found from [175], [176]. Open problems in localization are discussed in [177], [178].

5.5 Education

Research on intelligent systems realizing the Smart and Sustainable World vision requires wide expertise. In addition to the broad set of technological subjects, developing technology for humans and considering the societal dimension call for social sciences and humanities (SSH). We focus here on engineering degree programs, on updating the curricula to prepare the students for the systems approach and interdisciplinary projects. We emphasize systems thinking and systems engineering and concentrate on natural sciences, technology, engineering, and mathematics (STEM) topics. Moreover, we suggest content for degree programs that already provide the required preliminary knowledge and skills for studying the suggested content, specifically the system-theoretical content listed in Table 3. This content was inspired partially by [24].

Additional expertise needed in inter- and transdisciplinary research can be built in research teams after graduation. Working in such teams can be practised during studies in interdisciplinary project courses. Education curricula are needed for continuing (i.e., life-long) learning as well, but this is outside the scope of this article.

Many computing curriculum efforts already include systems thinking and systems engineering [178]. A comprehensive guideline is included in [179] and the Systems Engineering Body of Knowledge (SEBoK) [35] contains a wealth of information.

The curriculum should offer enough general knowledge to students and provide an integrated hierarchical world view where development is evolutionary and based on generalized feedback from the environment as in [53]. This can require a hard-to-be-achieved paradigm shift from purely reductive approach using multidisciplinarity to a combination of reductive and systems approaches using inter- and transdisciplinarity. As suggested in [53], [81], [103], the concepts of hierarchy and feedback are essential tools in most sciences including social sciences and should be included in the education of all students. Teaching a world view is more important than teaching disconnected fast changing facts. The world view integrates the facts into a whole, and the details can be recalled from books and papers. A world view is not easy to form but usually changes slowly.

The compulsory courses should include enough material on mathematics, physics, signal and circuit theory, electronics, control theory, computer science, software engineering, and communication theory. The target is to avoid isolating students in separate compartments. Instead, with overlapping knowledge in the curricula, future interdisciplinary projects become manageable. Research methods must have a sufficient role in the curricula as they are an essential part of our research culture. Sustainable Development Goals need to be considered as well; to educate experts that can contribute to sustainable development [180]. Social and human sciences need to be introduced at sufficient detail to support broad inter- and transdisciplinary work and contributing to sustainable development.

The reasons for and dependencies of courses should be explained, for example using diagrams. Specialists have the expertise to teach the courses. The bottom-up reductive approach should be combined with the top-down systems approach, in this order, by giving links to history and system ideas. That is, the combination of reductive and systems approaches used in research should be used in education as well. History and analogies can make the topic more interesting to students appreciating systems thinking [19], [61], [79]. Analogies are very efficient in learning new subjects and in developing conceptual thinking to gain transferable knowledge to manage the world. A preliminary systems view in the beginning may be useful. In addition to analogies, complexity can be managed using hierarchies and abstractions that ignore nonessential details through idealizations.

Students may find separate system-theoretical courses demanding, hence the material could be included in the existing and carefully selected new technical courses supporting interdisciplinary systems thinking. A separate system-theoretical course using horizontal integrative learning is most useful during doctoral studies or at the end of masters studies after appropriate vertical integration using systems view has been made in each course. One must know the parts that are going to be integrated, and therefore horizontal integration transcending the borders of courses should
patterns, traditions and life styles, and historic trajectories

norms, ethics and legal frameworks, production and consumption
different aspects of politics, social and cultural

and understand the human and social dimensions one needs to analyze

and humanities (SSH) are needed. Broadly, to correctly con- 

wide range of expertise. In addition to STEM, social sciences

education curricula. This set of actions was inspired by [94],

ing the research profile and environment, and reviewing the
collecting background material, focusing the vision, review-

collecting experts to participate in the effort, networking,

the Smart and Sustainable World vision by generating new

We recommend actions to start refining universities ICT re-

group could be aligned with the existing management. Since

To avoid extra administration and meetings, the working

collaboration, the university can focus on its own strengths

and agree division of responsibilities within the network,
collaboration, the university can focus on its own strengths

not be started too early. Examples of horizontal integra-
tive learning include phenomenon-based, problem-based,
project, situated, and authentic learning, and thesis work.

6 RECOMMENDED ACTIONS

We recommend actions to start refining universities ICT re-

research and education so that they can contribute to realizing

the Smart and Sustainable World vision by generating new

knowledge and educating experts. We propose actions for

collecting experts to participate in the effort, networking,
collecting background material, focusing the vision, review-
ing the research profile and environment, and reviewing the

education curricula. This set of actions was inspired by [94].

The research team performing the actions should have a

wide range of expertise. In addition to STEM, social sciences

and humanities (SSH) are needed. Broadly, to correctly con-

sider the human and social dimensions one needs to analyze

and understand different aspects of politics, social and cultural

norms, ethics and legal frameworks, production and consump-
tion patterns, traditions and life styles, and historic trajectories.

As an example, the required wide range of expertise is

recognized in the EU’s Ethics Guidelines for Trustworthy

AI stating that trustworthy AI requires a holistic and

systemic approach, encompassing the trustworthiness of all actors

and processes that are part of the systems socio-technical context

throughout its entire life cycle.

The recommended actions are summarized in Table 4. The first recommended action for a university is to form a working group to support both research and education. The group participates in the rest of the actions by making plans, sharing experiences, providing lectures, and collecting material. Experiences are shared to give insights of the potential gains to commit the key personnel to the actions. To avoid extra administration and meetings, the working group could be aligned with the existing management. Since the members will be mostly professors and senior staff members, they will naturally be responsible also on the implementation of the actions.

The second recommended action is to nominate tutors for young researchers. Basically, all doctors and doctoral students should act as tutors to younger students; this should be a mandatory part of their education. The tutors are educated to become next generation system thinkers so that this idea will continue; otherwise the reductive thinking with its shortcomings will again dominate. The third action is to participate in selected networks to collaborate, obtain state of the art knowledge, and gain visibility. Through collaboration, the university can focus on its own strengths and agree division of responsibilities within the network, in both research and education. Networks such as public-private partnerships facilitate building critical mass to be attractive partners and to generate significant results, and they are preferred by funding organizations as well.

The fourth recommended action is to collect background material in the form of annotated bibliographies, chronologies, and vocabularies. Background material for research and education supports using the existing body of knowledge and avoiding work already done. Vocabularies form the basis for conceptual analysis and include definitions of terms, synonyms, antonyms, taxonomies, hierarchical relationships to other terms, and acronyms as in a thesaurus. Translations into students native language are also useful for learning. The starting point could be [88]. In addition, the IEEE has a thesaurus and a hierarchical taxonomy based on the thesaurus to unify terminology.

The fifth action is to plan the university’s role in realizing the Smart and Sustainable World vision, the first four steps from Table 4. This plan covers the scenarios and the initial system specification, including definitions of enabling technologies and the research environment. The plan should look proactively about ten years to the future.

| Field | Open problems |
|-------|---------------|
| General | Privacy protection in the Internet of Things. Wearable device development and security challenges. Bridging the gap between the world and its computer model. How to process heterogeneous big data from smart things. Ubiquitous computing and security. Smart software infrastructure for smart worlds. How to evaluate the intelligence of the smart world [165]. |
| Collaborative systems | Autonomy, sensing of environment and neighbors, cooperation, and precise communication [166]. |
| Artificial intelligence | Optimizing AIs economic impact, law and ethics, robust AI [167]. Frame problem [168], [43], [55], [169]. |
| Security | Risks of cyber-attacks, defensive schemes, and integrated evaluation platforms to protect IoT-based systems against cyber-attacks [170]. |
| Human control | Transparent and controllable intelligent systems. General theory for meaningful human control over autonomous systems [166]. |
| Internet of Things | Massive scaling, architecture and dependencies, creating knowledge and big data, robustness, openness, security, privacy, and humans in the loop [9]. Interoperability, scalability, flexibility, energy efficiency, mobility management, and security [171]. |
| Networked control systems | Time delays, packet losses and disorder, time varying transmission, competition of multiple nodes, data quantization, clock asynchronism, and network security and safety [172]. Networking technologies, fault-tolerant control, bandwidth allocation and scheduling, and integration of components [116]. Coding for robustly stable control, time-varying data rate, nonlinear feedback, routing [173]. |
| Green IoT | Energy efficient system architecture, energy efficient service composition strategies, situation and context awareness regarding users and applications, energy efficient WSN management, energy efficient cloud management [174]. |

Examples of open problems

| Field | Open problems |
|-------|---------------|
| Energy efficient system architecture, energy efficient service composition strategies, situation and context awareness regarding users and applications, energy efficient WSN management, energy efficient cloud management [174]. |
into physical objects, and new materials for ICT components improved (e.g., with faster electronics), ICT is integrated when complete systems are developed, ICT performance is science, communication theory, and general system theory.

Physics, chemistry, electronics, control theory, computer science, communication theory, and general system theory when complete systems are developed, ICT performance is improved (e.g., with faster electronics), ICT is integrated into physical objects, and new materials for ICT components are developed, for example. Similarly, social sciences and humanities bring their expertise as required, for example, to guarantee that usefulness, usability, acceptance and meaningful human control are considered at sufficient detail, as discussed in Section 2. The identified new expertise calls for new openings and recruitments. For the actual research, we stress combining the reductive and systems approaches as described in Section 3.

The seventh action is to develop the research environment (Section 5.3) for conducting research and specifically to perform experiments. The research environment can be used in both education and research to test autonomous and remote-controlled systems and their components. Students can be familiarized with the technology and perform realistic experiments, and researchers can obtain more valuable results. In addition to testing individual intelligent systems, testing their co-existence on a shared platform can provide valuable insight. Moreover, deploying research results into realistic operation environment supports collaboration with companies and commercialization, thus amplifying the impact of the research.

We suggest that researchers define for the intelligent systems common structures that produce characteristic behaviors, that is, system archetypes that have survived the test of time [2]. These archetypes can be collected, together with their simulation models, into a system zoo [42] that can be provided to researchers, teachers and students as a part of the research environment. The system zoo can be used in courses and research projects and to introduce this knowledge to new disciplines as well.

### TABLE 3
Suggested system-theoretical subjects.

| Subject                          | Contents                                                                 | References                                                                 |
|---------------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Autonomous systems              | Positive and negative feedback, stability, hierarchy, degree of centralization, control and adaptive systems and automation, learning systems and autonomy, and self-organization, autonomous agents and robots, cooperation and competition, networked control systems, history | Albus 2001 [41], Bekey 2005 [119], Bernstein 2002 [121], Coulouris 2012 [108], Dorf 2017 [181], Ghosh 2015 [182], Kotseruba 2020 [183], Maurer 2015 [184], Mesarovic 1970 [104], Murata 2012 [120], Ogata 1995 [185], Ogata 2010 [47], Russell 2010 [44], Sheridan 2016 [186], Tanenbaum 2007 [107], Valavanis 2007 [187] |
| Optimization and decision theory | Traditional optimization, multiobjective optimization, multiple-criteria decision making, artificial intelligence, computational intelligence, deductive logic, pattern recognition, statistical methods, history | Coello 2007 [188], Bishop 2006 [189], Eberhart 2007 [190], Figueira 2005 [151], Gass 2005 [192], Kksalan 2011 [193], Konar 2005 [194], Marsland 2015 [51], Michalewicz 2004 [45], Mitchell 2009 [195], Talbi 2009 [196], Tsoukas 2008 [197], Yang 2010 [198] |
| Network and traffic theory       | Information theory, estimation theory, queueing theory, random graphs and stochastic geometry, history | Haenggi 2013 [199], Newman 2018 [200], Shortle 2018 [201] |
| Nonlinear system theory          | Nonlinear models, Volterra series, memory polynomials, nonlinear compensation, nonlinear control, nonlinear dynamics, solitons and chaos, Lyapunov stability, history | Haddad 2008 [202], Perona 2005 [203], Schetzen 2006 [204], Strogatz 2014 [205] |
| Systems thinking                 | System principles, general hierarchy of systems, system dynamics, stability, scalability, efficiency, deductive logic and pattern recognition, statistical methods, emergence, system archetypes and system zoo, tragedy of the commons, subsidiarity, springing the system traps, places to intervene in a system, complexity, measurement theory, reliability engineering, dependability and security, fundamental limits, methods and tools for systems thinking, history | Arora 2009 [206], Barrow 1998 [83], Bertalanffy 1971 [17], Bossel 2007 [42], Boulding 1985 [53], Checkland 1999 [19], Cockshott 2015 [207], Dewdney 2004 [99], Erdi 2008 [208], Forrester 2007 [209], [210], Hubka 1988 [54], Kahn 2017 [211], Kossiakoff 2020 [20], Liu 2016 [212], Markov 2014 [100], Meadows 2008 [2], Mesarovic 1970 [104], Nielsen 1995 [51], Nielsen 2015 [16], Norma 2013 [213], Repko 2020 [83], Richardson 1991 [51], Senge 2006 [211], Sterman 2000 [108], Trivedi 2017 [98], Yanovsky 2013 [215] |

### TABLE 4
Recommended actions

| 1. Form a working group   | 2. Use tutors as advisors of young researchers  |
|---------------------------|---------------------------------------------|
| 3. Participate in networks | 4. Collect background material              |
| 5. Plan the university’s role in realizing the vision | 6. Review the university’s research profile |
| 7. Develop the research environment | 8. Review the university’s education curricula |

### TABLE 4
Recommended actions

| 1. Form a working group   | 2. Use tutors as advisors of young researchers  |
|---------------------------|---------------------------------------------|
| 3. Participate in networks | 4. Collect background material              |
| 5. Plan the university’s role in realizing the vision | 6. Review the university’s research profile |
| 7. Develop the research environment | 8. Review the university’s education curricula |

The sixth action is to review the university’s current research profile and initiate the required new openings. This is the research part of the last step in Table 1. Planning the research to solve the research problems produces a coherent project portfolio to renew the research and contribute to the vision. This portfolio can form the basis for a research platform. The required expertise includes the disciplines needed in the interdisciplinary research. In the STEM domain, knowledge is needed from mathematics, physics, chemistry, electronics, control theory, computer science, communication theory, and general system theory when complete systems are developed, ICT performance is improved (e.g., with faster electronics), ICT is integrated into physical objects, and new materials for ICT components are developed, for example. Similarly, social sciences and humanities bring their expertise as required, for example, to guarantee that usefulness, usability, acceptance and meaningful human control are considered at sufficient detail, as discussed in Section 2. The identified new expertise calls for new openings and recruitments. For the actual research, we stress combining the reductive and systems approaches as described in Section 3.

The seventh action is to develop the research environment (Section 5.3) for conducting research and specifically to perform experiments. The research environment can be used in both education and research to test autonomous and remote-controlled systems and their components. Students can be familiarized with the technology and perform realistic experiments, and researchers can obtain more valuable results. In addition to testing individual intelligent systems, testing their co-existence on a shared platform can provide valuable insight. Moreover, deploying research results into realistic operation environment supports collaboration with companies and commercialization, thus amplifying the impact of the research.

We suggest that researchers define for the intelligent systems common structures that produce characteristic behaviors, that is, system archetypes that have survived the test of time [2]. These archetypes can be collected, together with their simulation models, into a system zoo [42] that can be provided to researchers, teachers and students as a part of the research environment. The system zoo can be used in courses and research projects and to introduce this knowledge to new disciplines as well.
The eighth and last recommended action is to review the university's ICT education curricula and build the required new content. This is the education part of the last step in Table 1. Weighting between the compulsory topics listed in Section 5.5 depends on the degree program. Horizontal integrative learning can be supported with project courses that collaborate with the research projects, thus also preparing the students for research career. The research projects provide a good source of examples for all courses in the curricula.

As discussed above, the aim is to define common goals and build a coherent project portfolio and education content. Common goals result when the research team performs planning together. The research portfolio can be built based on this work. In education, the refined curricula prepare the students for the systems approach and interdisciplinary projects. Research and education produce feedback to refine the plan.

7 Conclusion

We are convinced that common goals including shared visions and research problems promote teamwork and result in coherent project portfolios, thus improving the research culture. We suggest the Smart and Sustainable World vision, steps to plan research and education based on this vision, and actions for realizing the plan. Universities are the main actors in this plan; generating new knowledge and educating experts. Also Neubauer and Calame [180] argue that Higher Education Institutes (HEIs) should contribute to SDGs by producing and sharing relevant knowledge.

Intelligent systems are at the core of the vision. These systems fulfill the needs of society, individuals, and industries but also optimize resource usage as intelligent use of the limited basic resources will be crucial to realize sustainability. Scenarios are used to define system requirements and finally to specify the systems. Human acceptance and control are emphasized. Systems must have high availability, reliability, efficiency, safety and security. Research and education produce feedback to support an evolutionary development and encourage creativity in research.

The principle of subsidiarity is the best and most efficient way to organize hierarchy to minimize the nonlinear relationships between the parts. The closed-loop feedback concept is essential to produce intelligent behavior, that is, to advance given goals in an uncertain environment. As setting goals implies self-consciousness, humans are needed to set goals for intelligent systems when the systems are developed and during operation. We also suggest that humans stay in control and revise the operation of the intelligent systems when necessary.

Inter- and transdisciplinary effort is required to cover the wide expertise and to synthesize the research results into a coherent whole. Research on intelligent systems requires expertise from control theory, computer science, and communication theory. Social and human sciences and several other disciplines are need as well, as the intelligent systems coexist with humans and serve them.

We emphasize the systems view complementing the conventional reductive view as a new research paradigm. The need for systems view has been widely recognized and it is necessary both in the mission-oriented approach and to generate large impact. Systems thinking is a form of generalized inference that is needed to replace deduction in mathematically intractable problems. Understanding history is an essential part of the systems view and our general knowledge. The quality of research is improved by broad education, for which we have recommended concrete actions to prepare the students for the systems approach and interdisciplinary projects. There is a clear need for interdisciplinary surveys and vocabularies so that researchers can locate other fields results, use common, earlier coined terms, and avoid work already done.

Research and education should proceed from bottom-up reductive experimental-inductive approach to top-down hypothetico-deductive and systems approach, in this order, since this is the most natural way of learning. A preliminary systems view in the beginning is useful, and this view can be created starting from our Smart and Sustainable World vision, whose fundamental goal is prosperity for people and the planet, now and into the future.

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