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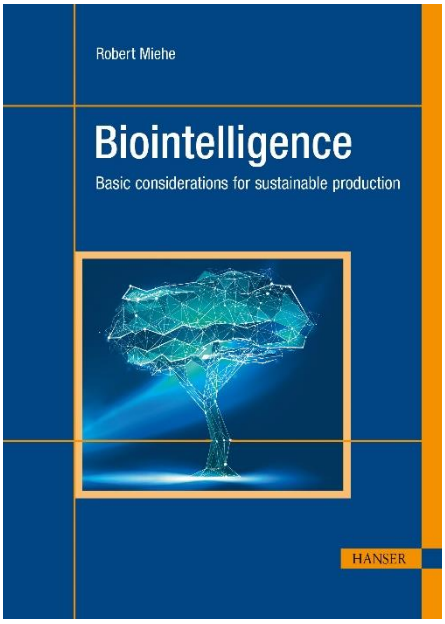

Sample Pages

Biointelligence

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Abstract

Sustainable production must remain within planetary boundaries, while being highly resilient and adaptable. Since socio-economic patterns of thought and production technologies prevailing today cannot achieve this, a reorientation in science and practice is necessary in the sense of Schumpeter's creative destruction. In this context, the concept of biointelligence has recently emerged in the scientific community. However, a comprehensive implementation is currently facing several challenges, among which are primarily the dissent about the definition of the term and its theoretical position in science. As a result, currently neither a congruent method of scientific knowledge retrieval exists nor a collection of methodological foundations for the development and management of biointelligent systems. The author thus presents basic considerations for a reorientation of the production sciences from a sustainability-oriented technology management perspective by adopting the concept of biointelligence, summarizing currently prevailing scientific trends, translating them into a coherent theory and examining them for congruence with current models and approaches. In doing so, the author sketches the picture of a normative, holistic scientific discipline that incorporates elements from engineering, information and life sciences and combines them for the purpose of sustainable production. The theories and methods developed and/or modified by the author on this basis are not to be understood as an ultimate solution to a societal challenge, but primarily serve to stimulate scientific discourse and the education of young scientists in the increasingly important field of biointelligence. Hence, the work is structured in form of a university textbook aiming to raise awareness among students and young researchers, particularly in production-oriented scientific fields, who have little experience in the scientific fields of life sciences and sustainability. Likewise, the publication is suitable for people who are committed to a reorientation of classical ways of thinking in industrial production.

Abbreviations

AAS	Asset Administration Shell
ADF	Abiotic Depletion Factor
AEL	Alkaline Electrolysis
AFC	Alkaline Fuel Cell
AFD	Allotrope Data Format
AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
AM	Additive Manufacturing
AP	Acidification Potential
BDA	Big Data Analytics
BDC	Biointelligent Design Cube
BFC	Biological Fuel Cell
BII	Biointelligence index
BIOTRAIN	Preliminary survey on the biological transformation of industrial value creation in Germany (German: Voruntersuchung zur biologischen Transformation der industriellen Wertschöpfung)
BIS	Biointelligent System
BM	Business Model
BT	Biological Transformation (of Technology)
BTI	Biology Technology Interface

C	Carbon
CAD	Computer Aided Design
CBM	Condition Based Monitoring
CC	Cloud Computing
CED	Cumulative Energy Demand
CML	Centrum voor Milieukunde at the University of Leiden
CNN	Convolutional Neural Network
CPS	Cyber-physical Systems
CRISPR/Cas9	Clustered Regularly Interspaced Short Palindromic Repeats/Cas9 system
CRM	Customer Relationship Management
CS	Cognitive System
DFB	Design for Biointelligence
DFD	Design for Disassembly
DFE	Design for Environment
DFR	Design for Recycling
DFS	Design for Sustainability
DL	Deep Learning
DM	Digital Model
DMFC	Direct Methanol Fuel Cell
DNA	Deoxyribonucleic Acid
DOE	Design of Experiments
DS	Digital Shadow
DSB	Double-strand Breaks
DSS	Decision Support System
DT	Digital Twin
E-FMEA	Environmental Failure Mode and Effect Analysis
ECA	Ecological Classification Factor for Aquatic Ecosystems
ECT	Ecological Classification Factor for Terrestrial Ecosystems
EFC	Enzymatic Fuel Cell

ELM	Eco Lean Management
EL-SCP	Eco Lean Sustainability Control Panel
EM	Environmental Management
EMS	Environmental Management System
ERP	Enterprise Resource Planning
FEM	Finite Element Method
FDM	Fused Deposition Modeling
FET	Field Effect Transistor
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
GE	Genome Editors
GBR	Green Biorefinery
gRNA	Guide RNA
GWP	Global Warming Potential
H	Hydrogen
H-FMEA	Human Failure Mode and Effect Analysis
HC	Human Toxicological Classification Factor
HDR	Homology-directed Repair
HHI	Herfindahl-Hirschman Index
1HPLC	High-performance Liquid Chromatography
HR	Homologous Recombination
HTEL	High Temperature Electrolysis
IPCC	Intergovernmental Panel on Climate Change
I4.0	Industry 4.0
ICT	Information and Communication Technology
IoE	Internet of Everything
IoMS	Internet of Manufacturing Services
IoP	Internet of People
IoS	Internet of Service

IoT	Internet of Things
ISM	In-situ Microscopy
JIT	Just-in-Time
JIS	Just-in-Sequence
JSON	JavaScript Object Notation
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCD	Life Cycle Design
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LDW	Laser-based Direct Writing
LFBR	Lignocellulose Feedstock Biorefineries
LIFT	Laser-induced Forward Transfer
LM	Lean Management
MAPLE DW	Matrix-assisted Pulsed Laser Evaporation Direct Writing
MES	Method of Ecological Scarcity
MCFC	Molten Carbonate Fuel Cell
MFC	Microbial Fuel Cell
MIPS	Material Intensity per Service Unit
MIR	Mid-infrared
ML	Machine Learning
mRNA	Messenger RNA
MVDA	Multivariate Data Analysis
N	Nitrogen
NHEJ	Non-homologous End Connection
NIR	Near Infrared
NN	Neural Network
NP	Nutrification Potential

O	Oxygen
ODP	Stratospheric Ozone Depletion Potential
OECD	Organisation for Economic Co-operation and Development
OPC UA	Open Platform Communications United Architecture
PAFC	Phosphoric Acid Fuel Cell
PAT	Process Analytical Technology
PCB	Polychlorinated Biphenyl
PDCA	Plan-Do-Check-Act
PEMEL	Polymer Electrolyte Membrane Electrolysis
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PHM	Prognosis and Health System
POCP	Photochemical Ozone Creation Potential
QbD	Quality by Design
QFD	Quality Function Deployment
R&D&I	Research, Development and Innovation
RAMI4.0	Reference Architecture Model Industry 4.0
RCIM	Resource-constrained Innovation Method
RCS	Resilient Control System
RDF	Resource Description Framework
REPA	Resource Environmental Profile Analysis
RGB	Red, Green and Blue
RNA	Ribonucleic Acid
SBMD	Smart Biomanufacturing Devices
SC	Special Characteristics
SCNT	Somatic Cell Nuclear Transfer
SD	System Dynamics
SLCA	Social Life Cycle Assessment
SMCA	Substance and Material Criticality Assessment
SME	Small and Medium-sized Enterprise

SMRA	Substance and Material Risk Assessment
SOFC	Solid Oxide Fuel Cell
SOP	Start of Production
ssODN	Single-stranded Oligonucleotide
STIA	System-theoretical Interdependency Analysis
TALEN	Transcription Activator-like Endonucleases
TCO	Total Costs of Ownership
TIMWOOD	Transport, Inventory, Motion, Waiting, Over-engineering, Over-processing, Defects (classic seven types of lean waste)
TPBR	Two Platform Biorefinery
TPS	Toyota Production System
TRIZ	Theory of Inventive Problem Solving
tRNA	Transfer RNA
TVT	Threshold Value Transmission
UML	Unified Modeling Language
VSM	Viable System Model
WCBR	Whole Crop Biorefinery
WGI	Worldwide Governance Indicator
XML	Extensible Markup Language
ZFN	Zinc Finger Nucleases
ZVEI	German Electrical and Electronic Manufacturers’ Association
3D	Three-dimensional
4D	Four-dimensional

Contents

1 Preface

1.1 Introduction

The manufacturing industry accounts for about one quarter of the German gross domestic product (Statistisches Bundesamt, 2019b). Yet, this indicator fails to adequately reflect the economic importance of industry for the German economy. In fact, the current economic conditions of the country represent historically grown interrelationships around an industrial core. Accordingly, a large part of gross value added in the service sector is still based on industry-related services. Whereas economists long assumed a 'natural' evolution of national economies, from rural to industrial to service-dominated economies, a robust industry is now regarded as essential for the resilience of the economy (Statistisches Bundesamt, 2019b). Reasons for this are complex. However, two arguments can be listed as essential. First, manufactured goods account for over 80% of the country's exports (Bundesministerium für Wirtschaft und Energie, 2018). Industry thus decisively contributes to the fact that Germany has had a positive current account balance for decades. Apart from China, Germany is the largest exporter of goods (Bundesministerium für Wirtschaft und Energie, 2018). Second, the industry is the driving force behind innovation in Germany, accounting for almost 70% of investment in research and development (Statistisches Bundesamt, 2019a). Albeit companies in Germany are facing a number of challenges that are difficult to predict in their dynamics (e. g., shortage of skilled workers, urbanization, individualization, growing competition from emerging markets) (Hoorens et al., 2013; European Commission, 2018), they have so far maintained an excellent reputation in terms of quality and reliability. However, the Covid crisis recently revealed the fragility of the current economic model by particularly impacting global supply chains. The resulting process of rethinking industrial practices promotes the vision of a resilient and adaptable production.

Although industrial production has undoubtedly contributed significantly to today's prosperity, particularly in the 'western world', its prevalent practice is responsible for immense environmental pollution and massive socio-technological consequences. Since the first industrial revolution, thoughtless economic practices resulted in various severe consequences to the ecosystem, including climate change, resource scarcity, human- and eco-toxicity, acidification, eutrophication, noise, radiation, loss of biodiversity, particulate matter, and chemical contamination (Rockström et al., 2009a, 2009b; Fava et al., 1994; Klöpffer and Grahl, 2014; Steffen et al., 2015). Global resource consumption has more than doubled in the last 30 years (United Nations Environment Programme, 2011). To date, human activities have already caused a global warming of about 1 °C above pre-industrial levels (Intergovernmental Panel on Climate Change, 2018). Yet, forecasts predict a further acceleration of causal effects (population growth and consumption). By 2050, the world population is expected to have increased to around 10.8 billion people (United Nations, 2015). By 2100, up to 16.6 billion people could inhabit the planet. Meanwhile, the proportion of global population actively involved in the consumption of goods grows. This consumer class includes people who have more than 10 euros per day (purchasing power parity) at disposal (Manyika et al., 2012). While this class accounted for around 13% of the global population in the 1950s, its share increased to 36% in 2010. For the year 2025, with an assumed world population of 7.9 billion people, a consumer class of 53% is expected (Manyika et al., 2012). Consequently, a further doubling of the global consumption of resources can be assumed by the year 2050. Likewise, anthropogenic CO_2 emissions will continue to rise considerably based on current political and economic efforts (International Energy Agency, 2019). If it continues to increase at the current rate, global warming is likely to reach the 1.5 °C limit commonly agreed upon in the Paris accords between 2030 and 2052 (European Environment Agency, 2017).

Albeit conventional economic practice was challenged as early as the 1970s and 1980s by the 'limits-to-growth' report (Meadows et al., 1972) and the sustainability concept (World Commission on Environment and Development, 1987), outlining a fundamental change, the expected effect has largely failed to materialize. Roughly half of the cumulative anthropogenic CO_2 emissions between 1750 and 2010 were emitted in the last 40 years, i. e. to a large extent in the period after the sustainability concept was published (Intergovernmental Panel on Climate Change, 2014b). Although a consensus exists today that sustainable production is only possible within planetary boundaries (Rockström et al., 2009a, 2009b; Steffen et al., 2015), a contemporary realization appears problematic. Traditional patterns of thought and behavior, which originate in early human history and early industrialization, are too deeply rooted in decision-making at all levels.

Since present production practices apparently fail to meet the needs of future generations in an equitable manner, innovative technologies are required in addition to adapting prevailing socio-economic patterns of thought (Bauernhansl et al., 2019;

Miehe et al., 2020a). In this context, several experts consider the biological transformation of technology (BT) to have great potential, causing fundamental changes in industrial production (Byrne et al., 2018; Patermann and Aguilar, 2018; Miehe et al., 2018). Recent successes in biotechnology (e. g., CRISPR/Cas, biocomputing, enzyme technology, bioreactors, biosensorics, and bioactors) and artificial intelligence (e. g., deep neural networks, adversarial learning techniques, deep reinforcement learning) offer great opportunities for innovation leaps. A continuation of this trend may result in self-reinforcing effects, which accelerate the generation of knowledge and application strategies for biological systems (e. g., advances in computing, bioinformatics, and artificial intelligence, advancing the analysis of omics[1] data and/or increasing possibilities of reprogramming DNA). According to Chui et al. (2020), with regard to biological systems, four essential fields of innovation emerge: [1] the mapping, measuring, and engineering of molecules, [2] the engineering of cells, tissues, and organs; [3] the interface between biology and machines, and [4] the use of cells or molecules such as DNA for computation.

With roughly 60% of global physical inputs to the economy that could be produced biologically and about 45% of the current global disease burden that could be addressed, the (direct and indirect) economic impact of biological innovations appears substantial (Chui et al., 2020). According to Miehe et al. (2018; 2020a), Bauernhansl et al. (2019), and Chui et al. (2020), fundamental human needs such as health, nutrition, energy, consumption, and housing are already beginning to be transformed by biological innovations. Prominent examples are CAR T-cell therapies, offering great potential for the treatment of liquid (short term) and solid tumors (medium term), as well as cultured meat, replacing entire value-added chains (Chui et al., 2020). The transformative potential of biotechnology also became apparent in the Covid crisis with the development of highly effective mRNA vaccines at a record pace. This example, however, also illustrates the current dilemma of these innovative approaches. Although the necessary knowledge for the development of vaccines has been gathered quickly, an equally efficient supply of the population was limited by the lack of local production capacities and expertise as well as the fact that existing regulations do not stimulate licensing models (i. e. 'the sale of blueprints'). Then again, biotechnological advancements are associated with potentially cascading and long-lasting effects on entire ecosystems or species. The most significant risks result from the creation of novel organisms by DNA engineering, to which current species and natural ecosystems are not adapted. Due to the interconnection of ecosystems, this may cause effects that cannot be foreseen today. In addition, access is becoming easier and cheaper, potentially enabling anyone to interfere with genetic material. Consequently,

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1 The term 'omics' refers to several scientific research streams in biology (e. g., genomics, epigenomics, transcriptomics, proteomics) that collectively characterize and quantify pools of biological molecules at different levels and processes of living systems.

extensive social reservations prevail. Apparently, humanity possesses more technologies than it is able to use in a commonly accepted manner. Yet, it is precisely this appropriate deployment that is decisive for the future viability of the socio-economic model. As prevailing socio-political conditions in form of existing individual, social, and political value systems largely determine technological development, a solution to a fundamental reorientation such as the sustainability issue can never be solved on a microeconomic basis only.

In this context, Miehe et al. (2018; 2020a) and Bauernhansl et al. (2019) present the concept of biointelligence, seeking to reinvent production by appropriately using the above sketched self-reinforcing moments of information and biotechnology. Based on developments in various scientific disciplines, a new form of application-oriented research is to be developed, which follows a normative, holistic maxim. This will be achieved by linking biological and technical systems via information and communication technology (ICT), enabling regional, small-scale, recyclable, resilient, demand-oriented, and highly automated production technologies and value-added chains, which in turn will allow the purposeful management of biological resources in the form of a technology-oriented demand economy. Crucial to the development of such approaches is a highly interdisciplinary research approach (Bauernhansl et al., 2019; Miehe et al., 2020a). Due to its recent emergence, the concept of biointelligence has not yet been sufficiently established in the scientific community, which hinders both its urgently required further academic advancement as well as a comprehensive dissemination and awareness of future decision-makers in higher education.

1.2 Objective and approach

The objective of this work is to establish the concept of biointelligence in science and practice. Rather than providing prefabricated solutions, this work presents basic theoretical considerations to stimulate scientific discourse and equip the reader with a specific mind-set. The here introduced normative framework of thought and design is intended to provide a systematic basis for a sustainability-oriented technology management with respect to recent findings in production science. The framework is supplemented by a review of essential approaches to developing and managing biointelligent systems (BIS). This work thus contributes to the structuring of an emerging field of research and promotes the necessary awareness of several generations of young scientists for a reorientation of science and practice in the context of sustainable production. The intention is not only to describe current trends in technology and economy, but to rigorously pursue a normative, holistic design logic.

The work represents a summary of selected research and teaching activities of the author. Its scientific approach follows the research process according to Ulrich and

Hill (1976), distinguishing between discovery, reasoning and application, whose respective requirements for insight generation are integrated into the chapter structure (Figure 1.1).

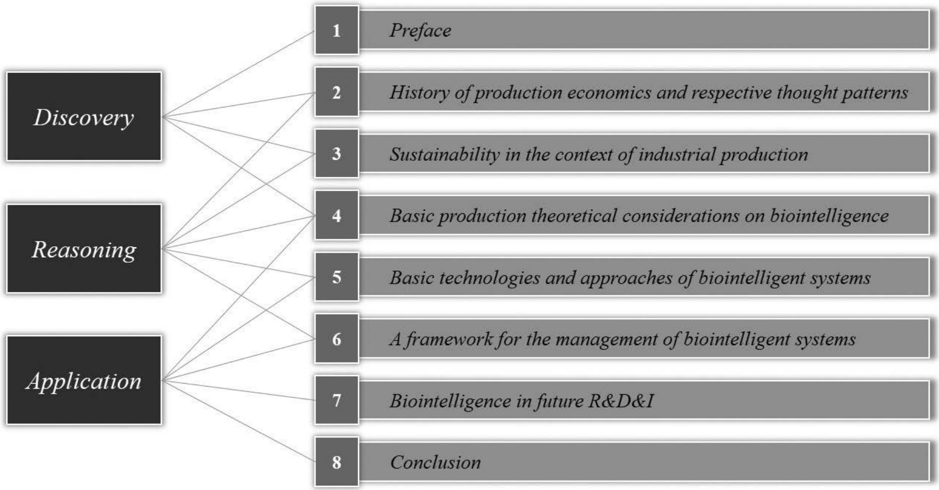

Figure 1.1 Chapter structure and research process according to Ulrich and Hill (1976)

The work is structured in form of a university textbook, which is intended to support the transfer of knowledge in academic teaching. The target group includes students and young researchers, particularly in production-oriented scientific fields (especially production engineers and managers), who have little experience in the scientific fields of life sciences and sustainability. Likewise, the publication is suitable for people who are committed to a reorientation of classical ways of thinking in industrial production. The document is structured as a coherent text. Each section closes with a conclusion, a bullet-point summary of the lessons learned, and a number of follow-up questions that facilitate the transition to the subsequent section. This will provide the reader with an understanding of essential interrelationships, challenges, basic technologies, and methods that will allow him or her to decisively support the necessary change to sustainable production.

After the introduction in Chapter 1, Chapter 2 provides a brief summary of currently dominant patterns of thought, which are commonly identified as the root cause of the sustainability problem. Based on the insight of a necessary fundamental reorientation, Chapter 3 introduces fundamentals of the concept of sustainability, discusses its implications for theory formation, and outlines existing models of future economies. Chapter 4 then presents basic production-theoretical considerations on biointelligence by summarizing the origin of the term, locating it in scientific theory, and reviewing the consistency of the current doctrine. On this basis, Chapter 5 outlines basic technologies and selected approaches for the development of BIS, while Chapter 6 summarizes basic thoughts on the management of BIS with regard to a holistic benefit criterion. Subsequently, Chapter 7 provides an overview of selected research and development issues, before the work concludes with a summary, a critical review and an outlook (Chapter 8).

2 History of production economics and respective thought patterns

In order to understand, classify, and change today's production methods and thought patterns, it is necessary to understand their origin. Thereby, it is not enough to consider the emergence of production technology or science exclusively. Rather, it is important to place it in its socio-cultural context and illustrate its impact on the environment. Hence, this section outlines the history of production on the basis of four essential characteristics: economic form, dominant economic theory, technological basis, and impact on the natural environment. The section, which is classified in a pre-industrial and industrial era, focusses on the major socio-economic upheavals in human history. The section does not claim to be complete in the sense of a historical scientific discourse, but rather serves the iterative understanding and awareness for the development of today's thought patterns in order to create the basis for a reorientation in the following section.

2.1 Pre-industrial era

Economic behavior is based on the cooperation of people in large groups. Crucial to this is the creation of so-called intersubjective realities, imaginary entities that only become reality because a large number of people believe in them (Harari, 2014). Examples of this are gods, states, companies, money and hierarchies. The mental abilities necessary to create these constructs developed comparatively late in human history and are closely linked to the creation of the first more complex tools and technologies (boats, needles, oil lamps, bows and arrows), the emergence of religions and trade, and the establishment of social classes. This epoch of human history is called the *cognitive revolution* and, as a process of intellectual and social transformation, is dated to a period of about 70,000 to 15,000 years ago. During this time, people lived in nomadic tribes (Spier, 1998; Harari, 2014; Parzinger, 2015). Their livelihood was based on hunting and gathering. Naturally, a consensus on an economic system of that time did not exist. Since the production of goods followed the current demand, the economic form can be described as an *early demand economy*. The technological basis consisted of a comparatively small number of tools, which almost everyone had to master equally in order to ensure daily survival. The only existing form of trade was barter (goods for goods) (Schenk, 1991; Rudolph, 2009). In contrast to the often expressed notion that people of this era lived 'in harmony with nature', extensive impacts on the ecosystem are documented. While the release of produced goods into the environment following their use without hesitation had no consequences due to the small number and complexity of the products, systematic hunting led to a substantial loss of biodiversity. The effective cutting of prey, the preservation of food and the development of thermal insulation from animal skins enabled the spread of humans across the entire globe, which in turn resulted in an extinction of about 50% of all land mammals over 50kg body weight by the time of the agricultural revolution. Compared to current standards, however, the total utilization of natural sources and sinks can be classified as marginal due to a small world population and the quantity and complexity of goods (Spier, 1998; Harari, 2014; Parzinger, 2015).

A first significant change in economic-social structures and lifestyles occurred shortly after the end of the last ice age about 15,000 years ago with the emergence of systematic production methods in agriculture (e. g., ploughing a field with the help of livestock). The groups, previously organized in nomadic communities, increasingly developed into a sedentary community characterized by agriculture and animal breeding. Animals and plants were no longer hunted or picked, but bred and harvested. This upheaval, which began about 11,500 years ago in eastern Turkey, is today called the *Neolithic revolution* (also agricultural revolution) (Harari, 2014). Similar to the cognitive revolution, the transformation was not a short-term global change, but a fundamental development over thousands of years, which continued to be affected by the parallel existence of nomadic tribes in different parts of the world (Spier, 1998). At the same time, it is regarded as a fact today that the Neolithic revolution did not have a single point of origin and spread from there, but started completely independently of each other in different parts of the world. Figure 2.1 illustrates the global development of the agricultural revolution according to Bellwood (2004) and Harari (2014).

For humanity, however, the change did not initially imply a comprehensive improvement in living conditions, since the transformation of the form of work, the restriction of nutrition to a few calorie sources and the hygienic conditions of settling down represented elementary challenges that first had to be mastered (Harari, 2014). At the same time, the systematization of production processes led to an increase in output. As the population began to grow, a locally heterogeneous dynamic developed, which resulted in new social and technical innovations. Elementary developments were the artificial irrigation (about 9000 years ago), the invention of the wheel and the training of farm animals (about 6000 years ago) (Parzinger, 2015).

Figure 2.1 Regions with own agricultural revolution according to Bellwood (2004) and Harari (2014)

Yet, the transition to sedentariness did not automatically produce complex societies and states, as there was simply a lack of any possibility of state organization. This changed with the emergence of the first state structures in the region of today's middle east in the 4th millennium BC (Spier, 1998). A decisive factor in this was the development of writing systems that allowed extensive amounts of data to be stored and processed (Harari, 2014). The first writing system known today is considered to be the partial writing system of the Sumerians, which originated around 3100 BC and was transformed into a complete writing system by the middle of the 3rd millennium BC. In a similar period of time a comparable writing system developed in Egypt with the hieroglyphics. Other complete scripts emerged in China (ca. 1200 BC) and Central America (ca. 1000 BC) (Harari, 2014).

Initially a consensus on an economic system did not exist. This form of economy, which dominated from the Middle Ages to the industrial revolution and increasingly appeared in monarchical forms of government, can today be described as an *agricultural-based demand economy*. In addition to the recycling of various resources (e. g., animal excrements for agriculture), increasingly complex goods were developed, which in turn required new raw materials. In the course of time, the products were further adapted to the needs of the individual and manufactured in local workshops by qualified specialists who passed on their experience and skills by qualifying young people. In this way, craft guilds and technological centers were formed, e. g., in places where ores were processed (e. g., the German Harz mountains) (Bauernhansl and Miehe, 2020). In addition to goods-for-goods exchanges, from about 1000 BC goods with established exchange values (e. g., shells) and from about 100 BC money was established as a form of payment (Schenk, 1991; Rudolph, 2009). In comparison to the previous epoch in human history, the Neolithic revolution and the increasingly complex societies that followed it resulted in far more extensive impacts on the natural ecosystem. The phenomena of natural species extinction, which had already occurred in ancient times and which was triggered by larger groups of people staying in one place for a longer period of time, was intensified by mass settlement. Similarly, the conversion of many areas of land into agricultural land, often in the form of slash and burn land clearance, led to a further decline in biodiversity. Due to the small world population and the still comparatively small quantity and complexity of goods, the utilization of natural sources and sinks was still limited (Harari, 2014; Bauernhansl and Miehe, 2020).

Until the first half of the 15th century AD only few people were able to learn, develop and document knowledge about natural, spiritual and religious issues due to their social position. This changed abruptly with the modern letterpress printing technology developed by Gutenberg (Eisenstein, 1997; Giesecke, 2006). Subsequently, a wealth of theories and approaches rapidly developed and spread, which continues to influence our thinking today. The most elementary approaches are likely to be *humanism* and *rationalism*.

Since the cognitive revolution, a multitude of intersubjective realities had developed in the form of gods and religions, serving to explain various unknown phenomena in order to give meaning and significance to human existence. In contrast, humanism emphasized the individuality of man (Campana, 1946; Kristeller, 1974). The development of this further intersubjective interpretation (of man as unique), raised man further above nature in philosophic theory. The natural environment as well as all its forms of life serve exclusively the well-being of man.[1)] The doctrine, formulated as early as the 14th century AD, spread throughout Europe in the following two centuries, driven by the new possibilities of reproduction (Böhme, 1986). According to Harari (2016), the early school of humanism later formed the basis for three different interpretations which decisively shaped the recent history of mankind: [1] liberalism (liberal humanism), [2] communism (social/Marxist humanism) and [3] nationalism (evolutionary humanism).

On the other hand, Descartes' rationalism (Descartes, 2011) elevated rationalist thinking ('cogito ergo sum', i. e., 'I think, therefore I am') to the most important building block of knowledge. While fragments of faith and culture indoctrinated up to this point (so-called *memes*[2)]) were accepted almost without contradiction, an epistemol-

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1 In sustainability research, this interpretation is referred to as an anthropocentric perspective.

2 Meme theory describes the formation of human consciousness based on biological processes. The idea is that the contents of consciousness in the form of fragments of faith and culture (so-called memes) are passed on through communication and shaped by environmental influences (Blackmore 2000). On the basis of the genetic preconditions of the single individual, coherent constructs of different memes (so-called memplexes) are formed, which in turn can be passed on and changed (Lenzen, 2003). Meme theory is used to describe socio-cultural developments, e. g., cultures, religions.

ogy developed that only accepted what could be verified as plausible by step-by-step analysis and logical reflection (Cottingham, 1988; Peacocke, 2002). Rationalism not only formed the basis for elementary scientific knowledge, such as Newton's mechanics (Newton, 1999), and for philosophical breakthroughs, such as enlightenment, but is still regarded today as a foundation of scientific epistemology (rationalism is partly considered as the origin of the so-called *scientific revolution*).

From the 16th century onwards, increasingly coherent theories also emerged in economics, accompanying the transition from feudalist to early capitalist forms of economy. Although these theories were not holistic, but rather individual concepts, the predominant economic school of outgoing European feudalism and incipient early capitalism between the 16th and 18th century AD is today referred to in the economic sciences as *mercantilism* or *pre-classicism* (Schaefer, 1993; Gömmel, 1998). In order to meet the demand of the still absolutist governed states of this epoch for strong armies and a growing bureaucracy, some theories developed which propagated the greatest possible promotion of productive domestic forces and the generation of surpluses in foreign trade. In economic practice, exports of manufactured goods were actively promoted, while imports were limited. The economic theory of mercantilism is characterized by its focus on the domestic market and interventionism as a structural tool (Bofinger, 2011).

Table 2.1 summarizes the socio-economic development of the pre-industrial era on the basis of its essential characteristics.

Table 2.1 Socio-economic development of the pre-industrial age based on various characteristics [own summary][3)]

	Cognitive Revolution	**Neolithic Revolution**	
Period	about 70,000 to 15,000 years ago	about 15,000 years ago to the 15th century	16th–18th century
Characteristics of the society or social upheaval	living in nomadic tribes	sedentary society based on agriculture and livestock	dissemination of knowledge through printing, humanism, enlightenment, rationalism, colonialism, strengthening of armies, establishment of large civil service apparatuses
Economic form	early demand economy	agricultural-based demand economy	

[3] Population data are based on Roser et al. (2020).

Table 2.1 Socio-economic development of the pre-industrial age based on various characteristics [own summary] (*continued*)

	Cognitive Revolution	Neolithic Revolution	
Form of trade	goods-for-goods	goods-for-goods (until 1000 BC) goods-for-goods with recognized value (from 1000 BC) goods-for-money (from 100 BC)	
Technological basis	simple tools and technologies (e. g., fire, boats, needles, oil lamps, bow and arrow, grinding)	more complex tools, technologies and goods, the production of which required extensive experience and skill, use of new raw materials (e. g., ores), development of local workshops, technological centers and craft guilds	
Prevailing economic theory	none	none	mercantilism
Global population	about 15,000 to 4 million	about 4 to 500 million	about 500 to 800 million

2.2 Industrial era

The industrial age can roughly be divided into three phases (also known as industrial revolutions), which were decisively shaped by social and technological transformations.

2.2.1 First phase of industrialization (around 1750 to 1850)

The emphasis on the uniqueness of the human being (humanism) and the turn towards natural sciences (rationalism), which was already initiated in the 14^{th} century AD, led to the development of a wide range of philosophical concepts and constitutional ideas in the following centuries, marking the transition from the Middle Ages to modernity. In interaction with the Protestant ethics of the Calvinists, Puritans and Quakers, which not only legalized the unbiased pursuit of property and the acquisition of goods, but regarded it as God's will (Weber, 1992), a dynamic developed which manifested itself in profound social, philosophical, economic and technological changes. Compared to medieval ideals of atonement and punishment, societies were from then on increasingly shaped by a belief in progress and self-determination (Bauernhansl and Miehe, 2020).

A decisive catalyst for this development was the rapid technological progress in Europe, which around the middle of the 18th century marked the transition to the industrial age. Three major breakthroughs were instrumental in what is today referred to as the first industrial revolution (primarily occurring in Great Britain): [1] the mechanization of work previously performed by humans and animals by machines (e. g., spinning machines, mechanical looms), [2] the mechanical generation and conversion of energy by the steam engine developed by Newcomen and Watt, and [3] the mass use of mineral raw materials (especially iron and coal) (Landes, 1986). The former provided the basis for the emergence of factories as separate socio-technical production units, a completely new form of production of goods that was already based on a partial internal division of labor. The importance of the steam engine for the mechanization of energy production and work only slowly increased, finally replacing regenerative generation technologies (especially hydroelectric power) as a primary energy source around the middle of the 19th century, i. e., a little more than 100 years after its invention (Mende, 1993).

The first industrial revolution enabled the entire population to be supplied with clothing and food at comparatively low cost for the first time, as the transport system (steam navigation, railways) was considerably improved in addition to production (Bauernhansl and Miehe, 2020). With the help of these working and power machines, structurally caused famines could be avoided in the newly industrialized countries, which in turn led to an exponential increase of population. On the other hand, the technological transformation had considerable effects on society: increasing productivity in the production of basic goods, e. g., in agriculture, led to a significant reduction in employment in areas of traditional crafts and agriculture. While the pre-industrial age was characterized by three social classes (clergy, nobility, citizens/farmer), the industrial revolution created two new classes: the factory workers and the factory owners. Through skillful economic activity, more and more people were able to achieve wealth. This perspective attracted many people to the cities, where they hoped to find well-paid work in one of the many newly established factories. Dramatic population growth, coupled with increasing urbanization, often led to catastrophic hygienic conditions in the cities of the early industrial era. Diseases and epidemics were frequent causes of death. In addition, adverse working conditions in the factories were a further factor. Child labor, high levels of pollution, and little or no occupational safety resulted in high mortality rates among factory workers. The exploitation of factory workers and the structural poverty of the workforce that accompanied it are referred to as pauperism (Bauernhansl and Miehe, 2020).

Fundamental social concepts of what is now known as the age of European enlightenment were the rejection of prejudice, religious tolerance and orientation towards so-called natural rights (Peter-André Alt, 2007; Ehrhard Bahr, 2008; Annette Meyer, 2009). These basic (intersubjective) assumptions, understood as universally valid principles of order, form the basis of today's conception of human rights, which in turn provided the foundation for the two major social transformations of the modern era shaped by the global 'west', the American revolution of 1776 and the French revolution of 1789. While the Declaration of Independence of the United States of America defined human rights as life, freedom, and the pursuit of happiness, the slogan of the French revolution emphasized freedom, equality, and fraternity. In comparison to the US-American interpretation, which accentuates the individuality of the human being, the ideals of freedom and equality formulated in the course of the French revolution, today a foundation of western European democracies, are considered to be an elementary contradiction. The incompatibility of these two ideals continues in different forms throughout the history of economics and politics, culminating in the sustainability debate to this day (Felber, 2010; Harari, 2014).

With the first industrial revolution, capitalism developed into the leading economic and social order in Europe. Elementary characteristics of this economic system are the control of production and consumption by the market, private ownership of production resources, accumulation of capital, and the pursuit of profit (Willke, 2006; Hüther, 2006; Weber, 2015). A characteristic feature of capitalism was the reinvestment of profits in order to increase productivity and generate even more profits. Figure 2.2 illustrates the core principle of capitalism in a highly simplified form according to Harari (2014).

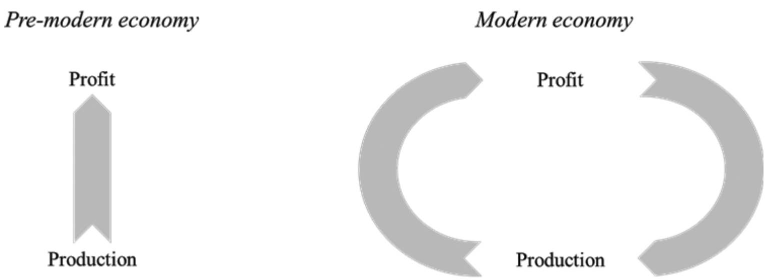

Figure 2.2 Basic principle of capitalism in comparison to pre-modern economic forms according to Harari (2014)

While the term capitalism is used consistently in English, the term market economy serves as a synonym in Germany (Woll, 2008).[4] Consequently, the loose economic theories of mercantilism and pre-classism were replaced by holistic theories that claimed to optimally represent the functional logic of 'markets' (Hüther, 2006). Economic and political theories, which from then on were renewed in an ever more rapid succes-

[4] In German, the term capitalism has a rather negative connotation.

sion, mostly emerged as a reaction to socio-political uncertainties and, depending on the socio-political conditions, formed the basis of the economic policy of various states for a limited time (Harari, 2014).

The first theoretical construct known as a holistic economic school was *physiocracy*, whose emergence can be explained by misguided developments in the mercantilist economic policy of late feudal France. The concept formulated by Quesnay in 1758 postulated land as the sole source of a country's wealth (Quesnay, 1971). While still under the impression of the strong expansion of bureaucratic apparatuses and loss-making state intervention in the economy, which led to the decline of French agriculture, Quesnay (1971) shifted the creation of added value to the production phase. While mercantilism attributed the wealth of a country to trade, the physiocracy emphasized that only agriculture produces surpluses (Priddat, 2001; Holub, 2010; Bach, 2018). The contribution of nature was seen as a 'gift', which is equivalent to a value that should not be assigned to it in any other economic school until the second half of the 20th century. The accumulation of monetary capital was rejected and instead a continuous circulation of money was emphasized. In the course of this, Quesnay developed the economic circuit model of macroeconomics[5], which is still fundamental today and explains the creation of added value through the interaction of three classes (today: households, companies, and capital providers). Figure 2.3 illustrates the economic circuit model in simplified form according to Quesnay (1971).

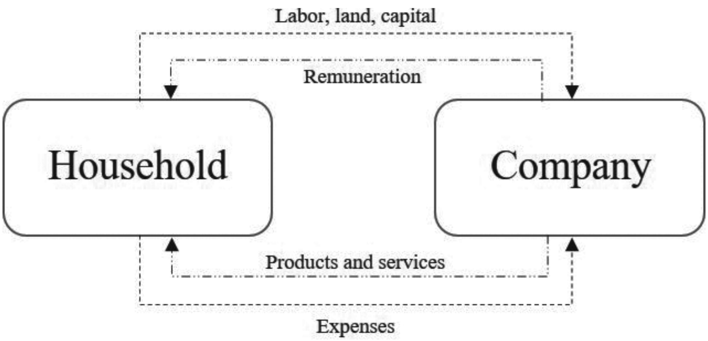

Figure 2.3 Economic circuit model according to Quesnay (1971)

Decisive for the physiocratic school was the notion of a natural law established by the enlightenment, which had to be harmonized with the law created by man in order to

[5] Today, empirical sciences essentially distinguish two perspectives for the analysis of socio-technical systems, the macro and micro level. While the macro level examines holistic system interrelationships, the micro level considers exchange relationships between related individual systems. Applied to concrete scientific questions, problems of economic relations and political options are to be assigned to macro or political economy. The analysis of possible actions of individual economic units (companies, households), on the other hand, takes place in microeconomics, the most common form of which is business administration (Miehe, 2018).

achieve the greatest possible welfare for all people and to allow a free economic activity. Free pricing, free trade, and a capitalist lease system were seen as prerequisites. Correspondingly, the physiocrats demanded a limitation of state intervention in the economy and in private ownership of the means of production ('laissez-faire policy') (Priddat, 2001; Hüther, 2006; Holub, 2010; Bach, 2018). Elements of physiocratic economic policy were implemented in the final stages of absolutist France, although without ever exerting great influence.

Far more significant influence continues to this day with the second major economic theory of this period, *classical national economy* or *classical economics*, which shaped European economic policy from the late 18th century onwards. The approach first formulated by Smith (2013) in 1776 in his work 'The wealth of nations' represents a transfer of the principles of liberalism to the economy. Influenced to a similar extent by the failures of mercantilism as Quesnay, Smith transfers the ideal of individual freedom, already emphasized at the time in both the US Declaration of Independence and the motto of the French revolution, to economic interaction between economic entities. The central concern was to promote the prosperity of the nation as a whole by creating a self-regulating system (Eagly, 1974; Aspromourgos, 1995; Ziegler, 2008). Smith (2013) assumed that the self-interest of the individual would bring the entire system into a state of equilibrium like an 'invisible hand'. To justify the principle of self-interest, Smith adopted the views of the Protestant ethics of the Calvinists, Puritans, and Quakers, praising the wealth of the individual as moral and outlining a vision of alternating advantage (win-win). As the representatives of classical economics partly contradict each other in certain points, the following basic principles are considered characteristic of classical national economy today: [1] the principle of self-interest, [2] the division of labor, [3] the equilibrium thesis, [4] the theory of labor value (i. e., the interpretation of the value of a good as the labor value contained in it), [5] the exchange of goods on a market (the greater, the better), [6] the formation of market prices through the agreement of suppliers and consumers, [7] the demand for freedom of economic activity (i. e., avoidance of intervention in economic activity). Classical economics further emphasized the concept of capital, already introduced by Quesnay, as that part of wealth that is used to generate profit (Hüther, 2006). Nature was regarded as free in the awareness of its infinity. At the same time, in 1798, Malthus already pointed out the techno-economic challenges of the emerging problem of overpopulation (Malthus, 2007). The end of the first phase of industrialization marked the first emergence of worker councils, which would provide the basis for a further upheaval of political and economic conditions in parts of the world during the second phase of industrialization (Schönhoven, 2017).

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