1

A Brief Introduction

I see it all perfectly; there are two possible situations – one can either do this or that. My honest opinion and my friendly advice is this: do it or do not do it – you will regret both.

Søren Kierkegaard

From the Ancient Greeks through the Renaissance, and until our present day, human beings have always tried to give meaning to the reality surrounding them. This effort was not based on tradition or myth, but on the human rational ability to describe reality through the laws of mathematics.

When writing a scientific text and trying to give reality a meaning by applying a mathematical model, we cannot ignore certain philosophical concepts. On the contrary, we must find inspiration in the opinions of the great thinkers of the past. We will only examine a few postulates, but you can rest assured that many more are available and extensively explained in the literature. We take advantage of the knowledge that was made available to us by such human talents.

Our calculus teachers would never stop saying that numbers have to be interpreted, understood, and explained organically. Thanks to numbers we can define an object, an event[26], or a physical phenomenon. Why is there a need to interpret numbers?

According to Pythagoras, numbers are the primordial elements from which reality is derived. The latter can be inferred through a strict mathematical and geometric sequence. The qualitative and contemplative elements coexist with the quantitative one. Each number is associated with a shape containing elements which allows them to stay together in a harmonized and neat manner. Therefore, if we base our interpretation of the world on its numerical and harmonious nature, we can come to understand it starting from its measurements. Are numbers all we need to understand the world? What is your idea of the reality surrounding us?

It is not easy to have an idea and expand upon it – we could find it difficult, for example, to distinguish true from false and zero from one. Once its traits are

Systems Engineering Neural Networks, First Edition. Alessandro Migliaccio and Giovanni Iannone.

defined – zero or one, true or false – an idea is absolute and unalterable, therefore we can associate it to reality.

To paraphrase the words of Plato and inferring his theories from his dialogs – we apologize in advance to our fellow philosophers and teachers of philosophy – the Idea exists outside of our mind. It is detectable only by our intellect and not by our perception, the latter being not sufficient to understand reality. We can simplify by saying that the idea is similar to a standard of judgment. We have access to the knowledge of things only if we have ideas (See Figure 1.1).

Ideas act as measurements to evaluate the tangible reality, and they do not reside in our imagination. The idea, as an objective entity, is not to be confused with opinion, which is instead subjective. As we know in physics and mathematics, we have to measure the phenomena we observe daily with certainty and precision. The idea is a model (or archetype) correlated to our empirical world – we should only try to imitate or duplicate this model. We will see later on how this model acts as an absolute reference for our implementation.

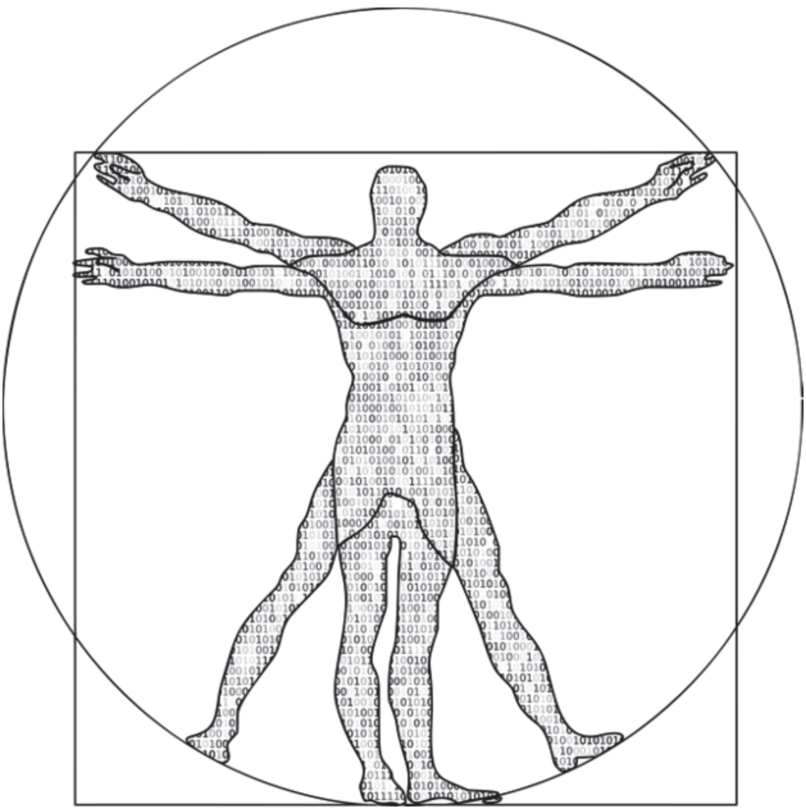

Figure 1.1 The human being becomes the standard for all things.

If we wanted to make a measurement of a particular event and then attribute to that event a meaning, we could start with the concept of an idea, in an absolute sense, as an essential reference. On the other hand, if the measurement is associated with a judgment, then we cannot know whether there is an absolute rule to discriminate that event. Surely we can trace back through experience to the general rule governing an event.

Therefore, as we have mentioned earlier in this chapter, human beings have always felt the need to explain the worldly reality they live in and, might we add, it could not be any other way. Man's senses can be accepted as an important source of knowledge.

However, would we as human beings be able to understand the world based on rules established by our rationality? The Vitruvian Man, famous work by Leonardo da Vinci, conveys a model of a human body that is analyzed and measured through mathematical and geometric tools. The human being becomes the standard for all things, therefore humanity as a whole gains full awareness. Man2, put at the center of the world, becomes the symbol of a better future.

We now have all the elements to start writing about mathematical models, which can also be referred to as rational and variable structures, integrated in logical processes. These structures are based on the concepts of Number, Idea and Human, which we have introduced earlier.

The ultimate meaning of an event is seen as a reliable reference, and we aim toward it. A systematic and methodical approach to the analysis of an event – as we will see in Chapter 3 – will help us interpret it. Its modeling can take us to more reliable, though not absolute, conclusions.

When applied to varied events in our lives, the use of mathematical models can help the reader to better interpret certain dynamics that are part of our daily life. The examples in this book are relevant to those aspects that are often difficult to decipher due to their complex nature. Processes such as decisional ones can be understood via computational models used in the examples provided.

The German physicist W.K. Heisenberg affirmed that concepts of probability apply to all cognitive processes. Human beings would not be able to reach a perfect understanding of a physical phenomenon because the observer is not able to determine how they are interfering with the observed object.

To build a mathematical model we need to define a prerequisite that establishes its efficacy: this is uncertainty (Figure 1.2). Uncertainty obviously plays a vital role in the development of complex models, as they require a reliable mathematical form to describe a real problem. We would be ignoring our reality, and our understanding of it, if we ignored the element of uncertainty. It is easily understandable that closed-form expressions offer a description of simple and less uncertain realities, which is more accurate.

But what if reality is instead complex, uncertain, and difficult to interpret?

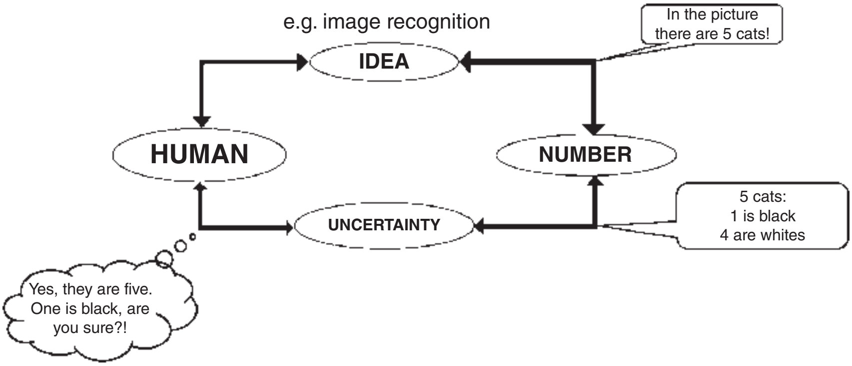

Figure 1.2 Number, Idea, Human, Uncertainty…what else?

Now, this is our objective: let us develop a tool that operates through estimates and aims at minimizing the possibility of error so that we can rely on a result as close to objectivity as possible.

How can we achieve that?

Below are two images, at first glance remarkably similar, depicting two different animals: a cheetah and a leopard (Figure 1.3). Would you be able to tell them apart and say which is which? How can we define the two animals if we do not have an extensive knowledge of zoology? The obvious solution, not to be dismissed from the start, would be to ask an expert and have him explain to us how to tell them apart. We can obtain an accurate solution to the problem if we make use of specific knowledge to define a series of characteristics. The solution, as a result of data processing, will be more accurate if we can count on all the applicable variables of the problem and if we can relate these to the characteristics of the animal depicted below.

Figure 1.3 Cheetah or Leopard? Could you tell them apart? Source: Image by Jonathan Reichel from Pixabay.

The approach we take in this book is a common application of linear and non-linear algebraic combinations – these somehow describe the various interactions happening in our brain when it is prompted to find a solution to a problem. The individual outcome of these efforts can be defined as the union of elements and variables working together to perform a specific function.

The reader will find a brief description of neural networks, as a calculation methodology, and some cases, taking the opportunity at the same time to exemplify the "system approach" used throughout the book. It is important to clarify that the learning phase is essential for the neural network to work as expected. A network can detect the trends in the data regardless of how they fluctuate, based on the exact behavior of all the involved variables. The scope of machine learning[3] as a discipline is to find a correlation between historic data and present (and future) data; when the correlation is found, the network detects it and uses it as the basis of its prediction[32].

Even a distracted reader can see that predictions are valid only if future data trends align with past ones. In other words, if we think of an unchangeable, static and frozen reality, we could set in stone all the algorithms that work successfully. Our reality is constantly changing, but we have to start somewhere – won't you agree? Therefore, let us build the basis of our models and then create an algorithm that can guarantee a certain degree of accuracy in analyzing specific dynamics, and also reduce uncertainty[34] as much as possible. In fact, the continuous changes of events can be managed by adapting and improving the algorithms.

Let us take the human brain as a reference to explain this better – after all, we have always been told that our brain is the biggest computer ever created.

Pieces of information move inside a neural circuit of two or more neurons, thanks to a communication process based on chemicals and electrical impulses that is repeated billions of times. Any piece of information in our brain travels at extremely high speed until it reaches the cerebral cortex where information is analyzed and ultimately "understood."

Before reaching the cortex, the information will go through a high number of synapses. As the same process is repeated time and time again, information will follow the same well-known route. Let us recap: as pieces of information go through the same process a number of times, synapses become so used to it that even different, but relevant, signals ignite the same sequence of impulses. The entire process of memorization is part of a "simplified" process that, starting always from the same point, travels easily through the same steps again and again.

The neural networks' learning process, as presented in this book, follows the general principles described above, though the process happening in our brain is way more complex than the one we will use for our artificial neural networks. Our brain is constantly reshaping, and old synapses are replaced by new ones when our brain goes through learning or memorization phases. On the contrary, the networks used in this book will remain quasi-static[46] once they are set up and will be used to process the same type of information.

We hope that the notion of "learning" is now established as the basis of the implementation of all neural network algorithms. Once all scenarios and conditions are memorized, we can proceed and estimate ways to learn the difference between right and wrong. Moreover, it is possible to only learn from pieces of information that are not decoded or limit our research to the correlation present among the available data. It is also possible to learn from known data and make predictions or decisions by comparing all the available options once the data is processed. If we think that reality is way more complex, the choice of learning and processing data with linear models might be oversimplifying. Our aim is to uncover the correlation that exists among the known data, or rather the physics and mathematical models at the basis of all the possible scenarios that the network needs to crunch.

We have noticed how cognitive science and neuroscience have come closer to each other in the last millennium. The technological advancement and research made by physicists, psychologists, and neurophysiology experts on the study of the brain enable us to develop more complex neural networks (Figure 1.4).

We would like the reader to focus on the concept of learning once more, and to try and optimize it so as to distinguish it from other concepts or processes. How can we improve the learning phase? Can we just increase the number of data or improve the quality of the data itself? By adding structure to the network, we would be increasing the complexity of the code and the processing time.

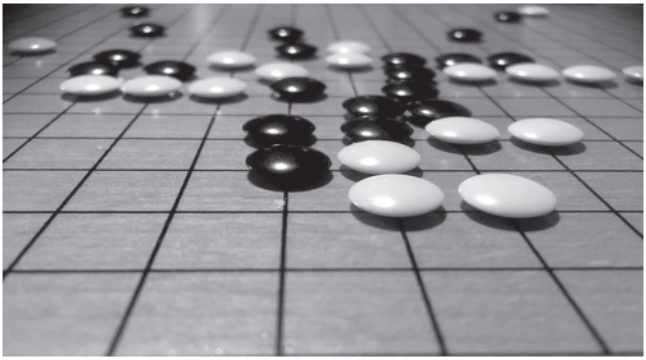

Figure 1.4 How many scenarios of a GO game can you imagine? Source: Image by Jonathan Reichel from Pixabay.

It is known that when we focus too much on the details of a simple problem, we lose sight of the context, and we can easily find ourselves with a foggy solution. Equally, if we had access to high processing capability but insufficient training data, we would need to steer the learning process toward a specific solution, rather than a generic one.

It is safe to affirm that a mathematical structure similar to the human brain cannot replace the reasoning of every human being, especially when it comes to the ability of a human being to make decisions based on their feelings or intuition – we know how these elements can at times be more efficient than reason! From a mathematical point of view, our aim is to help the reader to process the largest share of data that is possible and reach a reliable conclusion from a mathematical point of view. If you think how difficult it is to create a model based on a worm's 300 neurons, you can easily understand how arduous or impossible it would be to reproduce a model of the human brain, with all its 85 billion neurons. This is not surprising if we consider that the human brain has developed throughout millions of years and AI is a subject that was only born in the last century.

Note

In the book we shall refer to Neural Networks and Deep Learning[4] as AI for simplicity, keeping in mind that these are only some of the techniques covered in the wide spectrum of AI technology.

1.1 The Systems Engineering Approach to Artificial Intelligence (AI)

Systems Engineering (SE) represents an important paradigm to support the introduction of new process activities and new technology. The systems engineering approach emerged as an effective way to manage complexity and change and supplies a consistent framework to engineers who are willing to design intelligent systems. Chapter 3 will show how ultimately it takes no additional systems engineering effort to design and manage systems heavily reliant on AI. Nevertheless, it would be blind to ignore the necessity of injecting AI capabilities to augment the performance of existing systems. To put in simpler word, it is the opinion of the authors that when talking about systems making use of artificial intelligence (AI), systems engineering becomes, in essence, "common sense engineering."

From this point on we shall refer to ANN (Artificial Neural Network) and AI subsystems to indicate a black-box module performing machine learning functions. It is a good idea to start this endeavor with a clear understanding the existing system and look for points in common with those of an ANN-based system, from this point on called simply AI. An interesting starting point is that building a system around AI is not the most common approach. AI is most often a supporting

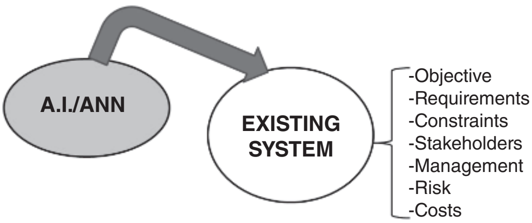

Figure 1.5 Integration of AI/ANN into an existing system.

element and can be a part of the existing system, usually with the aim of improving system performance such as its accuracy or reliability. Most of the examples presented in this book, from a spacecraft (system) or autopilot (subsystem), to the corrosion detection are existing systems that can be augmented with AI, while others like the LEGO® Sorting Machine is a system designed around the use of AI to perform its core function.

How the AI can be integrated into an existing system? Starting from system architecture is the best practice to have the correct knowledge of the system and its components (Figure 1.5).

When it comes to neural networks, the highest level of detail is certainly coded by a defined programming language. The entire system architecture should be clear to the system engineer and allow to readily extrapolate the part of the system in which the ANN is to be introduced. The now called AI-subsystem itself and the interfaces with other systems shall provide the available dataset, needed to build the algorithm. The in-depth knowledge of each system function will lead to defining the objective of the AI-subsystem and above all, a rigorous management of the constraints and requirements. In any field of work, the techniques for managing AI within a complex system are always the same and the reader should acquire the critical skills needed to make the best use of the systems engineering approach.

The first steps in the systems engineering approach to solve any technological or non-technological challenge are connected to answering certain basic questions: Who needs the system? What is the system meant to accomplish? Who is going to operate it? Who will benefit from the successful operation of the system?

By answering these questions, the developer of such a system will be able to setup a rigorous set of requirements and constraints, before moving on with the design, prototyping, verification and validation activities mentioned in Chapter 3 and in most of the literature (see INCOSE Systems Engineering Handbook).

Some of the more pragmatic readers, already familiar with the principles of systems engineering may think that the many software packages used to manage this complexity would overwhelm the "common sense engineering" mentioned above, that is not necessary as "system thinking" is not in contradiction with pragmatism.

Developing the system architecture is one of the most important phases of the SE approach. Creating an effective architecture draws on the experience, intuition, and good judgment of the engineers to devise an appropriate solution. The systems architecture builds on four methodologies:

- Normative (solution based) such as building codes and communication standards.
- Rational (method based) such as systems analysis and engineering.
- Participative (stakeholder based) such as concurrent engineering and brainstorming.
- Heuristic (lessons learned) such as simplify the framework.

Why is architecture an important phase? Because systems architecture is an adequate process, and because intuition and experience play such an important role, the systems engineer must pay attention to situations where past experience and intuition have been a handicap.

Even after all new system elements are deployed, (Figure 1.6) product/project management must continue to account for changes in the various system element life cycles. A new technology will impact one or more system elements, and an existing system is superseded by such improvement.

How is the correct integration reached? At first, the AI inputs and outputs have to be compatible with the existing system or its components. Such compatibility of components of a large and complex system is needed to work as a single entity. This is an important feature of AI. It can work autonomously in a complex system and can continue to improve when the system changes.

The AI capability is essential to avoid redesigning the existing product/project which cannot be easily reworked due to delays with concomitant cost overruns. Eventually, a production engineering analysis for each design alternative becomes an integral part of the Architectural Design process. The production engineering creates any constraints on the existing design. Such constraints shall be communicated and documented. For complex systems, a multidisciplinary analysis is a key task to clarify the existing design and reduce risk, lead time, and cycle time;

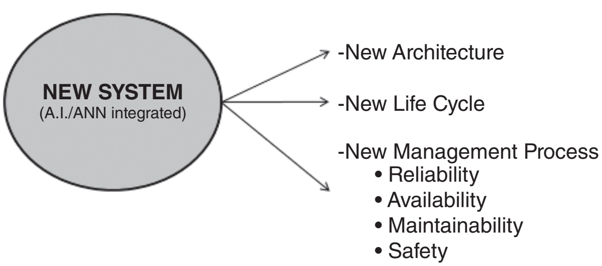

Figure 1.6 A new system is met when an AI is introduced.

and to minimize strategic or critical materials use. The design clarification should account for assembly and disassembly of the integrated AI for maintenance.

The existing system is surely supported by a qualified process. If the existing process remains satisfactory when the AI is integrated, then the AI impact on risks and cost-effectiveness becomes evident. The program risk analysis, if necessary, is a next phase to be performed to evaluate AI long-lead-time items, and special processes.

The next step is to share with the working team what is being done. In particular, it will be communicated as following:

- the level of uncertainty,
- the degree of complexity,
- the consequences to human welfare.

All systems work in an environment influenced by events (Figure 1.7). The events definition is the key to establishing the tasks and activities that need to be completed prior to introducing the AI. All projects are subject to uncertainty; an uncertain event may be harmful if it occurs (threats), another may assist in achieving objectives (opportunities). Dealing with both types of uncertainty under the single heading of "risk management" minimizes process and overhead and expands organizational and personal commitment toward finding and capturing opportunities. Since traditionally, project managers think of risks as threats alone, it may be a change to begin recognizing opportunities. If opportunities are handled along with threats, risk management language needs to be balanced

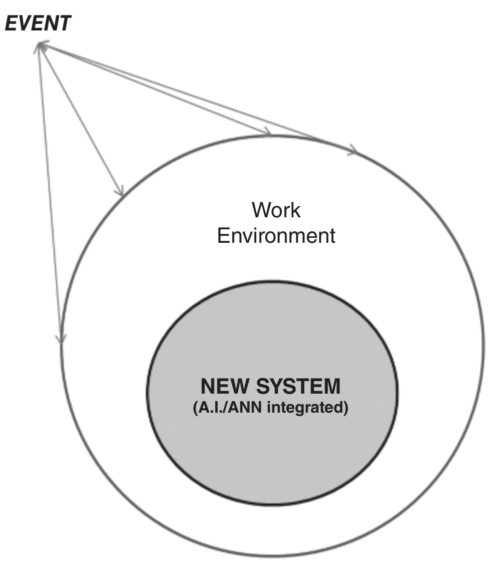

Figure 1.7 Development and deployment of a new system in the work environment.

with terms for opportunities such as "exploit," "share" and "protect." In this book the proper balance between the risk of missing project technical and business objectives on the one hand, and process paralysis on the other is not discussed.

Anyway, risk and opportunity management is a disciplined approach to dealing with uncertainty that is present throughout the entire system's life cycle. This process is used to understand and avoid the potential cost, schedule, and performance/technical risks to a system, and to take a proactive and structured approach to anticipate negative outcomes, respond to them if they occur; and to identify potential opportunities that may be hidden in the situation. Every new system or modification of an existing system is based on pursuit of an opportunity.

Risk always is present in the life cycle of systems, and the risk management actions are assessed in terms of the opportunity being pursued. Risk can also be introduced during architectural design caused by the internal interfaces that exist between the system elements. System development may be rushed to deploy the system as soon as possible to exploit a marketing opportunity or meet an imminent threat, leading to schedule risk. It will be stressed once more that a rigorous risk management process, in line with the project management doctrine as in SE will allow us to successfully integrate the new risks connected to the introduction of AI into the system, as well as the risks removed by such introduction.

In addition, it is important to mention the configuration control phase. Integrating AI in an existing system means making a change to a system. In this book AI is shown as a software referred to improve and control some product/process. The baselines are established by review and acceptance of requirements, design, and product specification documents. The creation of a baseline may coincide with a project milestone or decision gate. As the system matures and moves through the life cycle stages the AI is maintained under configuration control.

AI can be used to manage a lot of information and, as the system engineer, it would balance a complex system looking for optimal points between its elements, embedding in the system processes the concepts of AI, (AI for SE). On the contrary, the AI integration must not be concerned that a stand-alone product is used to solve a specific technical problem. For instance, considering that the airplane autopilot can be changed into an autonomous system, the next higher system, aircraft, is again considered in order to find the balance points and to create a new balanced system, (SE for AI). In general, we could theorize that AI must be embedded in a complex system, but it should not be seen as software since the right effectiveness cannot be achieved. In summary, any complex system that involves non-linear analysis of its processes to achieve a defined objective can be managed by the integration of AI/ANN.

By introducing the ANN as a Configuration Item (software/application) of a new system, this means that it is designated for a separate control of the New System Configuration. The Configuration Management (CM) shall ensure the control of the ANN functional, performance, and physical characteristics that are properly identified in the newly designed system. Hence, the CM helps to establish and maintain control of requirements, documentation, and artifacts produced throughout the system's life cycle. If the change is necessary, the AI impact shall be clarified, especially defining effects on the life cycle. This can increase risk which can adversely affect system cost, performance, and safety.

CM is the practice of applying technical and administrative direction, surveillance, and services to:

- Identify and document the characteristics of system elements such that they are unique and accessible in some form; assign a unique identifier to each version of each system element.
- Establish controls to allow changes in those characteristics; ensure consistent product versions.
- Record, track, and report status pertaining to change requests or problems with a product; maintain comprehensive traceability of all transactions.

1.2 Chapter Summary

Systems engineering is introduced here as a fertile ground for the application of neural networks. This chapter introduces the reader to the concepts that inspired the authors, and to some of the ideas presented in the book. It aims to put the reader in the right mind-set but also to give some useful guidance on the structure of the book. It also establishes a "pact" with the reader, aimed at a more effective use of the book. In the second part of the chapter the key connection between AI and Systems Thinking is established.

Take outs:

- Human beings have felt the need to explain the worldly reality they live in. However, we are able to understand the world by our rationality. The ultimate meaning of an event is seen as a reliable reference, and a systematic and methodical approach will help us interpret it.
- Our objective is to develop a mathematical tool that is more accurate when reality is complex, uncertain, and difficult to interpret. We apply linear and non-linear algebraic combinations to describe the various interactions happening in our brain when we solve problems.
- The human brain is the biggest computer ever created. The brain communicates by chemicals and electrical impulses, and the information is analyzed in the cerebral cortex.
- Neural networks are constantly reshaping their connections, but artificial neural networks remain quasi-static, so they cannot be used to analyze athlete's performance by using engine data.

- Systems Engineering is an important paradigm that supports the introduction of new technology and processes. AI can be integrated into existing systems using systems engineering.
- Starting from system architecture, in-depth knowledge of the system and its components, knowledge of the system's requirements and constraints, and knowledge of the AI-subsystem is the best practice for system integration.
- Risk and opportunity management is an approach to dealing with uncertainty throughout the entire life cycle of a system and anticipating negative outcomes.
- AI can be used to manage complex systems and to find optimal points between its elements, and must be embedded in the system processes to achieve the right effectiveness.

Questions

1 To extend the mathematics laws to reality, why do we need to consider uncertainties?

2 How can the SE approach support any Neural Networks application?

3 How can Neural Networks help manage complex systems?

4 Where can a Neural Network be introduced into an existing system?

5 When the system is already disposed, what processes will be used to introduce the Neural Network?