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Introduction

1.1 Life Sciences – A Definition

1.1.1 A Short Definition of Life

The term life sciences is ubiquitously integrated into our everyday life. It has become a standard expression. To understand the content, challenges, and tendencies of life sciences, it is necessary to define the term life. Today, there exist more than 50 different definitions depending on the scientific field and the strategic focus. In general, life can be defined as a characteristic property, which separates living matter from inorganic matter. The main characteristics include the exchange of matter and energy, reproduction, and growth.

The definition of the term life in philosophy also follows these criteria [1]. Aristotle differentiated three levels of life in a hierarchical order. The lowest level included plants, whose life is characterized only by nutrition and reproduction. The next level included animals, which have the additional features of sensory perception and movement. The human, whose life is, besides the fundamental functions, characterized by thinking processes, is the highest level in Aristotle's hierarchy.

In the western philosophy of the modern era, two contrary general opinions developed: mechanism [2] and vitalism [3]. Promoters of mechanism explain life processes from the concept of physical laws of movement. The living organism is considered a machine. Main supporters of this idea were William Harvey (1578–1657), Rene Descartes (1596–1650), and Wilhelm Roux (1850–1924). In contrast to this idea, vitalism proposed a significant difference between organic and inorganic matter, whereby life is connected to organic compounds. A targeted living power (vis vitalis) characterizes all living matter. Main supporters of vitalism include Jan Baptist van Helmont (1577–1644), Georg Ernst Stahl (1660–1734), Albrecht von Haller (1708–1777), and Johann Friedrich Blumenbach (1752–1840). Since the synthesis of urea by Friedrich Wöhler (1800–1882), this approach was deprecated, since it could be shown that no special living power is required for the synthesis of organic compounds. A combination of mechanism and vitalism is the organicism [4]. This approach explains processes of life using science principles from physics and chemistry. Living organisms are supposed to have properties that cannot be found in inorganic matter.

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Supporters of this idea introduced the hypothesis, that biological questions can only be answered considering the whole organism. Main supporters of the organicism were William Emerson Ritter (1856–1944) [5], Karl Friederichs (1831–1871) [6–8], and August Thienemann (1882–1960) [9].

In natural sciences, the term life describes characteristic properties that define living organisms. This includes the exchange of energy, matter and information, growth, reproduction as well as reactions toward changing environmental conditions. RNA and DNA are supposed to be the main building blocks of life. This general definition of life was already defined by natural scientists of earlier centuries. Carl-Friedrich Kielmeyer (1765–1844) defined sensibility, irritability, reproduction force, secretion force, and propulsion force as important criteria of life [10]. As an early evolution scientist, he described long before Charles Darwin (1809–1882) own ideas regarding the evolution of living organisms [11]. Perception, reproduction, movement, nutrition, and growth were the main characteristics of life according to the German zoologist and philosopher Ernst Haeckel (1834–1919) [12]. For Francis Crick (1916–2004), who was awarded the Nobel Prize for the discovery of the DNA in 1962 together with James Watson (born 1928), self-reproduction, genetics, evolution, and metabolism were the main characteristics of life. In 1944, the well-known physicist and philosopher Erwin Schrödinger (1887–1861), who is considered the father of quantum physics, introduced in his work "What is Life?" [13] the term negentropy, which had great influence on the further development of molecular biology. Supporters of this idea tried to explain biological topics with physical sciences and started to focus on the mechanism of inheritance, which was still unknown at this time. John Maynard Smith (1920–2004) introduced the "Concept of Evolutionary Stabile Strategy" and identified all "populations of units, which are capable of proliferation, inheritance, and variation" as life [14]. The definition of life generally accepted today is based on the eight columns genetic program, reproduction, adaptation, compartmentation, metabolism, catalysis, regulation, and growth.

1.1.2 What Is Life Sciences?

The term life sciences originated in the 1990s when it was established as a marketing instrument of the pharmaceutical and the chemical industry. With the definition of the term, attention has been directed to the large number of pharmaceutical products and pesticides that are required for sufficient nutrition as well as for health maintenance of the world's population. Meanwhile, the term has gained individuality and has a much greater meaning. All processes, products, and conditions that are connected to "life" itself, are summarized in the term life sciences. Today, life sciences include not only biological sciences, but also parts of medicine. The development of new drugs (e.g., using bio-catalytic methods) or the environmental friendly optimization of processes are included as well as the sequencing of the genome of plants, animals, and humans or the development of new therapeutic forms for different diseases.

Life sciences in general are research fields dealing with processes and structures of living organisms. Besides classical biology, this also includes related areas such as medicine, biomedicine, biochemistry, molecular biology, biophysics, bioinformatics, human biology, as well as agricultural technology, food, and nutrition sciences up to the use of biogenic natural resources and biodiversity research. The spectrum of methods comprises the complete device and analysis inventory and enters into the fields of humanities and social sciences. The methodical work and the theoretical background are highly interdisciplinary, but always have a clear relation to living organisms, especially to humans. Thus, life sciences comprise a similar huge scientific group as do the humanities.

According to the generally accepted classification of biotechnology, a distinction of “green” (agriculture, plants), “red” (medicine, pharmaceutics), “blue” (products from the ocean), “white” (industrial products), “gray” (environmental), and “yellow” (production of food) life sciences is possible.

Due to the still large number of diseases that cannot be treated with suitable medication (such as viral diseases), the occurrence of new diseases (such as SARS or bird flu), the knowledge about the side effects of commercially available drugs [15–17], or the increasing resistance against microorganisms (e.g., against antibiotics) [18, 19], a high demand for the development of new drugs exists today. In addition, the expiration of numerous patents and thus the synthesis of cost-efficient generics forces the development of new blockbusters for the pharmaceutical industry. Therefore, numerous new potential drugs have to be synthesized and tested; known drugs and drug candidates with side effects have to be modified; or completely new compounds (such as natural compounds) have to be discovered. The red life sciences are dedicated to the development of new drugs and therapeutic methods including modern developments in the fields of genomics and stem cell research.

Plant research (healing plants, nutritional plants, plants as raw materials, plants as energy suppliers), farming methods, cultivation, and resistance against vermin are typical topics of focus of the green life sciences. In addition, plant cells can be used for the production of industrial compounds or drugs [20]. Their use for the remediation of soils (phytoremediation) or as environmental sensors has also been reported.

The blue life sciences deal with the enormous potential of still undiscovered natural drugs from marine organisms. Extraction, isolation, testing, and identification of new compounds as well as the development of suitable synthesis concepts for industrial-scale production of these compounds are the focus of the current research. Especially, bacteria living in deep-sea regions under extreme conditions are seen as a potential source for biological substances, which can be used for technical processes. Usual enzymes denaturate at higher temperatures, whereas biocatalysts of deep-sea bacteria still work in extremely hot surroundings.

Gray life sciences (also called environmental life sciences) are dedicated to the processes for the preservation and regeneration of the environment. This includes all life science methods of drinking water purification, purification of wastewater, treatment of waste, and remediation of contaminated soil and air [21]. Methods of gray life sciences for environmental protection are mainly used at the end of the process chain (wastewater purification, bio filters, bio washers, etc.). Innovative approaches not only include the disposal of occurring environmental pollutions, but also focus on the avoidance of pollutants during the production process. Genetically modified enzymes can reduce energy and raw material consumption in the production of textiles, food, detergents, and drugs and reduce the occurrence of unwanted side products.

White life sciences (also called industrial life sciences) refer to the use of life science methods in industrial manufacturing processes. Industrial life science transfers biological and biochemical knowledge and processes into technical applications. Bacteria such as *Escherichia coli* and *Corynebacterium glutamicum*, yeasts, and enzymes are used in these processes. The term industrial life sciences is quite young, but some methods have been used for over 1000 years by mankind. Many cultures used yeasts for alcoholic fermentation, lactobacillus strains for malic acid fermentation, or acetobacter species for acetic acid production. Due to the advances in the development of life science methods and applications, the field of industrial life sciences gained high importance in the last years. Further potential is expected based on the optimization of production processes (e.g., basic and fine chemicals), the reduction of raw material dependency (e.g., through the use of renewable resources), the reduction of energy and disposal costs (e.g., by the substitution of chemical processes), and the development of new products and system solutions with high value-added potential (e.g., utilization of biological metabolic pathways using genetic methods) [22].

The yellow life sciences (also called food life sciences) are used in food industry, for example, for the production of beer using yeasts or yoghurt and sauerkraut using lactic acid bacteria.

Life science engineering is a scientific field at the interface of engineering and life sciences. It deals with the technical use and engineering realization of knowledge from the life sciences. The understanding of the functional mechanisms of living organisms is of great importance to ensure the application of this knowledge in modern technology. On the other hand, engineering knowledge is required to integrate biological systems into technical processes. A typical example is the production of pharmaceutical compounds in sufficient quantity and quality. A life science engineer can thus be considered an engineer who understands the scientific aspects and coherences in the life sciences and can integrate this knowledge into technical solutions. Aspects of sustainability as well as the use of suitable software (bioinformatics, simulation) are necessary.

1.2 Automation – A Definition

Automation is the transfer of tasks to automatic machines, usually realized by technological progress. Automation is a multidisciplinary field of technology and an engineering science containing all methods for automating machines and facilities to work independently without the involvement of humans.

The term automation can be traced back to ancient times. In ancient Greece, people admired the goddess αυτοματια [automatia] – "who manages things according to her own will" – and dedicated chapels to her [23]. Aristotle formulated in his work “Politics,” that self-working machines performing proper tasks would lead to a situation, where no assistance for the supervisor or a slave for the master would be required [24–27].

The definition of automation has changed during the ages depending on the actual state of the art of technology. Lothar Litz mentions a very early definition of the word automat in Meyers Neuem Konversationslexikon in 1862, which still has validity. In this definition, an automat is any self-moving mechanical tool, which for a certain time can be operated without interaction from the outside by hidden forces inside the machine; sensu stricto any mechanical art, which due to an inner mechanism can simulate the activity of living organisms, humans, or animals, and which form is analog to them [28]. About 100 years later Kienitz and Kaiser defined automation as a high degree of the substitution of human work by machines including control, decision, and adaptation functions [29]. The current industrial standard DIN IEC 60050-351, in contrast to previous versions, does not include a direct definition of automation, but is limited to the terms automatic and automat [30]. An actual definition of automation was given by Lothar Litz in 2013, whereby consciously a general form was used, to ensure the validity of the definition in the future: by automation, dynamic processes are captured over time and specifically modified, that they can independently execute predefined tasks and functions [28].

According to DIN IEC 60050-351, a process is defined as the unison of different interacting events in a system, which enables the conversion, transportation or saving of matter, energy or information [30]. Applied to technical processes, automation in this area is called process automation [31].

1.3 History of Automation

1.3.1 Automation from the Beginnings to the Nineteenth Century

The history of automatic machines originates in ancient Greece. Besides numerous myths and legends, the first historical evidences for automats can be found. The developers of such automats tried to investigate physics and copy nature using technical tools. A number of artificial birds, moving and speaking statues, and artificial servants and attendants can be found in Greek mythology. The aspect of usefulness was not the priority; the first useful automatic machines have been reported for waterworks and military applications. Homer reported in his “Ilias,” that Hephaistos, the god of craft, developed self-driving vehicles and artificially intelligent handmaidens that could learn different crafts. Many reports of historians from ancient Greece and ancient Rome with detailed explanations about self-driving mechanisms and androids are known. Similar reports are also known from other early cultures, especially from China. The main problem of all reports is that it is difficult to distinguish between myth and reality.

The first real automatic devices are known from the era of the Alexandrian school [32]. Excellent natural philosophers such as Heron of Alexandria (died later than 62 after Christ), Pythagoras (570–495 before Christ), Euklid (approximately third century before Christ), and Archimedes (287–212 before Christ)[1] were researching and teaching in Alexandria. The Alexandrian developers combined simple tools such as screws, wedges, and levers for the execution of complicated movements and used water, vacuum, or air pressure as driving forces for the designed machines. In his work Automata, Heron von Alexandria described self-opening temple doors. He also developed music machines and automated theaters with remarkable effects. Different researchers in this era proposed numerous designs of artificial birds that could move their wings and chirp, or automated machines that alternatingly delivered wine and water. An automat was developed that provided a defined amount of holy water after insertion of a specific amount of money. The researchers of the Alexandrian school developed many "programmed simulators and automates as well as tools for a feedback," which are still in use today such as the water flushing in toilets [33].

A vast amount of antique literature was lost in Central Europe with the collapse of the Roman empire, but could be preserved in the Arabian world [33]. In the ninth century, the Khalif of Bagdad Abdallah-al-Manun instructed the sons of his astrologer to systematically search all scientific literature. They translated the work of Heron and revised it. The work of Kitab al-Haiyal "Book of artful tools" can be affiliated with the Alexandrian school and became a standard book during this time. The aspect of practical applications was very important for the authors: one of them was manufacturing clocks. Most of these historical devices have been destroyed by the Mongolians in their attack on the Arabian domain in 1258.

Scholars in monasteries in Central Europe started the investigation of old antique literature and the Arabian revisions and advancements at the end of the middle age. A legend reports that Albertus Magnus (1193–1280) designed a speaking statue, which was destroyed by his student Thomas von Aquin (1225–1274) [33, 34]. The scholars during the second half of the thirteenth century relied on the doctrine of soul according to the work "De anima" by Aristotle (384–322 before Christ) [35]. The existence of a soul is the requirement for self-movement; thus, a statue should be given a soul to make it move. For Thomas von Aquin this was only possible with magic, he named people who were able to "make statues speak and move" as necromantici (supporters of black magic) [36].

During this period, the first pure mechanical clocks were developed (complex clocks so far were driven by water) and the craftsmen started to combine the measuring of time with moving figures and chiming mechanisms (early fourteenth century). One example is the clock of the Straßburger Münster with its mechanical cock (around 1350), which was able to move the wings and crow at noon. Following the tradition of the Alexandrian school, complete scenes with religious and secular backgrounds were designed, now driven by mechanical watches. In addition to the mainly humanoid automats, music automats in the form of self-playing instruments were developed. The oldest mechanical instruments that are still preserved are the glockenspiel in monumental clocks from the late middle ages. During the renaissance, craftsmen in Augsburg

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[1] Archimedes lived in Syrakus, which belonged to the Alexandrian cultural environment.

developed precious music automats and self-playing spinets that were controlled using pinned barrels.

The renaissance was an important era for the history of technology as well, which is called as the "technology revolution of the renaissance" [33]. The Alexandrian school mainly developed models, whereas the technological progress during the renaissance enabled the construction of life-size automatic devices. Engineers such as Leonardo da Vinci (1452–1519) studied books about mechanics and designed many new machines. Around 1550, they started to write technical literature. In the 1950s, a draft of a robot from Leonardo da Vinci was found [37, 38]. This robot could move its arms, stand up, and move the head. The French engineer Salomon de Caus (1576–1626) was the author of a comprehensive work "Les raisons des forces mouvantes" (about moving forces. Description of some artificial and enjoyable devices). He described many automats from Heron and revised them. He constructed the Hortus Palatinus (Pfälzischer Garten) in Heidelberg and later a series of moving figures driven by water mills and cam rollers in the palace of the duke of Burgund in Saint-Germain near Paris. Similar constructions were set up in 1613 in the Castle Hellbrunn; between 1748 and 1752 the facility was extended with at least 256 figures [39]. A hydraulic organ was used to eliminate the noise from the driving mechanism. De Caus can be acknowledged as a pioneer in the construction of life-size automats. At many courts engineers were employed to develop androids and other automats "which worked rough-and-ready" [33]. Another development was the construction of automated toys as in ancient times. One of the founders of this technology field was Juanelo Turriana (1500–1585), who worked as an engineer for Karl V and revolutionized the water supply of Toledo. His reputation was so great, that it is reported that he designed an android, which could go shopping for him [33].

During the seventeenth and eighteenth century, the natural sciences turned toward engineering. Engineering was understood as applied natural sciences. Different engineering schools, such as the École polytechnique, were founded in France.

In Germany, some goldsmiths and precision engineers, who were leading in the field of automat construction, were located in Nuremberg and Augsburg. Around 1585, Hans Schlottheim (1545–1625) constructed the most important ship for Karl V. The ship had wheels and was moving on a wriggling track. An organ and different other instruments were playing and cannons crumped periodically. In addition, "people" were performing different tasks on board the ship such as hoisting the sails and making an inspection round. The imperator himself was sitting on a baldachin throne and moving his head [40]. Investigating the control mechanisms of this time shows that highly developed technologies were used, which "since that time have been rediscovered several times independently from one another" [33].

Automatic devices were widely known in the seventeenth century and gained high interest under the philosophers of the burgeoning enlightenment. Cartesianism [41] was characterized by the great advances of scientific and rational dealing with reality. The mechanism postulated parallels between the laws of mechanics and machines and natural bodies. Rene Descartes (1596–1650) [42] explained in his work "Discours de la method" (1637) the difference between humans and animals [43]. Both are God created, but only the human has an immortal soul. Animals can be seen as very complicated machines (la bête machine), as automats. He was convinced that humans would be able to construct an animal-like machine in the future, which would also behave like an animal. He compared the heart with a hydraulic pump and described other organs such as tendons and muscles analogously to automated tools that were available in this period. The German Jesuit Athanasius Kircher (1602–1680) realized the ideas of Descartes and constructed a speaking head, singing birds, and figures playing instruments. He followed the tradition of Salomon de Caus (1576–1626) and developed automated theaters for gardens [33].

Public interest in automats was very high during the eighteenth century, especially since different cases of fraud were uncovered. In the seventeenth and eighteenth century, many reports were published about autonomous driving vehicles and other automats; however, a majority of these were unmasked as fakes. The technological development was far behind the wishes and expectations of the people at this time.

A highlight in the development of real automatic devices was the achievement in the constructions of Jaques de Vaucanson (1709–1782). He studied anatomy since he wanted to design three-dimensional anatomic models (anatomis mouvante – moving anatomy). This would have led to a realization of the philosophical basics from Rene Descartes. He designed a life-size flute-playing shepherd. This was not a realistic anatomic model, but an automat driven by clockwork and bellows. Nevertheless, this automat was highly acknowledged. Vaucanson continued following the idea of a moving anatomy with the development of a mechanical duck, which was able to waddle, and could also eat, digest, and excrete [44]. Vaucanson was also a highly valued member of the Académie des Sciences. Later, Vaucanson stopped building automatic devices and, in 1741, became the director of the state silk mill factory. With his further inventions and constructions, he provided many suggestions for its mechanization and automation. He thus initiated the change from pure invention due to scientific technological interest to the introduction of automation devices into industry. "For thousands of years, the construction of automats was more an enjoyable then a useful dissipation. Thanks to the contributions of Vaucanson, it was possible to overcome this level and use automats in industry. Only now the ideas of the Alexandrian school could mature so that an automatically controlled system could become reality" [33]. Vaucanson developed a mechanical weaving loom for patterned fabrics, which control used the same principle as his flute player; however, the system was not used. In 1804, Jacquard revised this weaving loom and invented his weaving automat. Vaucanson can also be seen as the father of modern fabric. In 1756, he built a silk mill near Lyon and designed every detail of the building and the driving. This can be considered as the first industrial facility in a modern sense. He recognized that manufacturing has to be done in a facility, where devices are driven by one central force. Although his inventions are in great contrast to the simple constructions of cotton spinning machines of the Englishman, Vaucanson's inventions, just like many other ideas, could not gain access to the market in the catholic Ancient Régime (France) in the middle of the eighteenth century [45].

The industrialization started then in England, where complete different sociological conditions existed. Cotton was used instead of silk, which enabled a mass sale. In addition, the promoters of industrialization were mainly social climbers instead of aristocrats or established citizens. They built their factories in relatively new cities that were not bound by old guild regulations [45].

After Vaucanson, many, and sometimes very complex, androids performing real tasks have been reported. The automats from father and son Jaquet–Droz (1721–1790) are the most well known. Along with a mechanical engineer Jean-Frederic Leschot (1746–1824), they developed the three nicest automats that can be seen today in the museum in Neuchatel (Switzerland). The "writer" is a small human-like automat with moving head and eyes. It is able to write a text with up to 40 letters. The text is coded on a wheel and the letters will be written one by one. The writer can write in different lines and considers blanks. This machine can be considered as a precursor of a computer, since the machine has a program and a memory and can be programmed with different texts.

At the end of the eighteenth, and the beginning of the nineteenth century, many automats were developed. One of the master constructors was Johann Nepomuk Mälzel (1772–1838), who constructed numerous music automats including the highly applauded trumpet player, which played in Vienna [46, 47]. Famous composers such as Jan Ladislav Dusík and Ignaz Pleyel composed concert pieces for this trumpeter. The organ clock was invented in the eighteenth century, for which Haydn, Mozart, and Beethoven composed original compositions. The introduction of pneumatics enabled the development of self-playing pianos with a satisfying dynamical gradation.

Additional masters of automats were Johann Gottfried Kaufmann (1751–1818) and his son Johann Friedrich Kaufmann (1785–1866), who developed a trumpet player in Leipzig and revised Mälzels development. In Paris, organ developer Beaudon developed in 1810 a mechanical elephant, which was made of 4800 parts and could eat and drink [48].

Preserving the spirit of the ancient times as well as the knowledge transfer from the Arabian era, especially in mathematics, enabled new academic progress in physics during the renaissance. In 1745, the English blacksmith Edmund Lee developed an early automation device for a self-dependent movement of wind mills [49]. According to records from the ancient times, there were already machines during this time, which were able to actuate a windmill. They thus executed work, which was previously done by humans or animals. In the middle ages, windmills were constructed with a vertical axis. The windmills were moved in the direction of the wind to enable continuous working. With the invention of Lee, who integrated an additional windmill with a gear, the machine was able to react autonomously to changes in its environment as required to fulfill its tasks.

With the advances in the field of mechanics and the new drive technologies such as the steam engine, the age of industrialization started. Mass fabrication in factories became possible. Animal and human power could be substituted by motors. In 1785, Edmund Cartwright (1743–1823) patented a mechanical weaving machine, which was still hand driven. Only one year later in 1786, he introduced a revised version of the machine, which used a new mechanical drive for the moving parts of the weaving machine [50].

These were the first automated machines for industrial production. Although Cartwright was not successful with his weaving mill, his inventions gained acceptance and had extensive social impact. The automated weaving machines destroyed many work places. In 1811 in England, weavers started to revolt against the machines. The machine breakers destroyed the machines and attacked the supporters. The revolts were finished with the help of the military; the participants were executed or banished. Similarly motivated revolts also occurred in Switzerland, whereas the revolts in Germany known as weavers' uprising were focused against foreign workers and suppliers.

The beginning of the industrial revolution is connected with the invention of steam engines. James Watt (1736–1819) did not invent the steam engine, but brought numerous technological advances to it in 1788, including the use of a centrifugal governor to ensure a constant number of revolutions [51]. With the operation of the weaving machines using steam, the industrial revolution started. Tasks and functions, which had been executed before by humans, could now be realized with machines. Similar processes could thus be standardized and the productivity was significantly increased. This general endeavor to execute rigid and repeating procedures by machines has been transferred to many other technical fields.

A great number of automat developers in the first half of the nineteenth century were magicians or engineers inspired by illusions. Jean Eugène Robert-Houdin (1805–1871), the father of modern magic, constructed numerous real automats, which he showed in a special theater. In addition, he also developed trick automats that were controlled by wire rope hoists or pedal systems driven by humans inside the objects [52]. The French magician Stèvenard was the most talented precision engineer of this time, since he developed very small but complex automats, which he introduced to the public in 1850 in Paris. The described automats were single devices and thus quite expensive. A small automat-producing industry developed in Paris in the nineteenth century. Families such as Vichy, Lambert, Decamps, and Roullet produced the automats in limited editions [40]. This development was stopped at the beginning of World War I. Many small automats were produced in Germany, such as singing birds, which have been produced up to the 1970s in Black Forest.

1.3.2 Automation Since the Nineteenth Century

The discovery of electricity and the developments in electrical engineering (nineteenth century) enabled the decentralization of production. It became possible to send energy over long distances. First attempts had been made to utilize electricity for tasks such as measuring, regulating, and controlling.

In 1833, Samuel Morse (1791–1872) constructed the first workable electromagnetic telegraph. The signals were coded and were serially transmitted. This led to the development of the telex machine and standardized serial interfaces. These were the basis for our current bus systems [53]. The development of the relay by Joseph Henry (1797–1878) in 1835 was another milestone in the development of modern automation technology [54, 55].

In 1939, Hermann Schmidt (1894–1968) founded in Berlin a Section for Control within the Society of German Engineers (VDI). He defined the term general control technology, which includes technical and biological systems and thus conforms to the definition of cybernetics by Norbert Wiener (1894–1964) [56]. The scientific field includes, for example, the feedback mechanisms on technical and biological systems.

Computer technology started a technological development, which led to an increase in the degree of automation in the production with industrial robots, complete automated production lines, and technologies such as pattern recognition in artificial intelligence. The Z3 calculator, which Konrad Zuse (1910–1995) introduced in 1941 was the first workable digital calculator working with binary floating-point numbers [57]. According to our current linguistic usage, this was the first computer. The century of the digital revolution started.

In 1948, William B. Shockley (1910–1989) introduced the term transistor for already developed semiconductor devices [58]. The development of the microprocessor followed in 1970/1971. Innovations in the field of electronics, especially the development of transistors, led to a radical decrease in the size of electrical circuitries. With the decreased dimensions, the effort for switching algebra applications was reduced as well. The development of integrated circuitries enabled the equipment of devices with logic circuits without great efforts. Digital technology became the main driver of automation. Innovative field devices such as sensors and actuators communicate with the control and guarantee a constant quality of the products, even in the case of process variations.

In 1953, John W. Backus (1924–2007) proposed the advanced programming language Fortran (formula translator) [59]. The production of the first numerical control with tubes can be dated back to 1954. In 1958 followed the market introduction of the first electronic control SIMATIC. The invention of the first solid-state sequential logic solver by Richard E. Morley in 1969 was the basis for the further development of the programmable logic controller. Odo J. Struger (1931–1998) significantly contributed to the formulation of the necessary institute standards in the United States. The PLC control replaced pneumatic and relay-based control systems.

A further important step in the automation of industrial processes was the establishment of the Universal Product Coding (UPC) and the introduction of the barcode in the United States in 1970. The EAN code (European Article Number) followed in 1977. These identification methods built the basis for automated logistics. Currently, the barcode technology, which reads the barcodes with optoelectronics, is increasingly substituted by RFID technologies (radio frequency identification).

In 1981, IBM introduced the first personal computers, which could be used in offices and schools. Before this time, several MS-DOS based computers have been on the market. As smaller computers became more powerful, they could be linked together, or networked, to share memory space, software, and information, and communicate with each other. The first satellite-based global positioning system (GPS) was established in 1995. Besides the development of navigational systems, this led to the possibility of automated guidance of agricultural engines.

One of the most important people influencing the modern industrial automation was Henry Ford (1863–1947). His concept of a modern manufacturing of vehicles revolutionized not only the industrial production (basis for line production), but also had significant influence on modern art (Fordism) [60].

Today's automation technology is based on a variety of knowledge. Realizations have entered industry as well as our everyday life, and are taken for granted. Today, design, implementation, and commissioning are mainly method oriented and dedicated to specific processes. Automation is a solid part of our society. Communication technology and the underlying networking are used by everybody. Field bus systems such as profibus, interbus, real time Ethernet, and wireless communication systems are used for networking. Machine-oriented networking is in most cases part of the closed functional chain and has thus to fulfill real time requirements. The Internet of Things, where machines are communicating with each other and with their workpieces can be seen as the temporary highlight of automation.

1.3.3 History of Laboratory Automation

Laboratory automation is a special field of automation dealing with the automation of laboratory processes in chemical, biological, pharmaceutical, and food technologies as well as in medicine. It is a discipline combining the knowledge of laboratory science with process engineering. Reports of automated devices for scientific investigations have existed since 1875. These first automated devices were special solutions built by scientists for specific applications in their laboratories [61]. The first time automation was mentioned in the chemical literature of the United States, was an unattended device for washing filtrates [62]. In 1894, Edward Robinson Squibb (1819–1900) created an automatic zero burette [63]. An automated pipette for use in the Babcock milk test was described by Greiner [61, 64]. During the 1920s, different devices were developed for solvent extraction in botanical research. The first continuous liquid–liquid extractors with internal diffusers were reported by Palkin *et al.* [61, 65].

Besides laboratory use, automation also developed in the coal and power generation industry. The first device specifically manufactured as a piece of laboratory automation was a grinder for preparing coal samples [61]. At the beginning of the twentieth century, different systems were used for measuring carbon dioxide in flue gases in order to optimize combustion control. A continuous system has been sold as the Autolysator by Stache, Johoda, and Genzen since 1912 [61, 66]. The first system for measuring carbon monoxide was reported by Guy B. Taylor and Hugh S. Taylor, who used an automatic volumetric approach [67]. A conductivity-based measuring system was developed by Edelmann in 1921 [61]. Since the 1920s, a new era started in laboratory automation with the increasing development of electronics. The need for rapid gas analysis during the First World War led to the development of new principles such as the use of thermal conductivity as the basis of gas analyzers [68]. The next step in the development of laboratory devices was the introduction of pH electrodes; one of the main drivers was the sugar industry. Early tungsten–calomel electrodes showed only insufficient reliability and it thus took some time to install automated pH control in this industrial field [69].

In 1929, Partridge and Muller of the Department of Chemistry at New York University introduced their first automated titrator. A photocell was used to detect the color change in the titration process; signal amplification was realized with a radio tube [61]. A more sophisticated titrator was built for acid-based titrations at Eastman Kodak in Rochester. It included a set of valves that enabled emptying of the previous sample from the titration vessel [70].

In 1942, Bassett Ferguson introduced a semi-automated still for petroleum analysis. This development is a typical example of the type of automation for conserving manpower [71]. An example of devices specifically designed for alleviating skilled labor shortages is the mercaptan automatic titrator. The potentiometric titration procedure was developed by Shell Oil Company in 1941 [72] and automated in 1943 [73].

Different companies started to provide automated equipment after the Second World War since the use of automatic control devices had become routine in chemical laboratories.

A new type of titrator was designed in 1948, which used a motor-controlled syringe instead of a dripping burette for adding the titrant. A recording potentiometer was used for plotting the titration curve [74]. The automated Karl Fischer titration was announced in 1952. A polarization end-point was used, where an increase in the current between two platinum electrodes corresponded to a depolarization of the electrodes found at the end point of the titration [75]. Another important step was the introduction of the coulometric Karl Fischer titration in combination with a regeneration of the Karl Fischer reagent from the iodine present in a solution of depleted reagent [76]. Due to an increasing use of automation technologies, a new journal devoted to automation and instrumentation started in 1952, the Instrument Engineer.

The first computer used in connection with laboratory automation was an analog computer that, for the first time, allowed chemical researchers to create electronic simulations of their processes [61]. The first use of a digital computer was reported in 1952, when the Atlantic Refining Company introduced a mass spectrometer and a digital computer for the determination of hydrocarbon mixtures [77]. The development of the transistor also revolutionized laboratory automation since it offered the possibility of collecting thousands of data points.

The development of laboratory automation was heavily influenced by medical applications. The first truly automated systems appeared in medical laboratories in the mid-1950s. In 1956, a blood analyzer for the determination of urea, sugar, and calcium was introduced (AutoAnalyzer, manufactured by Technicon) [78]. Later designs offered the possibility of simultaneous determination of over 20 analytes with 150 samples per hour. Many other batch analyzers had been developed, which could test up to 100 samples in continuous mode. The introduction of the photodiode array for spectrometers with grating monochromators in the early 1980s allowed the simultaneous detection of multiple analytes using various wavelengths [79]. A different approach to clinical automation appeared in 1959 with the production of the Robot Chemist (Research Specialty Company) [80].

The Robot Chemist automated all manual steps performed by lab technicians using conventional cuvettes and automatic pipetting and mixing but was too complex to be practical [81]. The introduction of robotics and informatics to clinical laboratory automation in the 1970s led to the development of total laboratory automation (TLA) [82]. In the early 1980s, Masahide Sasaki opened the first fully automated laboratory [83–85]. Driven by the requirement of increasing the laboratory services without increasing the costs, he and his team assembled robotic manipulators, conveyor systems, and a software system into a complete automation system first installed in 1982 [86]. Many other researchers were inspired by the work of Masahide Sasaki and developed laboratory automation systems for different applications. These automation systems usually consisted of various automated work stations and a connecting conveyor belt based transport system. In the following years, more than 800 laboratories invested tremendous amounts of money in laboratory automation to reduce costs, speed up turnaround, and to develop high-quality sample handling in clinical laboratories [87].

In 1993, Rod Markin designed the worldwide first clinical automated laboratory management system at the University of Nebraska Medical Center. In the mid-1990s, he was the chair of the Clinical Testing Automation Steering Committee of the American Association for Clinical Chemistry [88], which later became an area committee of the Clinical and Laboratory Standards Institute. In 2004, the National Institutes of Health (NIH) and more than 300 leading partners from science, industry, government, and the general public completed the NIH roadmap to increase medical discovery to improve health. Despite the success of Sasaki's laboratory, the high cost of automated clinical laboratories prevented the spreading of this technology [89]. Another limiting factor was the proprietary interfaces and protocols of different vendors, which did not allow for a communication of devices from different manufacturers. The recent development of scripting languages like AutoIt enabled the integration of equipment from different manufacturers [90].

Automation in the field of life sciences developed rapidly over the last 20–30 years. Main drivers besides medical applications were bioscreening and the development of high-throughput screening technologies (HTS) according to the requirements of the pharmaceutical industry. HTS means the use of highly developed and completely automated laboratories, which enable 24/7 operation. HTS also means the interdisciplinary collaboration of life sciences, natural sciences, and engineering sciences [91], whereby robotics, electronics, information technology, analytical chemistry, chemical synthesis, optics, imaging technologies, cell biology, molecular biology, and biochemistry play important roles [92]. The main goal of biotechnological HTS is the efficient utilization of new active compounds by testing high numbers of samples with special focus on time and cost reduction and increasing information content [91]. Using the example of the pharmaceutical company Pfitzer Global Research and Development, Pereira and Williams described the origin and development of HTS [93]. The early development stage can be dated back to 1984–1995. Between 1995 and 2000, conceptual use occurred for the investigation of drug metabolism and toxicity. This included three consecutive phases that are generally valid for the development of HTS processes. The first phase is concept development and planning followed by implementation. The second phase includes the technical development and practical realization. The final third phase includes the logical extension with the integration of additional specialist disciplines [93]. It can be seen that the target, which means the screening target compounds, developed over time. Around 1984, mainly natural compounds were the matter of interest for screenings and, until 1990, target molecules for therapeutic applications. Since then and up to now, ADME targets (absorption, distribution, metabolism, excretion, toxicology) are the focal point [93]. In other areas, an increasing demand for suitable high throughput automation solutions exists as well. This includes agricultural and environmental laboratories, quality control, and the academic sector [93–95].

The developments in the automation of life science processes have mainly been driven by the requirements of the pharmaceutical industry. Within the last 25 years, the number of samples to be screened increased significantly. Until the end of the 1980s, approximately 10 000 compounds have been tested per year and target. In the early 1990s, the sample throughput increased up to 10 000 samples per month and target and increased only 5 years later to 10 000 samples per week [96]. Today, high throughput screening is defined as the investigation of different thousand samples per day. An enhancement is the ultra-high throughput screening, which enables the processing of more than 100 000 samples per day [92, 97–100]. With the help of these high throughputs, huge compound libraries can be established within a short time. Today, the big pharmaceutical companies use compound libraries with synthetic compounds for the area of drug discovery (including lead discovery). The development of HTS was shown using the example of the continuous extension of the Bayer HTS library [101]. In 1996, Bayer decided to extend the low molecular drug development with a significant extension of the proprietary compound library. Today, more than 1.5 million single compounds are routinely tested in screening programs.

A further increase of the expansion rate of such company libraries is limited. Reasons include the logistic effort to allocate the compounds on microplates, the required storage, as well as the relocating of the compound samples in big compound storage places for subsequent medical studies [101].

1.4 Impact of Automation

1.4.1 Advantages and Disadvantages of Automation

Automation technology is an ancillary discipline for all parts of engineering sciences, including all methods for the automation of machines and facilities. While the original approach was to use automation for mass production, the focus today is on releasing humans from dangerous, exhausting, and routine tasks. Automation has many advantages including increased throughput or productivity, improved quality or increased predictability of quality, an improved robustness or consistency of processes or products, an increased consistency of the output, and reduced direct human labor costs and expenses. Improving the productivity, quality, or robustness can be achieved with different methods.

One main point is the installation of automation in operations to reduce the cycle time or in processes, where a high degree of accuracy is required. Another point is to replace human operators in tasks that involve monotonous or hard physical work [102] or those that have to be done in dangerous environments such as fire, underwater, volcanoes, nuclear facilities, or chemical facilities. In addition, tasks that are beyond human capabilities in terms of size, weight, speed, endurance, and so on, can be performed by automation systems. Automation can significantly reduce operation times and work handling.

Today, most factories in industrial countries manufacture their products with the help of machines. In principle, it is possible to automate the production of small batch series up to single devices. A higher automation degree in industry and other economic sectors results in increased productivity, simplification, and changes of work processes. Thus, rationalization is always a result of automation. Due to higher productivity in the manufacturing industry, other industrial fields had to follow the automation trend as well. This resulted in a significant increase in the economic output of these industrial fields and companies. For example, this can be seen in Germany or Japan, which increased their incomes due to automation in the twentieth century.

For a long time, automation was only used in industry to reduce the amount of monotonous work for humans. In the last years, automation also gained more influence on other fields. This includes, for example, the service industry, where electricity billing has been automated and online banking is possible. In addition, many other things became possible due to automation, such as safety technologies in automobile industry, including electronic stability control/electronic stability program (ESP) or airbags.

In this connection, the question of safety plays an important role as well. The observance of regulations is a basic requirement for the development of efficient and reliable working machines and facilities. Automation contributes significantly to this development.

Besides the positive effects of automating industrial processes, there are also some disadvantages. One of them is security threats because automated systems may have a limited level of intelligence. Therefore, they are more susceptible to errors since they are typically unable to apply the rules of simple logic to general problems. A second great disadvantage is the high initial cost, since the automation of a new product line or a plant usually requires a large initial investment. This applies also to unpredictable and excessive development costs. The research and development costs especially for complex processes can exceed the cost, which might be saved due to the automation itself.

1.4.2 Social Impact of Automation

A social result of the automation is often the loss of workplaces. Taylorism tried very successfully to establish a rational and efficient mode of production (assembly line production) and thus changed the work environment and the role of work. The efficiency of work was increasing constantly, but was repeatedly connected with physical and psychological burdens for the employees. Repetitious work led to exhaustion and alienation of the employees from their work. It also produced conflicts between employees and employers since the increase of productivity was not correlated to the wages. In the 1980s, automation was linked to the loss of workplaces. Many simple but also dangerous, monotonous or very precise and fast tasks can be realized with automation technology using machines. This can be much more productive compared to manual operations. Automation frees up workers to take on other roles and provides higher-level jobs in the development, deployment, maintenance, and running of the automated processes. The role of a human in the production process is changing from production to administration, planning, control, maintenance, and services. It also has to be mentioned that the high degree of automation contributed to the further existence of a high amount of industrial manufacturing in Germany: one good example is the automobile industry.

In 2013, a group of scientists calculated that computers would be able to take over every second job [103]. Frank Rieger (Chaos Computer Club) warned that increased automation will lead to a significant loss of classical workplaces (e.g., truck drivers due to self-driving cars). Rieger argues for a "socialization of the automation dividend," meaning a taxing of non-human work, so that economic growth also affects general prosperity and its fair distribution [104].

1.4.3 Limitation of Automation

Automation has many advantages, but also limitations. The currently available technology is unable to automate all the desired tasks.

One main limiting factor for the practical realization is the economic effectivity. The automation of complex processes is very expensive; thus, it is often more economical to purchase expensive robots for simple often-used steps in the production process. In principle, the use of robots is possible for all complex processes; however, operation and programming of these robots is very costly. Thus, only companies producing high quantities can afford such automation facilities. For many small companies, the use of human labor is more reasonable. Partial automation in combination with human labor is more profitable for these companies. Another limitation is the assembly of fragile, very delicate, and complex technology. Highly complex machines are required to automate these production steps. These often cost more compared to the economic savings due to the decreased number of employees.

In addition, machines currently do not have creativity or the possibility for flexibility, since they can only execute preprogrammed process steps. If a product requires this creativity, such as in the case of single pieces, the machine is reaching its limitations. Many operations using automation bind large amounts of invested capital and produce high product volumes. This makes malfunctions extremely costly and potentially hazardous. Therefore, trained personnel are required to ensure that the entire system functions properly and that safety and product quality are maintained.

Sometimes, all optimizations that could result from automation are limited. This can be the case if manual tasks are more economic compared to the complex automation solution or if human creativity has priority.

Activities where humans still have advantages compared to machines include, in general, higher qualification than automated tasks. At the same time, humans must obtain this qualification using simulators, as production lines and facilities should not be interrupted and learning by doing is not possible or connected with high risks (e.g., flight simulator).

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