4 History of Complexity Management

Globalization, interconnectivity and advancing technology are some of the reasons often mentioned when investigating the origin of increasing complexity. It might look like the challenge of complexity and the solutions supplied by complexity management arose from questions and constraints in modern times. However, there are circumstances, trends and developments that led to the modern form of complexity management. A historical classification shall provide a better understanding and explain the fundamentals of modern complexity management. Over a long period of time, many scientists have worked on the phenomena of complexity. And due to approaching challenges, developed approaches, methods and tools have been applied to important challenges in practice.

When looking for significant increases of complexity in history, one can reach back to several important events, which planted the seeds for further societal, political and technological development. For example, Schwanitz explains the end of the 7 Years' War in 1763 as the beginning of complexity [1]. While the start of free worldwide trade is obviously relevant in terms of upcoming complexity, developments during the Second World War and the second industrial revolution maintain perhaps even more importance for today's state of complexity management. While the Second World War accelerated many inventions and (product) developments, the second industrial revolution generated the need for effective methods for controlling and managing large projects and systems.

Scientific and methodical knowledge about modern complexity management has been aggregated over a time span of approximately 70 years. With increasing complexity and new challenges this knowledge has been constantly developed. Today, the problem is often not a lack of methodical approaches but missing knowledge about implementation details when dealing with complex challenges in the industrial context.

Thinking about the phenomenon of complexity and dealing with this challenge can be traced back to ancient Greece. Beginning with Plato and especially Aristotle, complexity became an important topic of interest. From the seventeenth century on, exceptional

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mathematicians like Isaac Newton and in the nineteenth century philosophers like Emanuel Kant were dealing with complexity and changed the view of the world. In various disciplines they thought about newly upcoming challenges and developed knowledge and approaches to tackle the challenges.

If one name needs to be associated with modern complexity management, it is Ludwig von Bertalanffy, who developed major parts of system theory. His work still represents fundamentals for most work in the field of complex systems. Based on Bertalanffy's understanding of systems and their characteristics, a variety of approaches for dealing with complexity have been developed—from which complexity management emerged as its own discipline.

Generally, the history of science is in close relation to contemporary, social, political and military challenges. This also accounts for complexity management. A major part of basic science and method development for complexity management have been created in the context of the Second World War. Norbert Wiener created the fundamentals of complexity science—named cybernetics [2]. After that pioneering but still abstract theoretical work, applicable methods and instruments for solving complex challenges were created: operations research, system dynamics, systems engineering and game theory. These approaches emerged from different questions and therefore tackle different problem areas. And for example, the more holistic approach of systems engineering integrates the possibilities of more focused approaches than operations research or game theory. Significant challenges like those presented by the Cold War and the beginning of astronautics acted as catalysts for those developments on complexity management. The innovations resulting from solving these challenges have in common that they are trans- and interdisciplinary science approaches and that they transcended system borders that existed in the centuries before.

Cybernetics meant a revolution in thinking and paved the way for today's "cyber" world. In several aspects, modern data processing and the computer are based on cybernetics. And those developments led to increasing system dependencies and more dynamics in products, processes and organizations—which meant an increase of complexity. On the other hand, cybernetics also provided the basis for solving modern complexity challenges.

Operations research, system dynamics, systems engineering and game theory have been further developed for the application of complexity management in fields like economics. And as mentioned before, they are partly interconnected. Game theory represents an instrument used within operations research, which has been developed at the time of the Second World War for optimizing the British radar monitoring. Since then it has been adopted to a multitude of problems, many of them in economics. Operations research is a quantitative method, i.e. it requires an algorithmic problem description and aims at optimizing specific target parameters.

System dynamics is a cycle-based methodology for the simulation and analysis of non-linear behavior in complex systems. Therefore, a system structure is created and extended by stocks, flows and feedback loops. System dynamics is often applied to management tasks and economic challenges, but has successfully been transferred to many other systems as well, using qualitative as well as quantitative models.

Systems Engineering provides a comprehensive framework for designing complex technical systems. It includes many methodologies along the whole system development process and life cycle, e.g. requirements engineering, quality and risk management or system modeling. Systems engineering overlaps with many related approaches, e.g. software engineering (also software systems engineering) or project management. At first, systems engineering came up in the 1940s in applications of the Bell Telephone Laboratories and became a significant attraction when successfully applied to the Apollo Program and the Space Shuttle program in US aeronautics.

It is difficult—and sometimes even impossible—to clearly distinguish the developments of complexity management methods in their historical context, especially because of the interdisciplinary approach of these methods. Already the founders of the fundamental ideas were working in interdisciplinary groups and transferred concepts from one field to another. In fact, systems thinking and complexity management generally require holistic approaches, as reducing problems to specific, isolated aspects would neglect the essence of complexity.

Pioneers in system thinking and cybernetics like Ross Ashby and Heinz von Foerster disagreed with the fragmented scientific world, which was the status quo before their time of research. Mostly because of historical reasons, scientific disciplines were clearly separated at this time. But system thinkers did not see these separations as being helpful for describing complex phenomena. Ross Ashby was a psychiatrist and discussed questions on cybernetics with psychologists, physiologists, mathematicians and engineers in the Ratio Club [3]. Ludwig von Bertalanffy, the originator of the General System Theory was a biologist and Norbert Wiener, who first introduced cybernetics, was a mathematician and philosopher.

These initial thoughts indicate that complexity management is not an invention made at the end of the twentieth century. It is based on long-term developments originating from different disciplines. The following sections will give a deeper insight into the historical development of system thinking, which is a fundamental basis for dealing with complexity. With the background of system thinking, the next sections describe the historical development of complexity management approaches.

During the Second World War scientists worked on possibilities for controlling complex systems—based on scientific thinking that had been developed for more than 2000 years. In the 1940s, Norbert Wiener worked on solutions for controlling complex systems. He introduced the term cybernetics in his book titled Cybernetics: Or Control and Communication in the Animal and the Machine [2]. The term cybernetics is derived from the ancient Greek word for steerman (kybernétes). Here, the link to the ancient Greeks can be seen as a reference to the basis of scientific thinking, as they have been constituted by Socrates, Plato and especially Aristotle. According to Laszlo, increasing complexity led to system science and to cybernetics as approaches toward controlling complexity [4].

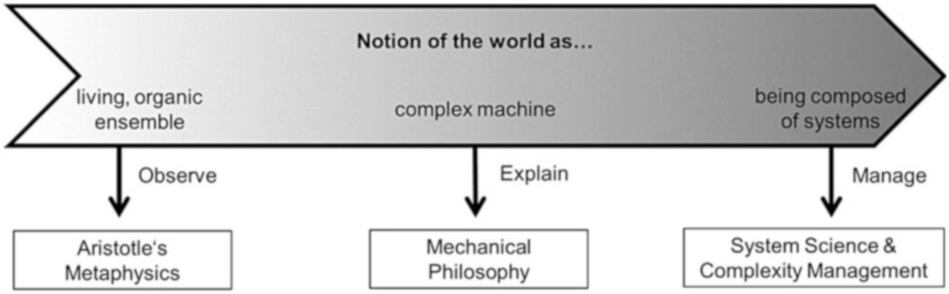

Fig. 4.1 From system awareness to complexity management

Figure 4.1 aggregates the main perspectives of system interaction into a logical sequence. In the beginning, living, organic ensembles but also societies became recognized as systems. And their observation resulted in complex questions of life and the early system thinking, as introduced by Aristotle. Progress in disciplines like mathematics, physics and astronomy and the possibilities to precisely describe new findings by laws were the fundaments of the mechanical philosophy. The means of mathematical and physical descriptions for simple technical constructs were applied to explain the perceived world and the composition and behavior of their beings as complex machines. The subsequent notion of the world as being composed of systems and the increasing need to manage these systems prepared the groundwork for system science and finally complexity management.

4.1 The Emergence of System Thinking

Inspired by Socrates (469–399 BC) and Plato (428/427–348/347 BC), Aristotle is considered as the founder of science [1]. He made the famous statements that "[. . .] the totality is not as it were, a mere heap, but the whole is something besides the parts. . ." (Aristotle, Book VIII, 1045a. 8–10) and "[. . .] the whole is greater than the part" (Aristotle, cf. Euclid, Elements, Book I, Common notion 5). This thought can be seen as the basic idea of system thinking, which requires awareness of not only the parts, but also their interdependencies [5]. The statement also includes the awareness that important aspects of a system get lost when subdividing it and considering only its components. Aristotle applied a general definition of a system, which has a purpose and an objective. The system-based worldview of Aristotle has largely influenced later scientific development until the Renaissance, when it was challenged for example by the mechanical philosophy.

Starting in the sixteenth and seventeenth centuries many discoveries have been made, which questioned the worldview that before had been taken for granted. This was the starting point for the mechanical philosophy. The core of this scientific revolution was driven by people like Copernicus, Galilei, Descartes, Newton and Kepler, and comprised the analysis of elements by disassembling materials into smaller pieces and by giving them mathematical descriptions. The fundamental thought of this concept was that the behavior of a system can be fully understood if the characteristics of its parts are known and understood [6]. Descartes thought of the cosmos as a giant machine following eternal laws. Newton formulated this worldview with mathematical descriptions. In order to belong to natural science he demanded things to investigable by experiments, exactly measurable and describable by mathematics. Newton developed a theory of mechanics that was formulated with mathematical exactness, which allows one to derive particular cases that can be empirically validated [7].

One striking example of the thinking in the mechanical philosophy is the "Digesting Duck", created by Jacques de Vaucanson in 1739. Vaucanson was an engineer who invented and built innovative automata, e.g. for looming. The "Digesting Duck" was an impressive mechanical construction, which exemplifies the belief in mechanical explications for nature and the world in general. Figure 4.2 shows an illustration of the Digesting Duck clearly accentuating the mechanical thinking at that time. While this illustration is widely known and nicely highlights the mechanistic concepts, it must be mentioned that Vaucanson's real machine worked differently and was unfortunately destroyed in the late nineteenth century.

In the eighteenth century, Romanticism raised opposition against the mechanical Cartesian views. For example Goethe and von Humboldt saw in nature a pattern of interrelations within a sorted system. This approach gets close to modern system thinking [8]. Goethe questioned Newton's hypothesis that things only exist when they can be described in mathematical form. Goethe emphasized that it is not only about the analytical description, but also about its composition—and that the existence of things is not directly bundled to the possibility of quantification [8].

Emanuel Kant contributed important thoughts to the later emerging worldview of the Romantic period. He distinguished between self-reproducing and self-organizing

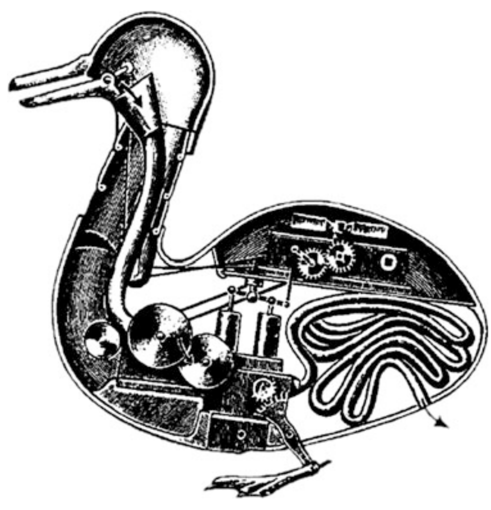

Fig. 4.2 Illustration of the "Digesting Duck"

organisms and machines. While the components of machines do only contribute to an entire function, components of an organism do also produce each other mutually—they exist because of their common existence [8].

In the following sections the scientific thinking about systems will be introduced. Starting with the ancient Greeks and the fundamental observation of systems, the application of mathematical descriptions to the explication of nature as reductionistic thinking to contradictory approaches of modern system thinking will be detailed.

4.1.1 The World View of Aristotle

The ancient Greek philosophers have laid out the basis for our scientific thinking in the fields of mathematics, nature, society and politics. Socrates, Plato and Aristotle stand out for having significantly influenced scientific thinking to the modern day. Socrates was the teacher of Plato, and Plato was the teacher of Aristotle.

Socrates was the first to notice that religion was no longer an adequate instrument for leading a state, which becomes more and more interlinked. These considerations and the new thinking were continued by Plato. He described the Ouroboros as a self-sustaining being without outward relations—which already shows similarity to modern system definitions [9]. In continuation of this thinking, Plato's student Aristotle developed metaphysics and teleology and today is referred to as the founder of science [1].

Aristotle (384–321 BC) conducted empirical studies and intensely studied living processes and organisms. He saw the universe as an organic, living and spiritual entity. He considered form and matter as being connected and that they can only be separated by means of abstraction. Aristotle no longer thought of an entity as only being composed of its parts. This awareness is documented in the famous statement that the whole is greater than the sum of its parts. And it can be considered as the basic idea of a system [5]; it gains many of its characteristics from interactions between its ingredients. A living organism is more than just an aggregation of its parts; it represents an assembled entity with greater functions like self-preservation, which cannot be association with specific elements of the entity. One can say that science started in the Antique when the great thinkers discovered fundamental principles of systems.

Aristotle's Metaphysics (a collection of some of his scientific papers) mentions aspects of organic systems, which cannot be originate from their parts only. Aristotle discovered that creatures act purposefully by targeting specific objectives. Many modern scientists picked up Aristotle's fundamental ideas in the concept of holism (from Greek holos "all, whole, entire") as the opposite to reductionism, which postulates that a system can be fully described by its parts [10].

Aristotle generalized his observations and postulations to a more abstract level and implemented them into his political models. In doing so he found similarities between the objectives in nature and in humans acting in society. Also in this use case the components do not sufficiently describe the entity of society, and only a holistic system view covers the objective. Thus, Aristotle was the first to create a general system concept that was applicable to different areas of life.

Martial, social and political events were often interwoven and represented complex challenges for the great ancient thinkers. More than 2000 years later, in 1946, the participants of the Macy Conferences referred to this epoch by selecting an antique word for their new science for controlling complex systems: Cybernetics.

4.1.2 Mechanical Philosophy

Aristotle's worldview dominantly influenced science for a long period of time. It took from his productive period in the fourth century BC up to the fifteenth and sixteenth centuries until his notion of the world was challenged by a significantly different approach, the mechanical philosophy. Nevertheless, it has to be mentioned that not only the reference of the term cybernetics remained as reminiscence to Aristotle's work. Many great scientists, such as Ludwig von Bertalanffy, directly picked up Aristotle's ideas for their scientific approaches in modern times.

Beginning in the late sixteenth century many groundbreaking works in mathematics, physics and astronomy were made. They challenged the view on the world as a living and spiritual universe, and raised the hope that the entire world can be explained by the new rules and analysis capabilities, which worked for many observed physical phenomena at that time. This was the beginning of the mechanical philosophy. People like Copernicus, Galilei, Descartes, Newton and Kepler advanced a scientific revolution, which focused on the analysis of elements and decomposing matter in smaller and smaller parts [5].

René Descartes (1596–1650) and Isaac Newton (1643–1727) have particular relevance for the development of the mechanical philosophy [6]. Descartes, a French philosopher and mathematician, understood the universe as a machine operating by a set of rules. According to the mechanical philosophy, the world was considered to be inanimate and living organisms to be machines. Several concepts emerged in the same time frame and are strongly related to this philosophy. Rationalism, determinism, reductionism and atomism have to be named in this context. Rationalism described the philosophical concept that only rational thinking should be applied for achieving and evaluating knowledge [11]. Determinism postulates that all events are clearly determined by preconditions—thus, knowing all influences to a situation "determines" the possible outcome [12]. Reductionism can be defined as the opposite of the holistic approach, as it is based on Aristotle's approach. Reductionism assumes that a system can be fully determined by an accurate description of its included parts. Descartes also thought of animals as being explicable by this reductionistic approach as complex machines. This leads to the notion of atomism, which represents the basic idea that everything is formed from smallest indivisible parts. This explication of observable things and effects can be traced back to an origin in the thinking of the ancient Greek philosophers [13]. All these ideas aggregated in the mechanical philosophy contributed to a different view of the world and provided explications for new findings made in science. With the new possibilities of mathematical descriptions, the mechanical philosophy advanced the view that knowing the characteristics of all parts allows understanding the whole thing [8].

Isaac Newton picked up Descartes' mechanical thinking and enhanced it by mathematical descriptions. He created a complete and mathematically formulated theory of physics, which permitted one to logically derive use cases, which then can be evaluated empirically [7]. This depicts the basic ideas of determinism, which—as introduced above—states that an exact description of the current state by physical laws allows determining each future state of the system. This way of thinking proved to be valid for a long time, as it seemed to be in accordance with findings in classical physics and astronomy.

Similar to the strict application of laws in Newton's classical mechanics, determinism became applied to phenomena of nature and even the entire universe. Thus, nature was supposed to be explicable based on distinct laws. Many scientists adopted Newton's classical mechanics, and along with it concepts like reductionism and determinism. A common hypothesis was that only matter exists, which behaves according to physical laws. This explication was transferred to all kinds of natural phenomena.

The mechanical philosophy was also adopted for explaining biological processes [14]. Prominent biologists like Rudolf Virchow, Louis Pasteur, Claude Bernard and Jacques Loeb made groundbreaking discoveries and created the impression that functions and characteristics of living organisms can be understood by applying chemical and physical principles [8]. In such a system, a separate principle of life was not considered to exist—which represented a point of criticism for disputants of the mechanical philosophy and was counteracted in concepts like vitalism.

An example for the application of the mechanistic philosophy in other areas is the so-called Taylorism, named after the American engineer and entrepreneur F. W. Taylor. Taylorism reduced the human to a "gear wheel" in a large production machine, which could be replaced by another human if required. Detailed work descriptions and target times were applied for each working task [15].

The exact, mathematical, quantifying, isolating, causal, analytical and mechanical approaches result in reductive thinking. If something could not be measured or not be described by mathematical means then it was not considered by science. One consequence of isolating small parts from a large system resulted in a fragmentation of science into more and more specialized and disconnected areas [8]. This represented a significant hurdle for future approaches towards the management of complexity—and was explicitly addressed by the pioneers of cybernetics.

4.1.3 Opposition to the Mechanical Philosophy

The beginning of Romanticism in arts, music, philosophy and literature also meant opposition to the mechanical philosophy and started in the late eighteenth century. Scientists of the Romantic period disagreed with the reductionistic thinking in the mechanical philosophy and rather referred to Aristotle's finding that the whole is more than its parts only. Romantics saw the mechanical explications as a too rational attempt to control nature. Cunningham and Jardine state that "the romantics were certainly hostile to the mechanical natural philosophy and descriptive natural history that they inherited from the Enlightenment" [16].

Also Emanuel Kant contributed to the (later emerging) romanticism. He studied the nature of living organisms and declared that they were self-reproducing and self-organizing organisms—in contrary to machines. In a machine the parts support each other, whereas the parts of a natural system exist because of each other's existence [8].

Discoveries in biology made at the end of the nineteenth century, e.g. about the behavior of living cells, could no longer be explained by a reductionistic approach according to the mechanical philosophy. The embryologist Hans Driesch (1867–1941) conducted outstanding experiments with sea urchin embryos and failed to explain the outcome by the common thinking of his time. In his experiments, Driesch removed parts of the eggs but embryos could still develop, which meant that that any single monad of the egg could develop any part of the embryo. A reductionistic approach assumed that distinct parts assemble the entity; however this did not explain his observations [17].

Driesch's scientific experiments and that of other biologists were decisive for the foundation of a scientific vitalism, which represents a concept postulating that the behavior of living organisms cannot explained by physical and chemical laws only. Rather, a separate life principle or soul has to be included in order to explain it. The vitalism predicates a fundamental difference between organic and inorganic systems [18, 19].

Even if most modern biologists reject the concept of vitalism, it contributed to the development of system understanding beyond the restricted view of mechanical philosophy with its pure reduction to system parts and its strictly linear, deterministic effects.

In the early twentieth century, opposition to the mechanical philosophy came from two significant scientific breakthroughs. Firstly, the development of a quantum theory that led to quantum mechanics explained physical behavior on the atomic level, whereas Newton's classical mechanics failed for such use cases. That is to say, the associated Heisenberg's uncertainty principle disproved strict determinism as a valid concept and introduced a statistical understanding of causality instead of linear cause-and-effect chains.

In the context of quantum developments, Einstein introduced his general theory of relativity in 1915. This theory postulated that energy and matter can be transformed into each other and therefore do not represent two different concepts. This disproved Newton's idea of inanimate matter affected by immaterial forces.

4.2 Bertalanffy's General Systems Theory

Ludwig von Bertalanffy (Fig. 4.3) was born in 1901 in Austria and studied the history of art, philosophy and biology, and since 1934 held several professorships, i.e. in Vienna, London, Canada and the United States. Bertalanffy had significantly contributed to the idea

Fig. 4.3 Ludwig von Bertalanffy (1901–1972). BCSSS—Bertalanffy Center for the Study of System Science, Vienna, Austria, BCSSS-Archiv: Ludwig von Bertalanffy Teilnachlass 2 [LvB-TN-2], Porträtfoto Ludwig von Bertalanffy, June 1966

of a systems approach for explaining complex phenomena. And today he is seen as one of the most important protagonists of system theory in the twentieth century. His works on the General Systems Theory (GST) represent the basis for definitions and terms in all forms of system science [20–22].

Bertalanffy introduced a new paradigm of science as an alternative to the mechanical worldview, which has been adopted by many scientists of his time. Bertalanffy criticized reductionism, deductive procedures and the isolated consideration of singular phenomena as being insufficient for understanding real-world systems. Nevertheless, he did not reject the mechanical philosophy completely. Formal models should still be a part of system science, as they represented successful approaches for the depiction and explication of isolated scientific application.

Bertalanffy wrote, "Since the fundamental character of the living thing is its organization, the customary investigation of the single parts and processes cannot provide a complete explanation of the vital phenomena. This investigation gives us no information about the coordination of parts and processes. Thus the chief task of biology must be to discover the laws of biological systems at all levels of organization. We believe that the attempts to find a foundation for theoretical biology point at a fundamental change in the world picture, this view, considered as a method of investigation, we shall call 'organismic biology' and, as an attempt at an explanation, 'the system theory of the organism'." [23] according to [24]. And he added later: "Recognized 'as something new in biological literature' [. . .], the organismic program became widely accepted. This was the germ of what later became known as general systems theory" [24].

Bertalanffy did not consider linear, deductive descriptions as being sufficiently powerful for modeling biological systems. He argued that in such systems no independent use cases exist, but all aspects and phenomena are interlinked. Bertalanffy described a system instead of single phenomena, whereas the system definition comprised a quantity of elements and their interrelations. He further distinguished open and closed systems [21].

A closed system represents a special case of a general system and correlates with the approach of the mechanical philosophy with its descriptions of isolated (closed) phenomena. For such a closed system it is assumed that the initial state and final state are directly related and can be logically described. For example, this is the case in a chemical reaction, which starts with distinct settings and ends in a chemical equilibrium. Closed systems are independent from their environment and the interconnectivity of comprising elements can be described mathematically [21, 25].

According to Bertalanffy, open systems are characterized by constantly and non-predictable exchanges of energy and matter between the system and its environment; these exchanges pass across the system border. Open systems cannot reach a state of equilibrium with maximum entropy, as this would mean that no further exchanges of energy or matter would pass the system borders. But the internal variability enables the system to reach a dynamic equilibrium, which means the system changes its dynamics and its state without losing its general structure. In addition, in open systems the same final state can be reached starting from different initial states. Open systems can form self-organized, complex systems, which develop a specific higher-ranked structure without impact from the environment [5, 21, 25].

Bertalanffy considered the entity as being the result of continuous interaction between the system parts. And the development of life would be the result of processes like differentiation, specialization, and centralization in combination with an increase of complexity. For the creation of a commonly applicable model for complex systems, Bertalanffy took statistical thermodynamics as a guideline. Also in this discipline the differentiation between open and closed systems exists. Statistical thermodynamics, as formulated by Boltzmann, tries to describe the system without considering the impact of its elements in detail. Nevertheless, it is possible to create specific system laws [25, 26].

In his General System Theory, Bertalanffy formulated common laws in social, physical and biological systems based on a methodic holism approach. In this context he postulated that principles exist, which, if they have been discovered in one specific field, can be transferred and applied to others. Such principles are, for example: complexity, equilibrium, feedback and self-organization. Bertalanffy's General System Theory predicted that his stated system laws were applicable to scientific disciplines like biology and sociology, even if those cannot be classified under the framework of physical or chemical laws (see also [27]).

Bertalanffy distinguished four types of equilibria: dynamic equilibrium (used as an umbrella term), real equilibrium (as it appears in closed systems), steady state equilibrium (for open systems) and homeostatic equilibrium. The steady state equilibrium describes that energy and matter are exchanged over the system border but that the different streams add up to zero. The homeostatic equilibrium is an equilibrium which is reached by a secondary regulation mechanism [5, 21].

With his General Systems Theory, Bertalanffy created the necessary basis for a systems approach in complex biological systems. Wiener described this field by the name systems biology, which gained increasing importance since then [2]. Systems biologists see the organization and interdependencies as of high importance for understanding living organisms. The term system is used for organisms as well as social systems, and means an integrated entity which obtains its main characteristics from the relations between its parts. Living organisms are organized in a hierarchy, in which each subsystem forms its own entity. These subsystems can belong to a greater entity. In this context also the term organized complexity is applied [8].

4.3 Development of Complexity Management

Systems thinking has been a research topic for many scientists, who focused on explaining complex phenomena and the behavior of systems. Using the fundaments of systems thinking for the application of managing complexity was the next big step, which was approached in the first half of the twentieth century. At the time, scientists started to work on finding solutions to newly upcoming economic, social and political problems.

A small group of systems scientists were active in the time before the Second World War. However, the general political and social situation did not provide the circumstances for getting enough attention. The First World War and its negative consequences like tremendous human losses and economic crises did not prepare a fruitful ground for the development of new sciences. Finally, in 1929 the world economic crisis began and was followed by the rise of several totalitarian regimes in Europe. Especially, scientists from the German Reich often only saw the option of ending their ongoing research activities and decided to leave the country. This time meant the end of interdisciplinary and international science, and affected significantly the small group of systems scientists and their progress in those days.

4.3.1 Impact from the Second World War

In the Second World War, the multitude of new weapon systems and theaters of war made the organization of war become much more complex than ever before. The initial success of the German Wehrmacht had shown that conventional warfare did not succeed anymore. This initial course of the war made clear that new technologies became increasingly important for gaining an advantage over the opponent [28].

The changed situation of war resulted in a huge demand for new thinking and innovative technologies, which led to a scientific boom, especially in the USA and Great Britain. As the objective behind the boom was combating the enemy, science and military closely cooperated in creating new technologies, approaches and methods. Leading scientists from different disciplines started to research on effective solutions to urgent and painful challenges. The tremendous complexity of these demands showed the scientists the limits of applicability of the so far highly diversified partial sciences. They understood that the many and quickly changing problems required interdisciplinary cooperation; therefore they established collaborations, which should turn out to be fruitful.

These circumstances of war brought system sciences back in the spotlight. Based on systems thinking, new theories and methods for successfully handling complexity were created. The multilayered and heterogeneous challenges resulted in the development of three closely related disciplines for managing complex problems: operations research, game theory and cybernetics. While clearly related to each other, each single discipline forms its own field of research with specific problems to solve [29].

In the time after the Second World War, research in system science profited from the established close collaboration between the military, government and academia. This was the right time to transfer findings made during the war into civil applications, and to further develop and optimize them. The following sections will detail the historical questions and challenges, which resulted in new approaches and methodologies. Also the developed solution approaches will be discussed from a historical perspective.

4.3.2 Cybernetics

From the moment when it became introduced, cybernetics was designed as an interdisciplinary approach. It did not only apply mathematical and physical models, but aggregated opinions and findings of scientists from fields like mathematics, physics, economics, sociology, psychology and biology. Interdisciplinary collaboration became possible because cybernetics works at a high level of abstraction, which serves all the included disciplines. In the cybernetics approach a complex system gets described by its purpose and not by its components or specific functions and mechanisms. This was meant for improving system comprehension and reducing the model complexity. And it allows cybernetics to model the behavior of highly different systems [29].

Aerial warfare was a revolution in the Second World War. Airplanes were already used in the First World War, but not in a significant way. In WWII this new way of warfare dissolved the hitherto clear separation of the war front and homeland. Military planes started to carry battles far into the countries and caused fatal consequences for soldiers and the civilian population. The increasing threat due to aircraft bombs motivated Norbert Wiener to develop an air defense system. His findings from this development represented core elements of the cybernetics approach, for which he was one of the important founders [29].

4.3.2.1 Norbert Wiener

Norbert Wiener (Fig. 4.4) was born November 26th, 1894 as son of a Harvard professor for Slavic languages. Norbert Wiener was intellectually gifted and started a college career in mathematics as soon as he turned eleven. Later he also studied zoology and philosophy. Wiener visited and worked at the most famous universities of his time, e.g. Harvard,

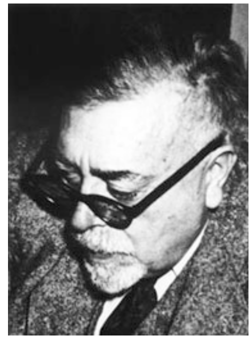

Fig. 4.4 Norbert Wiener (1894–1964), Konrad Jacobs (http://owpdb.mfo.de/detail?photo_id=4520), CC BY-SA 2.0 de (http://creativecommons.org/licenses/by-sa/2.0/de/deed.en), via Wikimedia Commons

Cambridge (UK) and Göttingen. In 1912, he completed his doctoral thesis at Harvard about mathematical logics.

During the First World War, Wiener taught philosophy at Harvard, worked as an engineer for General Electric and as an author for the Encyclopedia Americana. Later he worked as a ballistician for the US military in Maryland and started teaching mathematics at MIT once the First World War was over. In World War II, Wiener worked again for the military, especially in the field of communication and information technology. The heavy bombing of London by the German Air Force drew Wiener's attention to the development of anti-aircraft guns. Here, complexity arose from the fact that the defensive aircraft gun as well as the offensive aircraft were both controlled by humans. It turned out that this constellation was a highly complex problem of control theory. Wiener found that solving the problem required modeling the aircraft and the pilot as one integrated system, as well as the anti-aircraft gun and its operator. This new approach of system-building definitely blurred the boundaries between human and machine [2, 29]. Up to this time biological and technical systems were considered separately or, according to the mechanical philosophy, both were considered as technical systems.

Modeling a man-machine system required the cooperation of many different partial approaches. Natural sciences, engineering science as well as human behavior science had to be combined. This integration required the interconnection of these different disciplines by a discipline-spanning framework that can be commonly applied. Cybernetics was this integrated approach, which was mainly initiated by Norbert Wiener as a result from the research findings he made in different projects until the end of World War II [30].

4.3.2.2 The Scientific Approach of Cybernetics

During World War II, Wiener created the fundamentals of his new interdisciplinary and system-based science. In 1948 he published these findings in the book titled Cybernetics or Control and Communication in the Animal and the Machine [2]. Cybernetics had the main focus on controlling complex systems—and Wiener's book gained major importance for the future of complexity management [2, 31].

Besides the intensive interdisciplinary cooperation of sciences, Wiener's cybernetics also integrates technological progress into systems thinking. Wiener discovered powerful up-to-date possibilities for modeling interconnection and interaction for the man-machine. For example, his system descriptions included wave filters, calculators, automated control of assembly lines, chemical productions or even fibrillation of the organic heart [29].

Wiener's possibilities of system description enabled him to predict the impact and consequences of technical achievements to social life. At the time he introduced cybernetics, an equal treatment of human and machine in systems thinking represented a provocation, which was fought by many other scientists. However, in the 1950s technologization of common life became omnipresent. And Wiener's approach of blurring the boundaries between the human and machine became strongly supported in science [29].

In January 1950, Time magazine published the title story "The Thinking Machine", and put an illustration of the computer Harvard Mark III on the cover with the figure caption saying: "Mark III. Can man build a superman?" [32]. The illustration shows a man-machine computer in a military look (this was referring to the fact that cybernetics came from a military application field), feedback through self-control of outputs (the computer in the illustration visually "inspects" its output) and biomechanical design (a human eye and two arms connected to a computer rack). This publication was the final proof for how significant the impact from the new science became for common social life.

After World War II cybernetics got enduring attention from leading scientists. A milestone in the further development of this new cybernetics discipline were the proceedings from the interdisciplinary Macy Conferences, titled by the bio-physician Heinz von Foerster with "Cybernetics" (more about these important conferences below). This resulted in an even faster spreading in the science world.

In natural sciences cybernetics was the basis for a specific communication theory and informatics, which appears in cooperation with engineering sciences e.g. in fields like robotics, automation and artificial intelligence [30, 33]. Today, also the scientific fields of neurophysiology and genetics would be at an extremely different status quo without the preliminary work in cybernetics.

4.3.2.3 The Macy Conferences

From 1946 to 1953 the Josiah Macy, Jr. Foundation held ten interdisciplinary conferences, which are often called the "Macy Conferences". In fact, this term would officially include a much larger set of conferences over a broader period of time; however, people mostly refer only to the ten conferences on cybernetics. This specific set of conferences was an experiment on interdisciplinary research with the first conference entitled "Feedback Mechanisms and Circular Causal Systems in Biological and Social Systems" [34]. Conference titles changed over time and Heinz von Foerster (Fig. 4.5) proposed the name cybernetics. He applied it for the proceedings of the later conferences [35–38]. It is

Fig. 4.5 Heinz von Foerster (1911–2002), U of I publicity department, CC BY-SA 4.0-3.0-2.5-2.0-1.0 (http://creativecommons.org/licenses/by-sa/4.0-3.0-2.5-2.0-1.0)], via Wikimedia Commons

worth mentioning that the first five conferences were not systematically documented and results can only be retrieved from a few sources [34, 39, 40].

The central objective of the Macy conferences on cybernetics was to create the fundament "for a general science of the workings of the human mind" [34]. Therefore, the participants also applied the preliminary work of Norbert Wiener, who was one of the conference contributors. Besides him, a so-called "core group" of scientists attended the conferences, including e.g. the biophysicist Heinz von Foerster and the mathematician John von Neumann. Each conference was joined by additional, invited guest scientists (but also the core group changed over time), forming a highly interdisciplinary group of outstanding scientists. This group could claim significant progress in systems theory and in laying out the fundamentals for the then-upcoming cognitive science.

The interdisciplinary character of the Macy conferences on cybernetics becomes obvious when looking at a few specific topics of discussion. During the first conference self-regulation, neural networks and feedback mechanisms were presented, but also self-learning principles for computers and how to derive ethics from science. In the following year one topic was about communications among ant soldiers, while the third conference treated the topic of child psychology [34]. This widespread range of topics continued for the following conferences. A full list of conference topics can be seen at the website of the American Society for Cybernetics [34]. The scientific discussions formed a new worldview and the new cybernetics approach with a central element of communication and control mechanisms in complex systems. Already 1948, Wiener subtitled his book on cybernetics as Communication and Control in the Animal and the Machine [2] and hereby expressed the common core of this new approach [31].

4.3.2.4 Decoding the Basics of Self-organizing Systems

The contribution of Heinz von Foerster, an Austrian biophysicist, to the development of cybernetics is of major importance. He acted as co-organizer for the cybernetics conferences, was in charge of some of the proceedings and proposed naming the conference "cybernetics". During his entire career he was researching principles of interactions between humans, between humans and machines and between machines. This research was inspired by patterns of nature [31, 35, 41]. Foerster picked up many aspects of the cybernetics approach and developed them further. Since 1958 he held a research position at the University of Illinois and founded there the “Biological Computer Laboratory”. This laboratory became a place of research for many scientists in the field of cybernetics, e.g. Ross Ashby [31, 42, 43].

The research focus of the Biological Computer Laboratory was on common structures of circular processes and their organization, for example cognition processes. Here, self-organization was of main interest in the first years. Heinz von Foerster discovered that order can arise not only from order but also from disorder. Among others, he described the example from nature, where single elements can be in a disordered state, and shaking results in an ordered arrangement—e.g. a crystalline structure [31, 43]. Heinz von Foerster transferred these observations on ordered states to several areas of life. He considered the phenomenon of self-organization in nature, technology and society to be of highest importance in science. Consequently, in 1961 he successfully held a conference on self-organization titled “Principles of Self-Organization”, which generated results of major importance for this scientific field. Stafford Beer, a management cyberneticist called this conference the most important event of his life. And this event with its groundbreaking findings was the reason for the quickly increasing interest in self-organization as a field of research. Heinz von Foerster’s publications were translated into many languages and distributed worldwide [31, 41].

Von Foerster decoded the abilities of self-organizing systems. These findings support self-preservation and therefore are of great use in many fields, e.g. as a basis for successfully managing complex systems [44]. This permitted theoretical approaches towards the artificial creation of self-organizing systems. Self-organization is of great significance for many areas, one being management. One major question is whether self-organization can be initiated and when a system starts to organize itself. Specifically in the management domain, it is important to know if big companies or other social constructs (e.g. national states) organize themselves (in a directed manner) or if such organization happens unplanned and arbitrarily. Assuming that the intended self-organization happens, a subsequent question is if this organization is meaningful or not. In management science, major researchers like Stafford Beer grounded large parts of their management doctrines on the preliminary work of Heinz von Foerster [45].

Today, von Foerster’s findings get widely applied in the field of economics and management of social systems. Researchers like Stafford Beer and Frederic Vester picked up von Foerster’s work and made steps towards practical applications of cybernetics [31, 46].

4.3.2.5 The Bio-Cybernetics of Frederic Vester

Frederic Vester was born in 1925 and became a biochemist and an expert for ecology. He advocated for replacing the ordinary, linear thinking by systemic thinking in order to face complexity issues. Vester is known as the founder of biocybernetics and created the term networked thinking (German: Vernetztes Denken). One of his most important works was the development of the eight basic rules of biocybernetics, which—according to Vester—are the precondition for a system the be able to live. As well, Vester declared that most common mistakes that occur during system planning can be avoided if these rules are observed and networked thinking gets applied as the fundamental principle [47]. The rules are formulated on an abstract system level and therefore are applicable to a large variety of human and ecological systems:

– Rule 1: Negative feedback cycles must dominate over positive feedback.
– Rule 2: The functioning of the system must be independent of quantitative growth.
– Rule 3: The system must operate in a function-oriented, not a product-oriented manner.
– Rule 4: Exploiting existing forces in accordance with the ju-jitsu principle rather than fighting against them with the boxing method.
– Rule 5: Multiple use of products, functions, and organizational structures.
– Rule 6: Recycling: Using circular processes (material and resources).
– Rule 7: Symbiosis: Reciprocal use of differences in kind through link-ups and exchange.
– Rule 8: Biological design of products, processes, and forms of organization through feedback planning.

According to Vester, positive feedback is important for making things run by self-enforcement. Rule 1 sees negative feedback or self-regulation by loops as even more important, as this is required for bringing a system in a steady balance.

The second rule states that a system that is primarily based on growth cannot reach a long-term balance and is likely to irreversibly exceed critical values. Such behavior and associated consequences were the result of the World3 model and the associated publication The Limits to Growth (see Sect. 3.4.3 for further details).

The third rule addresses the requirement of "flexibility and adjustment" of systems. Vester mentions that "Systems capable of surviving are geared to their function, not to their product" and that "products often change rapidly, whereas functions remain the same for a long time".

Rule 4 says that the own energy should only be used for steering and control, and that "using existing forces benefits from current situations and promotes self-regulation". Vester uses the example of a jujutsu fighter (in contrast to a boxer), who ideally used his power only for turning the power of an opponent towards himself. Like the jujutsu fighter, successful systems should absorb external impact and apply it for their intended purpose.

Advantages of multiple uses are covered by rule 5. Multiple use reduces flow capacity, energy, material and information efforts while increasing the degree of interconnectivity.

The principle of recycling, as formulated in rule 6, declares that systems (and societies) have to reach a state without waste. This could be reached when inputs and outputs of systems get completely interlinked—as it is the case in natural systems. This principle helps to reduce the risk of irreversible effects in the system.

Nature is also indicated as an example for rule 7. "Symbioses replace 'short-sighted exploitation' by 'stable cooperation'. The ecological and economic advantage of symbiosis is that, in leading to substantial savings of raw material, energy, and transport for all concerned, it takes pressure off the environment. But symbiosis calls for a certain smallness of scale and decentralized structures; it need a certain blending of functions [...] In other words, it calls for variety within a limited space."

Finally, rule 8 claims that products, functions and organizations "must conform to the structure of viable systems". Vester describes that "non-biological design ultimately fails to address the relevant demand and as such is produced without regard to the market. Yet countless planning disasters continue to result from decision-making processes that ignore this rule" [47].

The entire scientific work of Frederic Vester has been inspired by the idea of nature as a teacher. Vester thought that all answers to complex questions in developing technical appliances as well as when organizing human societies can be found by analogies to nature. Vester applied cybernetics as a method for systemic thinking and he developed a method-based software toolset for managing complex challenges [48]. And he brought his developments to many industry applications. As an author of popular science, Vester explained the enormous, mostly unused possibilities of biocybernetics as a future path to solutions to a broad audience. And he uncovered the risks of a lack of understanding complex systems and networked thinking.

4.3.2.6 Management-Cybernetics by Stafford Beer

The findings of Heinz von Foerster permitted, for the first time, to organize real complex systems without tremendous reduction or simplification. Stafford Beer was the first one to use these new opportunities for applying cybernetics to the field of management [49]. The mathematician, psychologist and philosopher was born in 1929. His lifelong scientific topic was about the effective organization of complex systems. This challenge was what Beer saw as a key factor for mankind in the future. Beer developed models and methods for managing the complexity of life, and called this work management cybernetics.

Stafford Beer identified the need for innovative and creative solutions in the field of management science and organizational design for industry as well as government. When starting his work in management cybernetics, he had already acquired substantial management experience from practical work in industry and the military. Beer had founded and led the largest operations research group in the industry for UK's former leading steel company United Steel, a group comprising 70 specialists from different disciplines. He had worked on highly complex problems in industry and disposed an interdisciplinary scientific thinking [31, 50]. Because of his practical experience, Beer already identified in the early 1950s the potential of Norbert Wiener's cybernetics for solving complex problems in the field of management. Based on this awareness, he transferred cybernetics' findings into a new management approach. Beer presented the results of this work in his book Cybernetics and Management in 1959 [51]. In this publication he strikingly showed that the highly abstract findings in cybernetics are fundamentally necessary for the successful design of complex systems [31, 50].

Beer's developments were influenced not only by the basics of Norbert Wiener's cybernetics, but also the fundamentals of self-organizing systems by Heinz von Foerster represented highly important groundwork for his management cybernetics. In fact, Beer based a theory of modeling comprehensively complex systems on the principles of self-organization [31, 52].

Stafford Beer had the intention to make the laws of organization and management applicable and therefore designed the model called "Viable System Model" [45]. He explained this model and its application in detail in the two books Brain of the Firm and The Heart of Enterprise [53, 54]. The Viable System Model describes the elements, functions and interconnections he thought of as being initially required for the viability of systems. It can also be applied for structuring information and communication in a large variety of systems [55–57].

Late in his scientific career, Stafford Beer published the significant book Beyond Dispute, which described further findings of fundamental importance [58]. He presented an innovative solution approach for one of the most significant problems of organizations—utilization of knowledge distributed in the organization. The so-called "Team Syntegrity" method matches the speed and effectiveness of small teams with the power of integration inherent in large groups [58, 59].

Beer's distinguished contribution to complexity management is the application of cybernetics for solving complex functions of human coexisting and cohabiting in organized structures like enterprises, states or other social systems. Before him, cybernetics had been applied to technical challenges; Beer succeeded in transferring the systems thinking and methods, and with that significantly widening the scope for this scientific approach.

4.3.2.7 Breakthrough in the German-Speaking Area

Three decades after its introduction, cybernetics has been implemented into many scientific areas. Also, the cybernetics approach significantly supported and enabled technical inventions associated with complex systems. Cyberneticists of the second generation like Stafford Beer and Frederic Vester extended the fundamental approach to new disciplines like management cybernetics and biocybernetics. But still publicity was lacking, for example no teaching programs existed in universities. And so the proliferation of cybernetics by spreading knowledge to young academics and entrants did not happen.

Early (first generation) cyberneticists like Norbert Wiener, Warren McCulloch and Heinz von Foerster were highly skilled scientists. The same accounts for the subsequent (second) generation of cyberneticists like Stafford Beer and Frederic Vester, who adopted and expanded the initial approaches. These scientists primarily aimed at improving their own disciplines, e.g. mathematics, physics, biology or psychology. And when they reached their discipline's limits they started to cross borders—and in doing so became system scientists. For the discipline of cybernetics the next step had to be a broader adoption of this science. Therefore the fundamental knowledge and its application needed to be significantly simplified and made applicable. Thus, the new challenge was to overcome the constriction of cybernetics to a small group of experts only [31].

Prof. Hans Ulrich taught at the University of St. Gallen, Switzerland and was among the first ones who focused on bringing cybernetics into broad scientific application. Ulrich recognized the significance of providing cybernetics' findings in an applicable form to a large audience. In 1983, Ulrich initiated the "St. Gallener Forschungsgespräche" (scientific discussions) with the topic "Self-organization and Management of Social Systems". The objective of this conference was to bring a large number of European scientists in touch with the fundamentals of cybernetics [60]. Heinz von Foerster, one of the early and famous cyberneticists (who disposed impressive rhetoric skills), was persuaded by Ulrich to participate in the conference and thus contributed to its tremendous success. Many participants adopted cybernetics in their later work. Those scientists can be seen as the third generation of cyberneticists. This includes for example the Austrian economist Fredmund Malik, who became the director of the Management Zentrum St. Gallen in 1977, the Swiss economists Peter Gomez, Gilbert Probst and the German psychologist Dietrich Dörner. This generation of cyberneticists began formulating the principles and methods of cybernetics in simplified language that allowed for its application without the need for highly specific qualification [31, 61].

4.3.2.8 Status Quo and Outlook

Many great scientists drove the revolutionary approach of cybernetics from the possibilities of holistic system modeling and understanding to applications in fields like biology and management. Some of the most influential people in this development of cybernetics are Ludwig von Bertalanffy, who developed the General Systems Theory; Norbert Wiener, the creator of fundamental cybernetics; Heinz von Foerster, the mentor of Biocybernetics; and Stafford Beer, who conceived applications of cybernetics in the management field.

Complex systems and their control require specific rules and approaches—this can be the summarized findings of cybernetics in the last century. And those rules and approaches as formulated by Norbert Wiener apply in the same way for systems of inanimate and organic nature. None of the single scientific disciplines (mathematics, physics, biology etc.) by itself is able to model and explain the phenomenon of complexity. For this reason, cybernetics had to be designed as an interdisciplinary approach from the early beginning on. If a phenomenon gets observed in one specific discipline, cybernetics can bring it to a higher level of abstraction. This way is also becomes manageable outside of the originating discipline and represents a new object of research [2, 31].

Today, cybernetics is widely applied in many different fields. The development of the computer, business management, education science, automation and psychotherapy are only some examples, whose growth are hardly imaginable without the influence of cybernetics. Or at least their development would had been tremendously different from what we know today.

In this context it is an interesting observation that most people are not familiar with the approach given by the Control and Communication in the Animal and the Machine. In fact, not even the term cybernetics can be denominated as general knowledge. If people have some association with the word, then it is most likely with one of the derived terms like cyborg, cyberspace—and yes, also cybersex. While the implications of cybernetics in these terms is obvious and meaningful, it can only be speculated that there is no broader knowledge about it. One possible explication is that cybernetics is so heavily interwoven into the daily life that it is not specially noted and seen as a matter of course.

While cybernetics has been and still is applied in many technical and natural scientific applications, there is still much unused potential for organizational and societal design and improvement. One striking example could be the new appearance of wearable computer devices, specifically the augmented reality device Google Glass. There are still many technical challenges for this man-machine-interaction device that have to be solved, e.g. adequate energy supply, possibilities of intuitive user input and context-based user support. But the even larger question is how millions of those devices in daily application will impact society. Challenges to be solved are for example, the impact and limitations of data tracking, personal privacy and information-sharing behavior. Organizational design and new management approaches for the digital age are challenges on the doorstep—and for those challenges cybernetics provides powerful fundamentals.

4.3.3 Operations Research

The approach of operations research came up around 1940 from a military context. It arose from a group of British scientists (later joined by American scientist), who developed a scientific approach for investigating military operations during Second World War [62].

One central idea when developing operations research was to consider the entire system when solving a problem (which appears within this system) [63]. Therefore, the approach included intensive interdisciplinary collaboration of military and scientific experts. Operations research did not aim at gathering new scientific findings, but solving specific challenges, which could also be characterized by significant dynamics. As well, problem solutions included the readiness for applicability, thus solutions were not only given on a theoretic level, but as an instruction for implementation. Up to the present day, this understanding of operations research is still one of its main characteristics.

Operations research arose during the Second World War. Other than cybernetics, operations research cannot be traced back to a single founder or name patron. The breeding grounds for this new approach were in wartime Britain shortly after the start of the Second World War. Great Britain suffered severe defeats in the first year of the Second World War. The beginning of German air strikes in 1940 aggravated the problematic situation. Soon Great Britain was largely depending on supply ships from the United States. But even those ships were soon under massive attack from the German submarines and suffered significant losses. Consequently, one of the most urgent challenges for the Allied Forces was to detect and destroy German submarines [28].

Because of this state of emergency, the English command was forced into an extensive search for solutions to this challenge. They encountered an interdisciplinary group consisting of scientific and military employees, which had already been founded in 1937. The group's mission was to investigate the optimal layout of a radar control system for the British military [64, 65]. Three years later the group could already claim some success in early radar detection of hostile airplanes in the Battle of Britain [66]. In 1940, this success resulted in building up similar groups for the British air force, army and navy [65]. One exemplary follow-up project was the analysis of air force attacks against submarines, which was executed by the Navy Operations Research team. A statistical analysis of previous strikes against submarines led to the suggestion of changing the depth adjustment of depth charges. This action was reflected in a significant increase of hostile submarines sink rates [64].

The physicist Patrick Maynard Stuart Blackett was the head of a famous interdisciplinary team and convinced the British leadership of the necessity of a scientific approach for complex operations. For this reason, he is often mentioned as the founding analyst of operations research [67]. In 1942, similar groups were started in the United States, which also generated a new research field of mathematical strategies for the planning and optimization of military operations.

In the following years, operations research was increasingly applied to many problems of strategic relevance that the Allied Forces were confronted with. One famous example of applications became the protection of US convoys against German submarine attacks. Those convoys were shipping supplies over the Atlantic Ocean under the constraint of extremely limited resources for each military operation. The challenge was about optimizing the chances of success for the convoys (meaning to minimize losses of ships by submarine attacks) by disposing the limited defense resources.

The successful, efficient solution for the configuration of ship convoys was of significant importance for the entire course of the Second World War [64, 65]. And the formal collaboration between science and the military made a substantial contribution to the victory of the Allied Forces in the naval war against the German navy [68].

This impressive success of operations research applications during the Second World War led to intensive subsequent use and further development of this approach in the US and Great Britain. After the war, experts left their military field of work in order to migrate into economics and proceed and extend their applications of operations research. The application of electronic calculators for solving scientific and administrative challenges was a pioneering work in the field of operations research, and this work was powered by the findings gained during the Second World War [68].

At least since the invention of the simplex algorithm for solving linear programming in 1947, operations research became noted as a scientific approach [66, 69]. In close connection with the development of computers in the 1950s it finally became accepted as an independent scientific discipline. One of the drivers of this movement was Saul Gass, working at the University of Maryland [70].

Especially in the United States the successful collaboration between scientists and military personnel has been cultivated ever since then. Until today, so-called “think tanks” serve as advisors for the political government [68]. One important institution is the RAND Corporation, founded at the end of the Second World War in the environment of the US Air Force [71]. During the Cold War, the main objective of RAND was to generate strategic military scenarios for the US government. But also socio-scientific research has been conducted by this company, which had famous employees like John von Neumann and Donald Rumsfeld. Besides solutions to security and political questions, also many other important questions were on the agenda of RAND. One exemplary project from recent times is the increasing obesity of the US population [65, 68]. Many companies made successfully use of operations research for solving complex challenges. And operations research became established in several scientific fields, e.g. engineering and economics.

Since the 1960s, operations research also became mentioned in technical literature in Germany, beginning with translations of publications by Curchman, Vazsonyi and Sasieni. In the beginning, distinguished German expressions were created, e.g. Unternehmensforschung, Optimalplanung, Planungsforschung, Planungsrechnung or mathematische Entscheidungsfindung. However, none of them really gained traction and operations research became the common term in use [70]. Operations research became introduced to universities and lectures as an interdisciplinary approach of applied science—and finally as a research field of its own. For example, the Rheinisch-Westfälische Technische Hochschule in Aachen (RWTH Aachen) possesses a chair for operations research. Today, operations research is widely accepted in industry as a method for planning and decision making.

The development and application of operations research has been influenced significantly by the advent of electronic data processing systems. Today, it is possible to tackle complex problems with software programs, assuming that one is capable of the operations research basics. Especially in the field of simulation, electronic data processing provides tremendous possibilities. Operations research gained the widest penetration in the field of economics, where the term management science was established for this kind of approach [72].

Organizations and conferences carry the knowledge and carry out new development in the field of operations research. On the international level IFORS (International Federation of Operations Research Societies), INFORMS (Institute for Operations Research and the Management Sciences) and SIAM (Society of Industrial and Applied Mathematics) should be mentioned. IFORS further comprises continental and country-based sub-organizations; for Germany this is the GOR (Gesellschaft für Operations Research e.V.), a lively community that organizes many conferences worldwide.

4.3.4 Systems Engineering

It is rather difficult to identify the origin of systems engineering, as the basic concept is so universally valid. Marvel mentions that one could see the earliest systems engineering approach in the first house construction that required different specialists for executing the construction [73]. Consequently, collaboration between those specialists was useful and required planning and communication, which is challenging, because of differences in terminology in different disciplines. A central communicator, planner and organizer became necessary to manage the project. Brill states that "Based on the impressive civil engineering and other projects of ancient cultures, it is reasonable to assume that in today's terms these ancient engineers would be regarded as systems engineers. Also, few would argue that ancient philosophers such as Aristotle possessed the attributes often ascribed to individuals that take a systems or wholistic approach to problem solving" [74].

The continuous technological advance was boosted in the age of industrialization, which brought innovations like the steam engine by James Watt. In accordance with this advance, also expert knowledge and technical terminology in each sub-discipline increased dramatically. This led to linguistic differences which impeded communication across disciplines. And finally, this fostered the barriers between disciplines and impeded collaboration of specialists from different fields. An improvement to this situation was to install a coordinator for managing the collaboration between the specialists of different fields [73].

During and shortly after the Second World War significant research was done in the field of systems thinking, resulting in new approaches and methods for managing complexity. While this research was targeted at specific applications, e.g. anti-aircraft cannons, the scientists involved were mostly theorists with little relation to complexity issues as they occur in evolving enterprises. But such enterprises were lacking management approaches for the development and management of complex technical systems.

At the end of the 1940s, US-containment politics brought up war scenarios between the two new superpowers of the USA and the Soviet Union. The US government felt responsible for containing the spread of communism in the world, as it was enforced by the Soviet Union. In the shadow of the mobilization for the Korean War in 1950, the demand for application-oriented research became more explicit. The new systems engineering approach was meant to fulfill these demands. Engineers with a holistic thinking in the sense of cybernetics linked established methods from communications engineering with cybernetics. This formed the methodical framework for dealing with engineering disciplines, as the manifold aspects of cybernetics became integrated into engineering—which meant a contrast to the trend of differentiation of technical disciplines [30].

Systems engineers thought of themselves as pioneers who would change engineering sciences with interdisciplinary approaches. An engineer should become a technical generalist who can overcome the frontiers between disciplines. This movement asked for a united engineering science, according to the large-scale military projects with interdisciplinary teams executed during the Second World War [30].

As already mentioned, it is not possible to identify the exact time of systems engineering's origin. At least the term arose from work done at Bell Labs in the US (see Sect. 3.4.2). In 1940 the term was used first in the context of new weapons development. The fundamental approach, however, was already in use at Bell Labs since approximately 1900. The US Department of Defense used systems engineering in 1940 for developing missiles and the defenses against them. Then in 1946 the RAND Corporation applied system analysis as a part of systems engineering.

Until the 1960s, most relevant work in systems engineering was motivated by the demands of the Cold War, e.g. network analysis in communication and transport, design of electronic system components, data processing, industrial automation, process control and development of weapon systems [30].

Early systems engineering could apply modern procedures and methods of probability theory, statistics, game theory, linear programming, information theory, cybernetics et cetera. In general, all these areas were highly theoretical and comprised significant amounts of mathematics. This changed the ideal perception of an engineer from being occupied with experiments, technical drawings or practical assembly work to instead work on the mathematical modeling of components, system characteristics and abstract computations. Thus, early systems engineering implied the mathematization of engineering. However, the initial positive acceptance of this development was later seen as a fundamental problem in engineering science [30].

Brill published a timeline indicating the development of systems engineering from 1950 until 1995 based on the work published by some of the key contributors. An adapted version of this timeline is depicted in Fig. 4.6. Statements cited by Brill from these key contributors are aggregated in Table 4.1.

According to Hall, “probably the first formal attempt to teach systems engineering was made in 1950 at the Massachusetts Institute of Technology by Mr. G. W. Gilman, then Director of Systems Engineering at Bell Laboratories, Inc.” [75] (according to [74]). Then, ”Goode and Machol of the University of Michigan published Systems Engineering in 1957 in which they observed a phenomena of systems thinking and approaches to designing equipment” [76, 87].

Hall published the book “A methodology for Systems Engineering” in 1962, which described a concept for Systems Engineering. In 1989, Hall published the book Metasystems Methodology, in where he laid out details about the approach he called system methodology. Hall highlighted the importance of these new methodologies for dealing with complex problems.

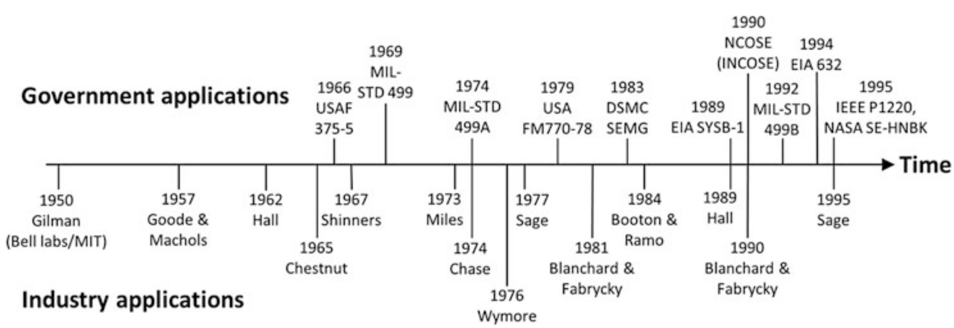

Fig. 4.6 Timeline of Systems Engineering Contributors (adapted from [74])

Table 4.1 Key publications in Systems Engineering from 1950 to 1995 (according to [74])

Author/Institution	Title/Description
Gilman	First teaching of Systems Engineering (according to [75])
Goode and Machol [76]	"for more than a decade, engineers and administrators have witnessed the emergence of a broadening approach to the problem of designing equipment. This phenomenon has been poorly understood and loosely described. It has been called systems design, systems analysis, and often the systems approach." "systems design entails many things: a new set of tools, a new classification of parts, an organized approach albeit seemingly chaotic, and a team of workers. The time is ripe to weld these many things together"
Hall [75, 77]	Concept of systems engineering consisting of three elements: systems engineering and its multifaceted definition, three divisions of the environment (physical/technical, business/economic, social), considering the needs of customers and how to fulfill these needs. Insights into systems methodology (SM), defined as: "A body of thought, theory, procedures, and specific methods applicable [. . .] to most if not all, 'complex problems'. The subject is enormously important, because it integrates all of the ways that man has to improve his world, and it adds a few to fill some voids, as if to glue together the parts into a new unified synthesis, with the power to cope with increasingly complex problems."
Chestnut [78]	Guidance on how to formulate the problem and acquire requirements
Shinners [79]	"seven general procedures are involved in engineering an overall large complex system"; "this logical unified systems engineering procedure is in reality a feedback process". "The best advice for solving a system-oriented problem is first to understand the problem. The systems engineer must fully determine the overall system requirements and objectives, and at the same time, fully understand the constraints imposed."
Miles [80]	A lecture series by experts on "Systems Concepts for the Private and Public Sectors", held at the California Institute of Technology in 1971, edited by Miles. Description of a six-step approach towards system management.
Chase [81]	General description of Systems Engineering. "there are tremendous language difficulties to be overcome in effectively communicating systems concepts and in describing the systems approach".
Wymore [82]	"an interdisciplinary team must be the nucleus of system design". "system analysis is driven by three imperatives: modeling human behavior, dealing with complexity and largeness-of-scale, and dealing with a dynamic technology".
Sage [83, 84]	Comprehensive overview of engineering of large-scale systems; explications on the topics of system methodology, design and management, system quality assurance, configuration management, audits, reviews, standards, system integration. "systems engineering is the management technology that controls a total

(continued)

Table 4.1 (continued)

Author/Institution	Title/Description
	lifecycle process, which involves and which results in the definition, development, and deployment of a system that is of high quality, trustworthy, and cost effective in meeting user needs”. Introduction of a three-level systems engineering approach (structure, function, purpose).
Blanchard and Fabrycky [85]	“System-life-cycle-engineering” defined as “starting with the initial identification of a need and encompassing the phases (or functions) of: planning; research; design; production or construction; evaluation; consumer use; field support; and ultimate product phaseout”. “systems engineers must discipline themselves to think in terms of the system-life-cycle to ensure that all aspects of the system are considered”.
Booton and Ramo 1984 [86]	“large scale attention to modern systems engineering occurred in the post-war (WW II) developments of ground-to-ground, ground-to-air, and air-to-air missile systems, where technologies involved included communications, radar, controls, aerodynamics, structures, and propulsion”.

Chestnut as well as Shinners pointed at the importance of early stages in the systems engineering process, giving guidance on formulating the problem, acquiring the system requirements and understanding the general problem that has to be tackled [78, 79].

In 1973, Miles published his edited version of a lecture series on system concepts, which was held by a group of experts at the California Institute of Technology. In this publication, Miles also presented a six-step approach for system management [80]. One year later, Chase provided a general description of systems engineering, which he linked to communication systems concepts [81]. Sage also contributed a comprehensive overview of methodical engineering of large-scale systems [84]. And Wymore strengthened the importance of an interdisciplinary team as the “nucleus of system design” [82].

Sage as well as Blanchard and Fabrycky mention the life cycle perspective of systems engineering. Sage mentions that “systems engineering is the management technology that controls a total lifecycle process”, and Blanchard and Fabrycky define “system-life-cycle-engineering” by the process steps from identifying the need until the “ultimate product phaseout” [83, 85] (according to [74]). And in 1984, Booton and Ramo describe in their retrospective publication “The Development of Systems Engineering” that (mainly military) system demands drove the need for modern systems engineering.

Because of systems engineering’s relevance, industry and governmental organizations developed their own standards and handbooks for this approach on solving complex challenges. The earliest of such documents was written by the United States Air Force (USAF) in 1966, when they published their Handbook 375-5, which contains exact descriptions of the systems engineering process [88]. Several other documents followed with the intention to improve the standardized guidance on systems engineering [89–94].

Professional associations like the Electronic Industries Association (EIA), IEEE and NCOSE/INCOSE started publishing their own standards in the 1990s [95–97]. Currently, INCOSE published the fourth version of their Systems Engineering Handbook [98], which has become a quasi-standard in many parts of industry.

According to Gorod et al., Keating et al. mention "shortcomings in the ability to deal with difficulties generated by increasingly complex and interrelated system of systems" represented the next challenge in the field of systems engineering. "There was a need for a discipline that focused on the engineering of multiple integrated complex systems [99] (according to [100]). "Today, we refer to this as SoSE [99]. So, system-of-systems engineering is a further development of systems engineering in recent times. A historical development of this approach is presented by Gorod et al., who also created a timeline of selected contributors similar to the timeline of systems engineering history published by Brill for the timeframe of 1950–1995 [74, 99]. This timeline covering the years 1990–2008 is displayed in Fig. 4.7. Selected statements of the authors appearing in this timeline are aggregated in Table 4.2.

In the early 1990s several publications introduced the term system-of-systems and provided initial definitions [101–104]. Owens as well as Manthorpe highlight the importance of this approach for military applications [105, 106]. Maier points to the fact that a SoS is an assembly of systems with operational and managerial independence of its components [107, 108]. Kotov then "was one of the first scientists to attempt to model and synthesize SoS", Luskasik applied SoS to the educational context and Pei contributed the concept of system-of-systems integration in a military context [109–111]. Next, Carlock and Fenton enhanced SoS to "enterprise systems of systems engineering" by integration of enterprise activities like strategic planning and investment analysis [112]. Several authors focus on a framework for SoSE, and Keating et al. published guidelines for SoSE phases based on a comparative study of systems engineering and system of systems engineering [100, 114, 115]. Other authors aggregated definitions for a system of systems based on various sources [117, 119]. And in 2008 two books were

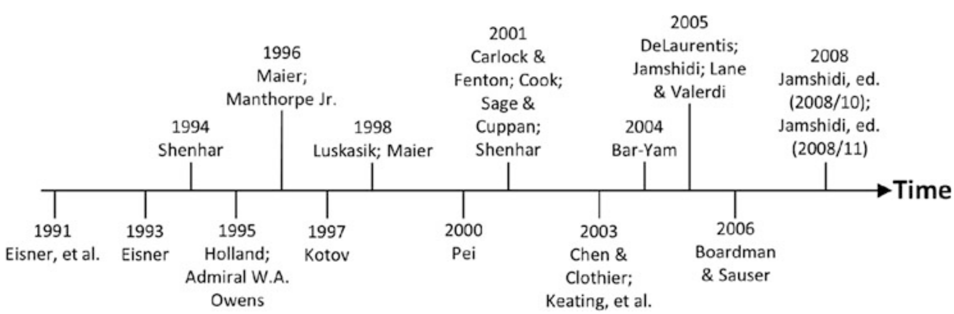

Fig. 4.7 Modern history of system of systems (adapted from [99])

Table 4.2 Key publications in Systems-of-Systems Engineering 1990–2008 [99]

Author/Institution	Title/Description
Eisner, et al. [101]	Definition of a system-of-systems as "A set of several independently acquired systems, each under a nominal systems engineering process; these systems are interdependent and form in their combined operation a multifunctional solution to an overall coherent mission. The optimization of each system does not guarantee the optimization of the overall system of systems"
Eisner [102]	Introduction of the modern term SoS
Shenhar [103]	Definition of a system-of-systems as "A large widespread collection or network of systems functioning together to achieve a common purpose". "Shenhar was one of the first to describe SoS as a network of systems functioning together to achieve a common purpose."
Holland [104]	"Holland proposed to study SoS as an artificial complex adaptive system that persistently changes through self-organization with the assistance of local governing rules to adapt to increasing complexities."
Owens [105]	Owens "introduce[d] the concept of SoS and highlight the importance of its development in the military".
Manthorpe [106]	"In relation to joint warfighting, system of systems is concerned with interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance, and Reconnaissance (ISR) Systems."
Maier [107, 108]	Maier "proposed for the first time to use the characterization approach to distinguish 'monolithic' systems from SoS. These characteristics include 'operational independence of the elements, managerial independence of the elements, evolutionary development, emergent behavior, and geographical distribution'". "A system-of-systems is an assemblage of components which individually may be regarded as systems, and which possesses two additional properties: Operational Independence of the Components [and] Managerial Independence of the Components [. . .]."
Kotov [109]	"Systems of systems are large scale concurrent and distributed systems that are comprised of complex systems". Kotov "was one of the first scientists to attempt to model and synthesize SoS".
Luskasik [110]	"SoSE involves the integration of systems of systems that ultimately contribute to evolution of the social infrastructure." "Luskasik attempted to apply SoS approach in the educational context".
Pei [111]	Introduction of "a new concept of 'system-of-systems integration' (SOSI) which gave the ability 'to pursue development, integration, interoperability, and optimization of systems' to reach better results in 'future battlefield scenarios'".
Carlock and Fenton [112]	Suggestion on joining "traditional systems engineering activities with enterprise activities of strategic planning and investment analysis"; introduced the term "enterprise systems of systems engineering"
Cook [113]	"Cook [. . .] described a distinction between 'monolithic' systems and SoS based on 'system attributes and acquisition approaches'. Constituent systems of SoS are acquired through separate processes."

(continued)

Table 4.2 (continued)

Author/Institution	Title/Description
Sage and Cuppan [114]	Proposition of "principles of 'new federalism' to provide a framework for the SoSE"
Keating et al. [100]	Comparative study of SE and SoSE; Provision of guidelines for several key phases such as "design, deployment, operation, and transformation of SoS"
Chen and Clothier [115]	Indicating the "need for a SoSE framework"; suggestion for "advancing SE practices beyond traditional project level to focus on "organizational context"
Bar-Yam et al. [116]	Suggestion to add "characteristics as opposed to definitions to provide a more comprehensive view of SoS"
Jamshidi [117]	"Definitional approach to SoS by collecting different definitions from various fields"
Lane and Valerdi [118]	Identification of "other universally known network-centric systems as examples of collaborative SoS (i.e., the internet, global communication networks, etc.)". analysis of "SoS definitions and concepts in the 'cost models' context"
Boardman and Sauser [119]	"outlined the characterization approach to SoS"; Identification of "patterns and differences in over 40 SoS definitions"; "comprehensive overview of five distinguishing characteristics of SoS"; the characteristics are: autonomy, belonging, connectivity, diversity, and emergence.
Jamshidi [120, 121]	"first two books dedicated to SoS", covering "a wide variety of SoS topics"

published with a special focus on SoS, covering many aspects of this enhanced systems engineering approach [120, 121].

Probably the most famous example of systems engineering application is the NASA Apollo Program in the 1960s [122]. In the context of the space race with the Soviet Union, President John F. Kennedy held his historic "Moon Shot Speech" in Congress on October 25 1961, stating: "First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the Earth." This extremely complex task was divided into manageable partial tasks and worked on by hundreds of agencies, authorities and enterprises involved in the Apollo Program (Fig. 4.8). And all partial tasks finally contributed to an integrated, holistic solution.

From its beginnings on, the application of systems engineering was closely linked with the aeronautics and astronautics industry and software for technical appliances. Besides the aforementioned Apollo Program, systems engineering became also applied and methodically improved in the development of the US Space Shuttle and in the European aeronautics program, e.g. for the development of the Ariane rockets. Nowadays, many universities offer systems engineering as a field of study, often linked to aeronautics or astronautics departments.

In 1990, the International Council of Systems Engineering (INCOSE) was founded as an association specializing in the teaching, application and research in systems engineering. Since then, national chapters have been founded all over the world with great success. Besides INCOSE, several professional institutions, e.g. the Institute of Electrical and

Fig. 4.8 President John F. Kennedy in his historic speech to the Congress, May 25, 1961, NASA (Great Images in NASA Description), via Wikimedia Commons

Electronics Engineers (IEEE) and the American Institute of Aeronautics and Astronautics (AIAA) run their own departments with a focus on systems engineering [123, 124]. And enterprises like Boeing and EADS operate systems engineering programs with own conferences and advanced training.

System Engineering vs. Engineering Design

When comparing approaches and methods of systems engineering with those taught in engineering design, large overlaps can be found. While it is difficult to draw a clear line between the disciplines, differences can be found in their historical origin. As introduced in this chapter, systems engineering was based on the holistic thinking of cybernetics and represented a technical application of the thus far theoretical methods. Statements like Kennedy's famous "Moon Shot Speech" represented top-down challenges, starting with a complex holistic target, which had to be broken down into manageable tasks.

Engineering design has its background in a systematic approach toward the engineering of products. Beginning with purely mechanical devices, step by step more disciplines became integrated for realizing more complex product functionalities. Electrical components became integrated, then electronics and software, which led to the definition of mechatronic products. Each discipline brought more complexity to the system, communication, interface and integration challenges. This development of engineering design can be seen as a bottom-up process, integrating more and more disciplines and bringing more and more complexity into the system. Finally, mechatronic systems like an automobile require a systems engineering approach.

Current Importance of Systems Engineering

Systems engineering concepts quickly received attention after successful application in the Apollo Program in the United States and additional aeronautics applications in Europe. Nowadays, its integration into large-scale technical processes is mandatory and regulated by several norms. Application of systems engineering results in faster problem solving and higher product quality, due to the fact that the amount of possible failures of an entity is generally higher than the possibilities to fail for its single parts [125].

Systems engineering became a synonym for a systematic approach towards the entire product design process of complex hardware and software systems. Also successful application to socio-economic systems have been documented [126]. Nowadays, systems engineering gets not only applied to extremely large projects, but significant effort is also put into transferring systems engineering methods into medium-sized businesses with their smaller scope of applications.

Enterprise Architecture and Architecture Frameworks

The design and application of architecture frameworks has become one of the major approaches toward managing the complexity of systems. The origin of this approach can be traced back to the works of P. Duane Walker in the late 1960s. As the director of architecture at IBM, Walker "had established an enterprise analysis-oriented planning tool called Business Systems Planning (BSP)" [127]. Beginning in the early 1980s, Walker's student John Zachman carried the BSP approach forward and in 1987 published his findings in the article titled "A framework for information systems architecture". Zachman stated that "with increasing size and complexity of the implementations of information systems, it is necessary to use some logical construct (or architecture) for defining of the components of the system" [128]. Based on analogies to other disciplines like (building) architecture and airplane design he elaborated a framework for information architecture, which has been the initial point for many frameworks to follow.

Zachman's conclusions from his research were that "There is not an information systems architecture, but a set of them!" and that "we are having difficulties communicating with one another about information systems architecture, because a set of architectural representations exists, instead of a single architecture. One is not right and another wrong. The architectures are different. They are additive and complementary" [128]. Zachman's information systems framework classifies types of architecture description by user perspectives (users are e.g. the owner, designer and builder) and by purposes (description of material, function and location). Each combination of perspectives and purposes (typically displayed in a grid) results in a different architecture representation (view).

While Zachman developed his framework specifically for application to information systems, he also provided model associations on a generic level. Material, function and location descriptions represent what the system uses to operate, and how and where the system operates. In later works, Zachman added the perspectives of people, time and motivation, which describe who, when and why the system operates [127]. Today, the education and consulting firm Zachman International states that "there is substantial evidence to establish that the Zachman Framework™ is the fundamental structure for Enterprise Architecture and thereby yields the total set of descriptive representations relevant for describing an Enterprise" [127].

Beginning in the late 1980s, several other architecture frameworks were developed, which were significantly based on Zachman's prior work. In 1986, the United States Department of Defense started working on their enterprise architecture reference model

Technical Architecture Framework for Information Management (TAFIM), which served as the basis for The Open Group Architecture Framework (TOGAF) published in 1995 [129]. The Federal Enterprise Architecture Framework (FEAF) resulted from the Clinger-Cohen Act in 1996, a US Congress initiative that aimed at improving the way of managing and investing in IT resources in federal agencies. The perhaps most popular architecture framework is the Department of Defense Architecture Framework (DoDAF), which was published as version 1.0 in August 2003 (current version is 2.02), but has its roots and precursor frameworks in the 1990s. “The Department of Defense Architecture Framework (DoDAF), Version 2.0 is the overarching, comprehensive framework and conceptual model enabling the development of architectures to facilitate the ability of Department of Defense (DoD) managers at all levels to make key decisions more effectively through organized information sharing across the Department, Joint Capability Areas (JCAs), Mission, Component, and Program boundaries” [130].

Within a couple of years, architecture frameworks became extremely popular and distinctive frameworks were created for many different use cases and organizations, e.g. AUTOSAR as a standard for the automotive E/E architecture [131]. Already in 2003, Jaap Schekkerman published his book “How to Survive in the Jungle of Enterprise Architecture Frameworks” [132]. A comprehensive and current survey of architecture frameworks can be found at the web site pertaining to the standards document “Systems and software engineering—Architecture description ISO/IEC/IEEE 42010” [133].

4.3.5 System Dynamics

Jay Wright Forrester was born in 1918 on a farm in Nebraska. In one of his later publications he mentioned that the practical and technical work at the farm during his youth did form his later thinking [134]. Forrester got a degree in electrical engineering, became a management expert, and researched and taught at MIT until he retired. He is known as one of the intellectual fathers of the computer and a pioneer in system dynamics. In the beginning called industrial dynamics, system dynamics represents a method for the holistic analysis and modeling of complex, dynamic systems [135].

After the Second World War, Forrester worked at “Whirlwind”, a flight simulator project for the US military forces. The objectives of the project were the development of a digital computer, creation of virtual reality and the investigation of the interaction between this virtual reality and humans. According to the cybernetics’ claim for a universal science, Forrester also aimed for a broad spectrum of application for these computers.

The computer, which resulted from Project Whirlwind was applied to the continental defense system of the United States and coordinated incoming data from radar stations, airplanes and other military objects. This application confirmed Forrester in his opinion that large projects require powerful computers, which work in real-time mode [136]. Forrester pursued this objective for the next decades.

One of the outcomes from Project Whirlwind was a new type of memory chip, developed by Forrester. This technological advance had significant impact on the further development of computers in general. Another side note worth mentioning is that the first animation in the history of computer graphics can be traced back to Jay W. Forrester [68, 135].

In 1956, Forrester moved to the MIT Sloan School of Management. His main objective in this position was to integrate economic science with engineering science in research and teaching. He planned to work in the field of operations research too, but was concerned about the missing relevance for the field of management; for example the success and failure of companies were not considered by operations research applications. As the applicability of research findings was of major importance for Forrester, he did not further pursue this approach [135, 137]. In 1957, Forrester founded the System Dynamics Group and laid the cornerstone for the system dynamics approach [134].

In Forrester's thinking, enterprises represent dynamic systems, wherein production parameters like staff, capital, commodities and machines are not static values, but parameters that are continuously developing. Consequently, this requires dynamic and real-time focused management [68]. As Forrester initially aimed with his method towards industrial applications, he called his method industrial dynamics.

Industrial dynamics still represents the standard work about system dynamics, published by Forrester in 1958 [138]. This work was preceded by a General Electric assignment, which asked for the origins of problems in capacity use in one factory. Forrester modeled the problem situation and simulated the temporal development by the use of a computer. His findings showed an oscillating structure of an unstable system. The consequence of this oscillation was that despite an unchanged order situation, unstable employment resulted because of existing policies. Once the system structure was understood, it became much easier to interpret similar system structures. While in the beginning only technical systems were modeled, now also social system structures moved into the focus of Forrester's approach. Consequentially, the term industrial dynamics was changed to system dynamics [137].

In 1971, Forrester published the book World Dynamics, which describes in detail his "world model" for simulations [139]. This model became adopted for the project "Limits to Growth", which was led by Forrester and was noticed by a broad audience. Forrester's "world model" became a topic of intense discussion by scientists at the time. One controversial aspect was the application of mathematical, computer-supported simulation to societal challenges. Compared to empirical approaches, is became questioned if such simulations—without empirical evaluation—can be seen as scientific procedures [68].

Similar to many other system science developments of the same time, Forrester's scientific approaches emerged from the cooperation between military and academia during World War II, the Korean War and until the time of the Cold War. However, Forrester did not only apply his findings in the military context, but also brought system dynamics into many civil applications. Due to the computational demands of his simulation approaches, Forrester was convinced that solving complex challenges requires mainframe computers [68].

Some system dynamics experts like Wolstenholme and Coyle aimed at spreading the method to a broader audience, especially to students in higher education. They thought that this can be realized best if methods and visualizations were kept simple, without the use of simulation techniques. Nevertheless, they propagated system dynamics as a method comprising two different modeling phases, the qualitative one and the quantitative one, and both can be applied for investigating problems [137, 140, 141].

J. Sterman thought that only simulation allows for understanding systems correctly and refused the sole application of qualitative system dynamics models [142]. J. Forrester did not change his methodical approach several years after his first publication, but enlarged the spectrum of application. In 1969, he published the book Urban Dynamics, investigating the interdependencies between governmental policies and poverty in cities [143].

Today's Significance of System Dynamics

In the early years after its development, system dynamics required large efforts for creating the initial models, which then build the basis for the simulation part. The model-building was executed by experts only. And computer-supported simulation required special software like DYNAMO [134, 139]. Therefore, system dynamics was applied on large-scale projects, where the efforts were affordable. This constraint was overcome when computer systems became more powerful, cheaper and consequentially more widely distributed. This development was accompanied by increasingly better software applications, which also became easier to apply. With modern hardware and software, the effort required for model creation and simulation is much smaller, hence making the application of system dynamics also profitable for small projects. Today, many simulation tasks can be run by a single user [144].

Nowadays, system dynamics gains worldwide interest, e.g. indicated by the increasing popularity of the "Systems Dynamics Society". Founded by academics in the 1980s, this association takes charge of an international exchange of opinions and findings in the field on yearly conferences and in interest groups. Since 1985 the Systems Dynamics Society publishes the journal System Dynamics Review [145].

In Germany the "Deutsche Gesellschaft für System Dynamics e.V. (DGSD)" acts as the local chapter of the System Dynamics Society with similar objectives. Prof. Gert von Kortzfleisch (1921–2007) was the pioneer of teaching system dynamics and its application in Germany at the University of Mannheim. Von Kortzfleisch worked together with Jay Forrester at MIT in 1968. Two of his co-workers, Peter Milling and Erich Zahn, worked in Dennis Meadows's group at MIT in the early 1970s and contributed to the model, which represented the basis for the famous publication The Limits to Growth [144, 146]. Over time, system dynamics became a commonly applied technique when analyzing complex challenges in the academic field. It is taught in many academic training programs and is a building block in many research projects. And an increasing number of enterprises make use of system dynamics for decision-making in case of strategic challenges [144].

According to Sterman, system dynamics gets widely applied in fields like society, politics, economics and science [142]. Examples that reached some popularity are recommendations for action for enterprises of the air traffic industry concerning the cyclical development of their industry and improvements of material flows in the enterprises' supply chain [144]. Rüffer describes the application of system dynamics for supplementing project management [147]. And Schwarz & Ewaldt describe the assessment of technological evolution by system dynamics modeling [148]. Besides problem-focused applications, system dynamics also gets applied for management training [149]. Based on a reference model, managers can analyze, validate and improve their own mental models [150, 151].

Information dynamics represents a specific development of system dynamics. It is based on the assumption that information is of major significance for system behavior, as this behavior results from interactions (information exchange) between system elements. Findings show that efficient system control can be reached with optimized information processing [152]. In this context, the "Beer Game" is a simulation game designed as a "flight simulator for management education" by Sterman, based on a preceding role game [153, 154]. "The game was developed by Sloan's System Dynamics Group in the early 1960s as part of Jay Forrester's research on industrial dynamics. It has been played all over the world by thousands of people ranging from high school students to chief executive officers and government officials" [153].

4.3.6 Game Theory

Game theory focuses on the search for optimal decisions in situations with multiple actors. These actors are interacting, acting rationally and are all aware of this fact. Rational thinking means that all actors aim at maximizing their own benefit [155]. The application of game theory analysis tools provides insights to popular situations, e.g. in politics or economics. One well-known example is the prisoner's dilemma, modeling the behavior of people in the context of self-interest and possible collaboration. Furthermore, game theory identifies structural interdependencies, which then can be verified in subsequent experiments. And it can provide acting guidelines for complex situations [155, 156].

Game theory has been applied to a wide variety of domains, with its first use cases in economics. Already in 1944, John von Neumann and Oskar Morgenstern applied their theoretic approach to economics in their groundbreaking book Theory of Games and Economic Behavior [157]. Besides economic applications like the consideration of market situations, game theory got also intensely applied to biological challenges and political, social and military problems [155]. Operations research applications also make use of game theory.

Originally, game theory served as the mathematical descriptions of decision behavior in parlor games like chess and checkers. Already in 1921, Émile Borel published an article with the title "La théorie du jeu et les équations intégrales à noyau symétrique" (English:

Game theory and integral equations with symmetric kernel) [158]. Game theory as a specific scientific approach was then introduced in 1944 with the book authored by von Neumann and Morgenstern [155]. During the Second World War, von Neumann worked as consultant for the US military, then joined the Manhattan Project and became a member of the RAND Corporation, where he applied game theory in strategic mental games [159].

After the Second World War, early applications of game theory were carried out in theoretical economics and strategic and tactical questions of warfare and military planning [156]. During the Cold War, game theory came to be applied on both political sides [159].

At the first level of its development, game theory could only be applied to zero-sum games, using the so-called minimax theorem. Those games are characterized by the fact that the total benefits and losses of all participating players equals zero (or a constant amount, which is known in advance). In 1950, John Nash extended the possibilities to non-zero-sum games by introducing the mathematical description of a general solution for non-cooperative games, later called the Nash equilibrium [160]. With these new possibilities, game theory became a dominant modeling method for decision making in economics and later in social sciences. In 1994, Nash was awarded the Nobel Prize together with Reinhard Selten and John Harsanyi for his findings in game theory. Several Nobel Prize awards are expected to follow for important enhancements in game theory approaches.

Over time the assumption of the "homo oeconomicus", a fully rationally acting human being, became questioned. Herbert Simon's research work showed that not only rationality, but also criteria like envy, greed or fairness can be part of the human decision [161]. In 1978, Simon was awarded the Nobel Prize in Economics for his findings.

In 2002, Daniel Kahneman was awarded the same prize for his experimentally based theory about spontaneous and situation-based decision making. According to this theory, humans often act reciprocally, which can result in a better outcome than what the "homo oeconomicus" could reach by strictly rational behavior. In addition, Kahneman showed that mutually cooperative behavioral strategies occur and can prevail [162]. Robert Axelrod developed ideas about the evolution of cooperation and e.g. showed how they apply to warfare [163]. Two more Nobel Prizes for works in the field of game theory were awarded to Thomas Schelling and Robert Aumann in 2005.

Biological use cases represented a significant enhancement to game theory applications. Evolutionary game theory states that human behavior is also resulting from genetically and culturally influenced processes, and not by pure rationality only.

Game theory allows modeling and mathematically solving strategic games and situations of conflict, which typically represent complex systems. A major point of criticism on game theory is that partly unrealistic assumptions need to be made. Especially the rational human behavior in complex situations has been shown as being unrealistic in recent times. Different further developed approaches of game theory therefore try to overcome such shortcomings.

4.4 Discussion of Historical Developments

Nowadays, managing complexity possesses a significant importance for many people. Compared to former times, job-related as well as private situations can be characterized by complexity. But already more than 2000 years ago, situations occurred that asked for managing complexity. In fact, the challenge of solving complexity can be seen during all periods of science history. For that reason it is not surprising that also at all times, procedures have been created for complexity management.

There are differing opinions on when complexity became such a relevant issue that a means for its management has been actively developed. And several major historical events meant a significant increase of complexity, for example the beginning of intercontinental trading, the industrial revolution or the two world wars. Another boost of complexity seemed just to have happened with the quick spreading of the Internet and interconnectivity by popular social networks.

The uprising of systems thinking in the early twentieth century stands out in the historic development of complexity management, as it prepared the basis for a systematic and scientific approach. Developing scientific methods and procedures was largely motivated and facilitated by the necessities of the Second World War. Those findings and experiences generated from war times then built the fundaments of modern approaches towards complexity management, which is also applied to civil applications.

For many findings, developments and innovations, war situations acted as the catalyzer and boosted scientific progress. This also accounts for system sciences and complexity management. And many developments in this discipline can even be traced back to ancient Greek philosophy. So, the historical developments described in this chapter indicate that modern methods of complexity management are the result of an evolutionary, not revolutionary process.

As the basics of modern complexity management have already been created in the 1940s, why did it take complexity management until recent years to reach public visibility? Two reasons can be found for this.

Obviously and already mentioned above, complexity increased dramatically in everybody's life in the last decades. Complexity did not only increase for governments, large organizations and enterprises, but also individuals experienced complexity increases in their jobs and private lives—mainly driven by an increase of information to be processed. This increased complexity naturally raised the demand for applicable methods for complexity avoidance, reduction and management.

The other reason is that scientists researching on systems and complexity in the middle of the twentieth century were way ahead of their time. It took time for technical equipment like computers to be developed and get distributed in large numbers. And as today every PC brings software for modeling a system network, this took half a century to get to this point. The same can be said about the use cases associated with complexity. Today, effects of highly interlinked networks are a common experience in everybody's life, for example when news, videos or pictures go viral on social networks. Fifty years ago, the notion of thinking in networks was rather abstract and was only a part of few people's daily lives.

In many ways, the breakthrough of complexity management is closely related to the development of the computer. While an increase of complexity can be associated with the triumphant success of computers, they also represent a fundamental prerequisite for solving complex challenges. Therefore it is not surprising that system scientists like John von Neumann and Heinz von Foerster were also deeply involved in the development of the computer. And only today's worldwide availability of computers allows many people to address complex challenges themselves.

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