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ARTICLE

Best Practices in Construction 4.0—Catalysts of Digital Innovations (Part II)

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ABSTRACT

Part II on Best Practices in Construction 4.0 follows up on the previously published study Part I. This study examines corporate strategies from different angles, defines potential fields of application and works out existing empirical values and trends in the digitization process of the building sector. It highlights the unintended consequences of technological development and offers concrete practical approaches for responsible use. Using the qualitative research method, the study concludes that digital methods, such as Building Information Modelling (BIM) and Digital Twins, and Artificial Intelligence (AI) can add value, significantly reduce resources and increase sustainability. The study is part of a larger primary research on Corporate Digital Responsibility (CDR) in Construction 4.0; it identifies, analyzes and systematically evaluates the pillars of a sustainable digital transformation, especially in the Construction Industry. The holistic, interdisciplinary view of this study aims to provide orientation for small to medium-sized companies (SMEs) developing their individual digital strategy. An outline of the necessary prerequisites but also design options, as they result from the evaluation of expert interviews and literature research, supports companies in the design of Construction 4.0 that is in line with the needs of people, society and the environment and shaping more economically efficient building life cycles. It highlights that digital transformation has also reached the traditionally small-scale AEC industry (small-scale architecture, engineering and construction industry) and catalyzes the variety of innovations.

Keywords: Digitization; AI; Digital transformation; Best practices; Smart cities; Circular economy; Cradle-to-cradle; Construction 4.0

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1. Introduction

New technologies such as AI are increasingly finding their way into the integration and operation of existing buildings, fire protection systems, circular economy, cradle-to-cradle and smart cities. The intelligent network of existing buildings and infrastructure enables smart cities to operate according to the latest energy and security standards. An innovative design may significantly support the achievement of sustainability and climate goals, and lead to a higher sense of human security and safety, and an overall increase in quality of life [1]. The building sector causes almost 40% of global CO_2 emissions and is the key to central climate neutrality by 2050. Innovative building technologies in existing buildings enable intelligent ecosystems as part of the 5th industrial revolution [2]. Empirical values from user practice, gained by expert interviews over the period from 2019 to 2021, are the basis for deriving new approaches and for setting the main pillars for a sensible, sustainable use of digital technologies. Overall, German companies were able to generate sales of €60 billion in 2019 with products and services that directly use AI [3]. In 2019, 30% of companies using AI in the German economy were previously vacant in the field of AI [4]. BIM and new technologies such as AI, Artificial Intelligence of Things (AIoT), Internet of Things (IoT) are technological prerequisites for sustainable digital transformation in all areas of buildings, mobility and smart cities [5]. However, this is based on human and social transformation, recognizing both ethical digital responsibility and the use of trustworthy technologies by showing transparency and human autonomy. Thus, Feroz, A.K. et al. [6] proposed that only human-technology interaction can ensure the development of resilient ecosystems. The literature research specifies comprehensive milestones that have already been achieved in the development of the AI strategy in Europe. Nevertheless, according to one of the results of the study, data sovereignty needs to be expanded in order to strengthen trust in new technologies and the will to innovate in the Construction Industry, which is still reserved. Dealing responsibly with digitization, as this primary study analyzes and gave its name to this new scientific niche, takes particular account of the "dark" side of this change presented in Section 6.

This study shows that new innovative technologies represent important catalysts both in the life cycle of buildings and in reducing the ecological footprint. Its design and application are inclusive and independent of time and place, thus, especially for people who are disadvantaged. The emerging technologies enable the access to digital participation and strengthen participation for everyone [7]. Digital technologies and AI enable data preparation that provides a more structured, transparent basis for decision-making processes and for predictions of potential risks to increase efficiency but also safety in working routines, as experts who were surveyed share in the study. Technologies such as Digital Twins, BIM, Virtual Reality (VR), Metaverse visualize the planned end product with its technical operating equipment, the building usage data and operating data. Malfunctions, risk hazards, environmental impacts, user behavior, energy consumption and a holistic life cycle of the building can be simulated. The study considers this as one of the decisive turning points if the digital change succeeds with a focus on sustainable economic development and the Sustainable Development Goals (SDGs) by the United Nations. BIM and AI provide the essential technical basis for making decisions as part of agile environments using consolidated planning results and a common data environment. As a consolidated coordination model, in which all relevant data and data interfaces are brought together centrally, BIM adds considerable value [8]. BIM, according to one of the research findings, is rising towards the next consolidated methodology: Building Life Cycle Assessment Management. In this way, the digital transformation can be designed collaboratively and environmental protection-related challenges can be consciously tackled [9].

AI, VR, Metaverse support human work with increasingly sophisticated technology, simulate the planned project in design and use all technical interfaces. As such, it not only allows the assessment of the necessary resources, completion and operating costs, time and quality, efficiency, but also offers a consistent data structuring without data loss, and a visualized representation of scenarios [10]. The study concludes that only through the sensible, responsible use of humane AI for reducing resource waste and protecting the climate and the environment, sustainability in a holistic sense can be achieved. Fields of application of AI and digital methods are being researched at various German and international locations; some have been partially put into practice based on the assessment of first practical experiences follow-up adjustments. The study recognizes Best Practices as role models for encouraging innovations. Innovation champions inspire others and encourage them to shape their own entrepreneurial digital future motivating to further explore new innovations [11]. Accordingly, this article presents findings from interviews with innovation champions and provides scenarios for the sustainability and future of the construction branch.

2. Primary study and method (Part II)

As demonstrated in detail in Part 1 of the article, section "Materials and Method", the qualitative method with interview surveys with experts was used in this primary study (*Part I, Journal of Architectural Environment & Structural Engineering Research JAESER, Vol.6, Issue 1, 2023*). Their experience and the study's observation, especially the lack of framework conditions for a successful digital transformation in the Construction branch, contribute to innovative approaches. Literature sources consulted that deal with similar research questions in other disciplines proving to be particularly useful in scientific research in the Construction Industry. This help to transfer to the construction industry similar questions and problem areas that other departments are also dealing with. Secondary data were collected to allocate the new scientific niche and get engaged in the cross-discipline debate. As part of this development, the study disclosed, that the social, economic and political influencing factors driven by innovative technologies have so far been neglected in the construction industry, thus, a more critical debate is recommended. And especially, due to the emerging technologies' severe negative impacts on people, the society and the common good, the value chain, nature and environment, the responsible design and use of such technologies mean strong signal to set new standards. The increasing technical feasibility requires social responsibility, as the study concludes. Therefore, the study recommends conducting the relevant discourse at all political, economic and social levels [12]. The corporate responsible application of digitization and AI (CDR) is not only one of the key approaches in the digital era, but defines a first time new scientific field to be researched more deeply. The Construction Industry is still hesitant to take on ethical, social issues, to cope with the multicomplex human factors involved, but driven by such a new research field and the transfer of knowledge between research and practice—can be considered as the decisive element for success and sustainability of the overall digital transformation, beyond the digital age. One in which the focus lies on people and human transformation, as requirement and enabler for the digital one, and which is holistically embedded. The primary study identified the critical path and factors that depend on or influence each other. As experts interviewed confirm, the study enabled an increasing awareness in the Construction Industry for a balanced, sustainable human-machine interaction. The interdisciplinary debate with research findings from Technology Ethics [13-15] and Technology Assessment by Armin Grunwald [16] and Hans Jonas, Christoph Hubig's [17] Practical Philosophy and Philosophy of Technology [18,19] represent fundamental scientific literature sources, as well as Ethical Engineering Responsibility [20], BIM and Digitization in Construction [21] and Corporate Compliance [22-24]. These fields of interest have several common interfaces in the processing of the research focus of this primary study in construction.

3. Key factors in the digital change in construction

The increasing will to innovate in companies and the search for ways to design digital business models, workflows and work processes more efficiently are catalyzed by the increasingly complex data environment, occupational safety, quality of data and time efficiency. The evaluation of the surveys has shown that one of the positive impact factors consists in using innovative technologies to implement highly efficient cost-time planning, to reduce production costs and achieve thorough economic efficiency, to merge data from all end devices, accessible for all users and without data loss, on one unified data platform. Since 2020, the development and application of AI in Construction steadily increases in Europe. According to forecasts Europe will be a pioneer and have overtaken other nations by 2027. In particular, the responsible, value-based design of new smart cities contributes not only to a significant reduction of CO_2 but to strengthening sustainable green tech and environment [25]. The study identified key elements for successful digital change in Construction (**Figure 1**) and summarizes milestones in Construction 4.0—specifically using corporate innovative Champions shaping the digital transformation based on initial experience in diverse fields of application (**Table 1**). **Table 1** provides an overview of the AI applications already implemented in practice, in selected areas ranging from structural and civil engineering, technical building automation, real estate management and monument preservation, tunnel technology, timber construction, to fire protection, intelligent buildings and smart cities.

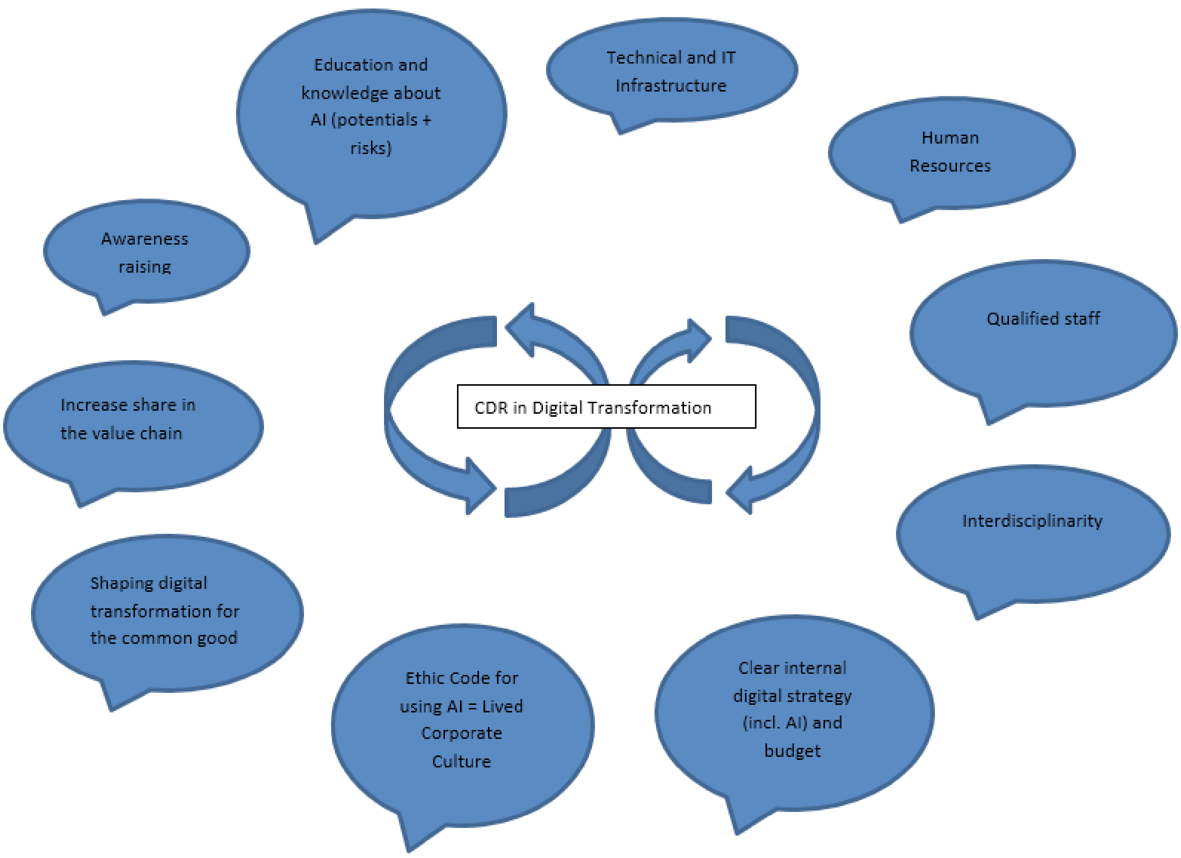

Figure 1. Mind map digital transformation strategy—Interaction of the key elements.

Source: Bianca Weber-Lewerenz.

Table 1. Milestones in Construction 4.0—Corporate use cases.

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
Real Estate, Facility Management	Predictive Maintenance (PM):	**APLEONA**
	"Fully automated building technology control" (goal: Energy Monitoring)	
	"energyControl" (goal: Predictive Control)	
Technical Building Automation	AI-based building simulations, PM with self-learning software for Predictive Maintenance, Remote Monitoring and Remote Maintenance. Detects hazards and identifies unknown incidents weeks before failure.	**general (see Anacision GmbH Karlsruhe focussing on Mechanical Engineering)**
	AI-based Operator Optimization	**general**
	AI-based Resource Optimization (energy consumption, electricity, water)	**general**
	AI-based Recommendation for Action	**general (applies to all areas of construction)**
IT- and Software Developpers for Construction Branch	Semantic Web, AI-based Hybrid Models (autoML combined with expert knowledge), Intelligent Product Development, AI-supported Product Generation Development, Automatic Quotation and Capacity Planning, as well as Process Automation	**EDI GmbH Engineering Data Intelligence Karlsruhe**
	Product "EDI hive IoT Framework" (Construction Industry): AI-based creation and design of Offer(large, simple hub), e.g. BIM can be used to collect a lot of data for the craftsman, and they - based on their experience - derive the right conclusions.	
	·EDI business consulting workshops (goal: demystifying the terms AI, cloud, BIG DATA, platforms),	
	·AI-based Data Analysis to quantify gut feelings and generate new insights,	
	·Semantic Data Management for experimental data, which is the origin of the company,	
	·Development of Digital Business Models with intuitive apps for customers, trades and management.	
Civil engineering (Building Construction, Formwork Technology)	In terms of **Visual Object Recognition**, we are currently using newer networks to ensure that parts can be recognized based on specific characteristics. The advantages here lie in the unnecessary marking of the parts. This can be particularly challenging due to the use of materials on construction sites etc. There are already prototypes/ models that can also be tested in an application (app) (goal: visual object recognition), e.g. QR code, tagging on the material is not sufficiently durable, e.g. for comparison: GPS transmitter for locating the building material, but : high cost factor. Current: Photos with data information for part definition (e.g. anchors, formwork panel), chip with no. to recognize the part, without QR/tag: the algorithm recognizes the building material through the photo and the photo data. Neural networks with automated detection.	**PERI Digital Transformation & Corporate Development**
	Automation of engineering tasks: Trying to solve engineering tasks (data-driven) using historical data by using appropriate models. Topic very complex, reaching the limits of computing capacity (goal: data-driven solution of engineering tasks) e.g. floor plan, formwork planning via spatial mapping, definition via rules	

Table 1 continued

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
	ESKIMO = Research project on AI application on construction sites (https://www.eskimo-projekt.de/)	**https://www.eskimo-projekt.de/**
	"VINCI Chronsite Program" (www.leonard.vinci.com): The VINCI Chronsite Program (www.leonard.vinci.com) involves the automated merging of all construction project data and information using Computer vVision and Deep Learning Technology can be gained.	**VINCI Construction**
	3D -Scans were carried out after the Notre Dame Cathedral in Paris burned down in 2019. The point cloud-based model captures the original structures and digitally preserves them for future generations. VINCI uses VINCI Construction Group's "Sixense" software and its ScanLab to carry out high-precision 3D and photogrammetric measurements that enable automated risk detection. The company's internal AI program is referred to as "Leonard VINCI". Façade recordings automatically depict the technical floor plans. The advantages and empirical values are that the intervention times and scaffolding times are drastically reduced. This results in an increasingly efficient, shorter restoration time, so that tourist masterpieces can quickly be accessed again. A classic practical example is Mont Saint Michel in Normandy, France.	**VINCI Construction**
Civil engineering (Construction and Civil Engineering)	Workflow up to 7-D as a continuous project flow	**WAYSS & FREYTAG INGENIEURBAU (Subsidiary of the Royal BAM Group)**
	Modeling: Deep Learning approach to model creation, e.g. for the basis of (partly) automatic component recognition from point clouds	
	Parametric Design (architecture) Objectives: Saving material, requirements for light transmission and aligned with the position of the sun.	
	"Generative Design": Design process in which the result is generated by a programmed algorithm.	
	Visual Image Recognition, e.g. of damage photos on motorways (crack detection)	
	Scheduling (4D) based on process building blocks that are linked to the model or derived from it (assign processes, assign sequences, sequences, use big data and algorithms for optimization.	
	AI-based Resource and Construction Process Optimization	**general**
	AI-based Supply Chain Optimization	**general**
	AI-based Lean Construction	**general**
Civil engineering (Building Construction)	Support for repetitive work and hard physical work (e.g. artificial, machine exoskeletons)	**general**
	3D printer for serial construction and prefabrication (e.g. Max Modul by Max Bögl, advantage with precast plant)	**Max Bögl**
	HOCHTIEF ViCon: Artificial Intelligence (AI), Internet of Things (IoT), Mixed Reality (MR), Augmented Reality (AR) and Virtual Reality (VR)	**HOCHTIEF**

Table 1 continued

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
	Incorporating Artificial Intelligence (AI), sensor-driven Internet of Things (IoT) technology and blockchain.	**Nexplore: HOCHTIEF Research and Development Center in cooperation with the Massachusetts Institute of Technology (MIT), University of Madrid and University of Darmstadt**
	Real-time control of the construction progress and improved planning processes through to the simplification of maintenance and operation of a building.	
	-"Cognitive Document Risk Analyzer" und	
	-"Cognitive Document Analyzer"	
	They should help to make the processing of offers more efficient through digitization and standardization, for example in contract analysis or in the preparation of tenders.	
	IoT applications can be used with the help of AI for Predictive Maintenance: Construction-related status data then enable proactive maintenance.	
	Factory and Building Planning using VR Virtual Reality	**MÖRK GmbH & Co. KG S-Leonberg**
	Digitized processes simplify construction registration, measurement and reconstruction work, component sections and measurements; they enable more efficient municipal management (firefighting, policing, sanitation, waste management). A strong signal to the construction industry to deal with potential and already implemented areas of application of AI: Self-learning construction sites, self-propelled construction machines (risks of failure of construction machines can be displayed in real time via machine learning), digital online construction site inspection with VR glasses, simulation of renovation concept + building in existing buildings and ongoing operation, simulation of acoustic + fire protection concepts, AI sensors for detecting and detecting defects/damage in the event of material, humidity, temperature changes, AI monitoring and controlling in the construction progress with continuously generated invoicing, forecast and strategy data systems as a basis for business decisions (predictive technologies). Remote monitoring and maintenance become even more efficient with AI. 3D-7D twin with simulation, reality and prognosis models provide mapping of the construction progress, time and costs at any time.	**general**
	Building types/classes can be recognized and localized on images by object recognition using machine learning and maintenance can be planned. 3D measurements, documentation and construction site monitoring can be implemented using a drone. In public relations, high-resolution 3D models can be used for digital tours. Tailor-made measures for energy-related renovation and energy-efficient construction can be agreed. Access to a uniform data platform of the model is guaranteed for all project participants with end devices at any time, from any location, without data loss.	**general**

Table 1 continued

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
	• 3-, 4-, 5-D twin with simulation, reality and forecast models, • Use of machine learning, deep learning, social computing, • Systems for structuring the data complexity, • Comparison between historical construction project data and new construction project data and selection for data evaluation and planning of a resource-, climate-friendly, cost- and time-efficient construction process, • smart technology and smart buildings, • Self-learning construction site. • Digitization tools that go beyond BIM, • Networking of all digital devices for complex data collection from all technical trades, • Forecast and strategy data systems as a basis for business decisions,	**general**
Building in stock, Renovation of old buildings	AI methods also enable data to be compared with stored data in order to comply with structural requirements and regulations (monument protection, fire protection, environmental protection) when taking measures. With the help of digital technologies, 3D measurements can be carried out by drone (UAV photogrammetry, UAV laser scanning). Drones for inventory and 3D documentation for the digitization of cultural assets are routine, stone-based measurements of facades (UAV photogrammetry) using high-resolution and calibrated camera systems or LiDAR scanners, true-to-scale, high-resolution facade documentation (UAV photogrammetry), the recording of listed buildings, high-resolution 3D -Scans of relics for the digitization of cultural assets and high-resolution facade views in the form of orthophotos (corrected measurement images) are used as a basis for planning and for damage mapping.	**general**
	High-resolution 3D models can be used for digital tours in the public relations work for building, ground and area monuments; high accuracy requirements can be met, and the entire documentation, cataloging and archiving, planning of rehabilitation measures and reconstruction can be supported. AI methods enable tailor-made measures for energy-related renovation, energy-efficient evaluation and acoustics on listed buildings.	
Protection of Monuments, Restoration of Monuments	Measurement and reconstruction work, component sections and measurements, fitting of reproduced components into the existing building, production of building materials, forecast modeling (investment planning, control) and simulation of construction models (3-7D, i.e. with continuous depiction of the actual construction time, costs and quality during construction compared to the Original planning).Virtual Reality and Augmented Reality are used to make churches, castles and historical buildings virtually accessible. Object recognition using machine learning makes it possible to identify building types, classes, damage or anomalies in images. Defective, often hard-to-reach areas can be localized and repair and maintenance can be planned. Digital construction site inspections are possible with VR glasses, simulation of renovation, acoustic and fire protection concepts can be implemented, AI sensors detect and detect defects and damage in the event of material, humidity and temperature changes.	**general**

Table 1 continued

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
Civil Engineering, Tunnel Construction	AI-based data on the drilling progress, typification of the soil layers encountered, movement of the machine, device data (dissolving energy requirement, fuel consumption, temperature), change of drilling tool and wearing elements, faults and the cause of the fault, maintenance or repair requirements, representation of the construction site performance, generation of the "as-built "Data.	**BAUER AG Schrobenhausen**
Timber Construction	AI supports the crafting process of better engineered wood. Machine Learning (ML) is already being used in wood technology applications: AI supports the digital wood selection and wood processing strategy to obtain specific physical properties. ML optimizes the functionalization of wood: material selection, physical data of the raw material, production steps, process parameter setting, quality control, processing, product quality prediction in real time. This replaces endangered tropical wood and enables particularly good, precise milling. With this social and economic contribution, the share in the value chain increases. The central topic in the context of the sustainability discussion about building materials is dismantling, re-usability, recycling, ecological and energy concepts.	**general**

Source: Bianca Weber-Lewerenz.

Note: In December 2022 the author's book "Accents of Added Value in Construction 4.0" was published by SPRINGER Publishing.

4. Signposts in the digital transformation—Part II

Dealing comprehensively and across disciplinary boundaries in discourses dedicated to digital transformation, the study considers the close interface work of several departments and adapted science communication as key for creating consciousness and to increasing knowledge. Where is knowledge, fear decreases. Thus, new skills, innovative approaches are needed along the critical path, which is not limited to the "dark" side of new technologies, such as digital ones and AI.

The 3rd Symposium Building the Future investigated the corresponding signposts [26]. Heike Klussmann, University of Kassel, emphasized that "*digitization must start in teaching and that the curricula must be adapted in the short term*". For Lucio Blandini, University of Stuttgart, Marvin Bratke, Urban Beta, Peter Kaufmann, Kaufmannbau, and Claus Nesensohn, Hochschule für Technik Stuttgart, this represents a success factor for future-proof sustainable Construction: "*The early integration of diverse and interdisciplinary teams and the collaboration using a sensible use of technology ensures cost savings and much more efficient communication*". Peter Kaufmann and Claus Nesensohn look at the "*human-centered approach as an important lever so that not only digital, but also human change is successful*". Laura Lammel, from Lammel Construction and Board Member of the Central Association of the German Construction Industry, emphasizes that "*value creation can be achieved only through responsible action in business processes in the Construction Industry*". The discussion participants emphasized "*that sustainability and a successful digital transformation in Construction can only succeed through human-centered work, close interface work with integral teams—far away from 'silo thinking'. This requires a fundamental re-thinking of the Construction Industry, innovative ways and the exchange between research and user practice*". According to the results of the study, meaningful and technically sustainable progress can only succeed if the common good, environmental and climate goals and resource conservation are taken into account. These include, for example, an innovative circular economy and a cradle-to-cradle approach. As a result, new technologies are taking on an increasingly important design role and require a new culture of thinking and value-based action.

5. Best practices—Key competence "AI—Made in Germany". Challenges and innovation champions

AI not only enables self-learning construction sites, but also real-time progress and performance checks and thus more transparency, corrective interventions real-time and construction projects that can be overall designed more efficiently. The study proves that the entrepreneurial will use innovations to fully exploit the potential increase. However, only large companies so far have been able to conduct their own research and implement innovations through their own departments led by Chief Digital or Chief Information Operations, simply on the fact to possess the required financial background. The interviewed experts highlight interdisciplinary interface work is a basic requirement. In corporate environments, such processes are based on close cooperation between the departments for development, design, Information Technology (IT), project management, execution, controlling, law and Human Resources (HR). In addition, uniform data platforms are used, which record all project data and continuously update according to the project's progress. SMEs have introduced BIM sporadically but not in a standardized way. More as individual processes and not over the entire project cycle, thus, holistically digitized processes are not guaranteed. Such inconsistent working habits lead to severe data gaps, and other weak points such as inefficient project processes, reduced controllability and low data communication. To ensure higher data security and compliance with the code of values, the focus of the study lies in drafting contracts with customers and suppliers in accordance with corporate compliance standards and risk analyses. With the help of AI-based methods, companies could significantly simplify the increasingly complex subcontractor checks, contract design and performance checks in real time. Thus, one of the study results consists in strengthening such digital applications since they may result in new decision-making bases speeding up contract reviews and risk analysis. Only a few—and most of them are experts in their field—recognize digitization and AI as the most suitable technological support for human work by linking multiple areas with each other, increasing transparency, safety, economical efficiency and sustainability. Companies with a pioneering role are aware of the severe impacts AI has on people and society as a whole. Therefore they assign AI innovations embedded in a value-based engineering environment and a new corporate thinking culture a very high value. They also address the responsible role of large best practice companies to share their newly won experience with SMEs. Such exchange may significantly ease the process of defining the own digital strategy, to choose first AI methods tailored to their individual business challenges. Here, start-ups offer support using the data already available in high quantity. Despite different financial backgrounds, SMEs must not be disadvantaged in the digital transformation process, but should be consciously supported. The study considers as one critical process, that digital change requires to be shaped from the bottom up, instead of dictate from above. The study derives constructive approaches based on individual entrepreneurial digital strategies in a targeted manner and to use methods responsibly. The study considers legal regulations and ethical standards as important guidelines as to ensure data protection, the protection of fundamental rights and the prosecution of illegal actions. In the interview surveys, experts consistently confirmed that every company in Construction is confronted with facing the challenges of digital transformation. Therefore, companies in the Construction Industry should consciously promote education and awareness-raising in order to increase skills, knowledge and strengths in the industry as decisive path for the equally important human transformation. In order to do justice to all technical aspects of responsibility towards people and society, ethical considerations play a key role. Corporate pioneers do justice via using interdisciplinary cooperations (innovation, IT, HR, law). They cooperate closely with universities and technical colleges in order to transport the most actual topics in guest lectures, and then use such exchanges between academics and economic practical knowledge to adjust teaching contents and curricula. Some of the interviewees involved see the severe content overloading of the educational landscape, due to the gap between basic engineering training and the new qualification profiles required—both for digital but especially human transformation—based on the lack of adequate professional competence among teachers and insufficient digital equipment [27,28]. On the other hand, universities use their excellent strategies to set themselves apart from the competition with research clusters, innovations and interfaces to entrepreneurship. The study noticed the same tendency in large, globally active companies aiming to redesign their attractiveness as employers, but also to fulfill their social responsibility and comply with ethical standards based on self-responsible action. AI as an engine of innovation can only be sustainable, responsible, safe and of the best support for human work to the extent that people make these technologies accessible, train and explain them, use them responsibly and provide orientation in what makes sense and where the line must be drawn to distinguish between artificial and human intelligence as to maintain autonomy and create trust.

5.1 Circular economy and cradle-to-cradle

To illustrate with practical examples, the study focuses on a few selected Best Practices in Smart Cities. The Smart City Strategy has 3 main goals: resilience, the city in transition and circular economy [29]. The European Circular Cities Declaration [33] defines how the digital transformation in municipalities can be shaped sustainably and how smart networking and intelligent operation of urban infrastructure according to the European Green Deal are increasingly finding their way in the design of Smart Cities and circular economy. The idea behind this is to decouple resource consumption from economic activity by preserving the value and benefits of products, components, materials and nutrients for as long as possible in order to close material cycles and minimize harmful resource consumption and waste [31,32]. With 75% of natural resource consumption occurring in cities and 50% of the world's waste coming from cities, the potential is huge. The signatory cities recognize their full commitment to the transition to a circular economy, thereby increasing their share in the value chain. In line with the Climate Strategy 2030 and the UN Agenda 2030, some German cities are pioneers, such as the city of Aachen. The Institute for Anthropogenic Material Cycles (Center for Circular Economy (CCE)), led by Kathrin Greiff, and the Institute for Sustainability in Construction (INaB), led by the second author, both located at RWTH Aachen University Germany—have an important role model function: They both bring their expertise to shape the transformation of the city of Aachen towards a sophisticated circular economy. What does sustainable building lifecycle management mean as part of the new urban agenda? [33] There are two goals: Develop livable cities; strengthen planners and operators of urban development [34]. Further samples of international pioneer cities represent Amsterdam, Copenhagen, Vienna, Barcelona and Singapore. The Governing Smart Cities Report [35] provides policy benchmarks for the ethical and responsible development of smart and sustainable cities. This should strengthen the trust of citizens as well as planners, manufacturers, users and operators of buildings and infrastructure. Sustainability also means firmly integrating the Cradle-to-Cradle Principle [36] in building practice wherever possible. The concept is based on three principles: understanding waste as food, using renewable energy and promoting diversity. A practical example: Digital twins—of both buildings and infrastructure—automatically generate real-time information and quantities of materials, the data is stored and can be called up at any time if the building is to be dismantled and the recycled material returned for use in the new building. Cradle-to-Cradle means building along the material cycle. Setting up a digital urban mining cadaster is an option, with an evaluation scheme standardized by so-called passports of buildings and goods. Thus, stocks of durable goods in the Construction sector can be recorded, future material flows can be forecast at an early stage and the best possible recycling routes can be derived. Especially through concrete recycling, 60 million tons of recycled building rubble could be used as aggregate for concrete production; but in reality *only about 0.6 million tons are used*. A nationwide mandatory reuse as part of the *Circular Economy standardization roadmap* and the guarantee of maintaining the necessary quality represents a constructive approach [37]. Through the increased *use of existing technologies, resources could precipitously be saved immensely and emissions reduced to a fraction, as well as CO_2 neutrality could be further accommodated* [38]. With increasing technical feasibility, societal responsibility and the need to specify and tighten the applicable legal framework data sovereignty may be increased [39,40]. In particular, the economic ecological responsibility in Europe is increasing, based on a common language to evaluate the sustainability performance of buildings, e.g. using a common European method of "Level(s)" in the life cycle assessment [41].

5.2 Integrating existing buildings into smart cities

Smart cities not only include new construction, but the upgrading of the comparatively larger building stock to intelligent building automation systems in accordance with standards, SDGs, climate and ecological strategies [42]. Innovative building technologies in existing buildings enable efficient construction planning through visual representation of all trades involved and support independent monitoring, control, analysis and optimization of energy consumption. In order to become neutral with the CO_2 emissions from real estate in Germany by 2045, with the aim to almost halve by 2030. The study recognized that Smart Cities are expected to reduce emissions by at least two-thirds and at least 90% by 2035 [43]. However, this goal can only be achieved if the potential of digital technology solutions is already being used on a large scale today, for example by controlling air conditioning systems efficiently and on demand by a cloud-based solution (*Remark: a cloud-based solution means controlling systems from anywhere, anytime, with a smartphone app and the computer interface, through a router connected to a cloud.*). It is of the utmost importance that such application of technology does not base on efficiency but on resilience. Because resilient Smart Cities can quickly, effectively and efficiently adapt to shocks and increasing natural and other risks to which they are exposed, learn from them and adapt to changing environmental conditions and social changes. One of the benefits the study identified is that new technologies allow decision-makers to understand the implications of policy recommendations or new proposals for urban systems. On the user side, they enable improved designs and analysis of city-scale interventions. In addition, smart technologies in existing buildings enable a much more efficient, economical and secure form of testing, building operation and maintenance (building automation, communication between buildings).

In view of the diverse challenges in dealing with the climate change caused by natural disasters and a sustainable design of the built environment, the study highlights the need to plan and build cities and buildings even more "with nature" and following changing natural and temperature conditions according to climate change. When planning Smart Cities, particular attention must be paid to less surface sealing, intelligent wastewater management, warning systems, e.g. flood disaster (e.g. Ahrweiler Germany in 2021), flood protection, stability and safety of tunnels, bridges and dams. The adaptation goes far beyond the newly required building materials and standards that are adapted to the requirements of climate change (e.g. acid rain, periods of heat).

Green building standards and certification schemes not only are limited to new requirements for both new and existing buildings. However, much of the existing building stock in cities have been built with limited attention to green design, energy efficiency and low carbon emissions, but its refurbishment can help meet national energy saving targets and reduce environmental impact. In addition, retrofitting existing buildings can often be less expensive than building new facilities. The potential of an existing building to achieve certification to a specific green standard, defined in this work as its Green Potential (GP), depends significantly on critical factors determined during the original design and construction process. Field reports from user practice demonstrate that digital twins, AI, AIoT, cloud computing, intelligent building operation and communication represent powerful tools for integrating existing buildings and upgrading to Smart City standards. But what are further advantages for owners, operators and users? To this end, the study summarizes several potential fields:

- More efficiency, comfort and safety;
- Increased efficiency and need for intelligent services through intelligent networks of technical building equipment;
- The construction sector causes almost 40% of global CO_2 emissions (= key lever for achieving climate neutrality by 2050);
- Independent monitoring, control, analysis and optimization of energy demand;
- Buildings that "think" and operate fully independently and for themselves;
- Recognize and rectify faults quickly, recognize pending maintenance early and embed automatically, optimize the use of areas and rooms;
- New dialogue between buildings and people = changed management processes, simpler maintenance, longer maintenance cycles, simplified remote maintenance;
- The intelligent building communication itself becomes the best partner for facility and energy managers, supports the daily work of everyone involved, simplifies processes and helps to permanently reduce operating costs.

Technical building solutions can be:

Building automation, light and energy management systems, security technology;

Integration of technical building systems and systems with fire alarm systems, access and intruder alarm systems, building automation and video surveillance systems as well as IoT components: connection to cloud-based platforms;

Digitized frequency of use: Utilization of areas in the building known and thus solutions for area management;

Basic requirement: Digital building twin that generates the holistic digital image of the building.

Building 4.0 means gaining a new sense of security [44] and "*greater responsibility of people for technology-based innovations.... and for the sustainable preservation of the world*...." [45]. The study concludes, that such progress and involved transformation processes require a new culture of thinking and a new way of thinking about unintended impacts and risks that technological innovations put on people.

6. The "dark" side of digitization

When it comes to designing smart Cities of Tomorrow, the question raises how intelligent digital standards can be achieved. How can Smart Cities not only be smart, but sustainable and resilient? In this respect, technological progress in Construction 4.0 is catalyzing the digital transformation. Unintended consequences and severe negative effects of digitization and AI are referred to as the "dark" side of digitization [46] because they have social and ecological effects, e.g. on the raw materials sector. Economic growth is difficult to decouple from resource consumption, which already exceeds the limits of the planet. The technologies of the future require extensive resources and critical raw materials. However, the recycling potential of these raw materials is very low and the return strategy is inadequate. Four times of the current lithium production, a three times increase in heavy rare earths and a one and a half times increase in light rare piles of earth and tantalum. The European Committee of the Regions therefore takes a specific position on the action plan for critical raw materials in order to supply Europe with raw materials more safely and sustainably [47]. Due to the increased use of electronics, the global demand for copper will grow between 231% and 341% by 2050 [48]. According to the DERA study, in 2035 up to 34 percent of the global indium production may be used exclusively for the production of displays [49].

The study identified several interdependent fields: Digitization and AI require new machines (robots, automation technology), much higher data speeds (fiber optic cables, routers, high-performance microchips, sensors, data transfer infrastructure) and data storage with larger volumes such as significant higher data capacity (data clouds, IoT, AIoT) for real-time transmission and error-free network communication. Such basic infrastructure has to be rebuilt and computers and, due to the high heat produced during operation, storage rooms are required to be continuously cooled and air-conditioned. The entire infrastructure must be expanded or completely rebuilt, and dismantling and recycling must be taken into account in the planning stage, as part of a holistic life cycle design. The health effects of continuous radiation generated during the operation of these innovative technologies on humans have not yet been adequately researched nor recognized in high-speed technical development: fully functioning Smart Cities require uninterrupted, intelligent networking of buildings, e-mobility, smartphones they all require data clouds, IoT and the expansion of multiple base stations. Therefore high, uninterruptible power supply and acceptance of the additional energy consumption, the high intensity of electromagnetic radiation (networking among the devices, radio) and further CO_2 production must be applied. The end-to-end full automation of buildings requires hardware such as machines and sensors, and thus an increasing production of the necessary inventory materials and with the corresponding consumption of resources. The fifth generation of mobile data transmission (5G) requires broadband expansion using fast fiber optic networks. 5G combines the previous mobile communications standards, Wi-Fi, satellite and landline networks into a holistic communication network. Such scenarios demonstrate, that digitization leads to significantly high energy consumption, because in 2025 data centers will account for around 4%-11% of global energy consumption. At the same time, high energy saving and waste heat utilization potentials are forecast and localized [50]. The study comes to the conclusion that the digital value chain is being taken as absurdum: How can the CO_2 footprint be reduced, managed sustainably when raw materials are increasingly consumed, inhumane mining work, abuse of people and the environment and long-term damage to health are accepted, in order to develop and apply more and more innovative technologies and with incessant focus on the economical benefits [51]? The study considers potential dangers not only in the consumption of resources, but in increasingly complex risk areas of data misuse. Protection is one of the success criteria for sustainability. This also applies to data communication: Municipalities are largely administratively unable to handle approval processes digitally, since many companies lack a digital infrastructure [52]. The Digital Innovation Agenda 2022 (EU), the Strategic Perspective on Digital Change 2022 (EU), declarations of intent by the German government and the G20 - Summit 2022 on digitization, innovations and data sovereignty do not correspond to current practice in public administration, in the companies as well as in the project-related data and knowledge communication between these parties.

Although the digitization of the supply chain offers great growth opportunities and long-term cost savings, it is accompanied by additional problems that are also covered in this study: the expansion of the IT infrastructure is not keeping pace with the development of new digital business models and the end-to-end digitization of the supply chain, companies are stuck in the test phase and projects are not used operationally, digitization is not yet declared an important corporate goal, development and expansion with targeted investment is not made a top priority and is promoted with the involvement of suppliers, traditional contractual and commercial processing structures are used recorded, real-time information and traceability are missing. However, research on CDR in Construction 4.0 recognizes these above mentioned conditions as the decisive factors for successful digital change and for adding value [53,54]. Blockchain technology cannot be built, nor can intelligent business transactions, cryptocurrencies and reliable asset tracking be implemented without transparent, end-to-end digitized supply chains [55].

Based on the knowledge gained, the study points out that when designing the digital transformation, it must be considered where innovative technologies make sense, reduce resources, and support people in efficient and safe work. A clear distinction should be made between the lack of knowledge, the lack of ability to assess security risks, the misuse of data and the exploitation of people and resources. There is a severe danger of becoming part of so-called greenwashing, i.e. propagating superficial advantages and high benefits, which, however, come at the expense of violations of personal and data rights, environmental depletion and resource consumption that is harmful to people and society. The research "CDR in Construction 4.0" investigates the question of how such a countermeasure can succeed. The *Excellence Initiative for sustainable, human-led AI in the Construction* raises awareness and gets engaged the branch in the global debate - especially recognizing that the Scientific Advisory Council of the Federal Government and the German Federal Office for Radiation Protection both warn against unchecked digitization that is not aligned with sustainability criteria.

7. Discussion

AI strongly influences the scientific discussion about technological feasibility, its sustainability in the AEC industry and ecosystems for shared value creation. The study provides concrete innovative approaches for the future of cities, working and living environments for today's society and all future generations. The sustainable design of intelligent, smart urban mobility, transport and traffic systems, assistive smart cities may only succeed through interdisciplinary cooperation and the integration of human and social science considerations. They are crucial for holistically thought-out legal, social and technical decision-making processes, the study determines. The results of the evaluation of the interviews, and experiences of best practice companies in combination with a comprehensive literature research emphasize education is the engine of success. In addition to an adapted competence profile of the Civil Engineer and contents of curricula, it also requires the adaptation of the qualification of academic and training staff.

From the surveys it can be deduced that companies do not only rely on legal and official guidelines to tackle emerging digital challenges. Such policies typically cannot keep up with the pace of technological advances. Rather, it is important to play a responsible role in shaping the digital transformation, as the EU Commission is striving for with the Digital Innovation Agenda 2022 [56], the Strategic Foresight 2022 [57] and the Task Force for Digital Common Goods [58]. The Construction sector stands out of other branches as one of the most important catalysts for CO_2 reduction.

8. Conclusions

The study concludes that the pioneers in Construction are role models offering other companies orientation in navigating innovative technologies in Construction 4.0. Thus, a milestone for Germany as a location for research and education may be achieved. In order to take into account the entrepreneurial, social, legal and political aspects that are critical for successful digital transformation, which makes up a significant part of the value chain for the Construction Industry, the study recommends deepening research work in this new scientific field. Engineers, architects, designers and craftsmen are more than just designers of living and working environments. They design technical, social, societal and human changes in construction 4.0. In the sense of the trustworthy development and use of a human-friendly AI, the study identifies as a critical path, that not only designer's planning but the holistic life-cycle of projects and the built environment involve dealing with the "dark" side of the technical feasibility. Considering technological development at high speed means a turning point to set the course immediately.

This success-critical factor has not been adequately researched though represents a significant limitation. Previous studies, e.g. by the Fraunhofer Institute Austria in 2022, highlight that sensible and sustainable technology development and the increase in the maturity of AI applications require new qualifications, new knowledge, improved transfer of knowledge between research and practice and a new corporate culture of thinking and openness towards innovation. Only then, so the study analyzes, digitalization and AI may be weighed up in a differentiated manner. The study also comes to the conclusion that there are still too few use cases and innovative champions, though having a high trust-inspiring effect on other companies. New insights won from interviewed Best Practice clarify that a radical re-thinking in the AEC industry is necessary to achieve an intended sustainable technical, social and human change of Baukultur 4.0 [59] and achieve trustworthy human-machine interaction [60,61]. This is one of the motivational elements for the first author's "*Excellence Initiative for sustainable, human-led AI in Construction*" - in research cooperation with the *Institute for Sustainability in Construction INaB at RWTH Aachen University*—to bring the Construction Industry into the global ethics and AI dialogue for the first time in an interdisciplinary manner and further expand this newly discovered field of research.

Author Contributions

This research article has been conceptualized and written by Bianca Weber-Lewerenz and reviewed by Prof. Marzia Traverso (Ph.D.).

Conflict of Interest

The authors declare having no conflict of interest.

Ethical Statement

The first author of this study conducts external research, is company-independent and is not financially supported by third-party funds, companies or other institutions. This enables neutral, critical, and inclusive research and promotion of ethical debate about AI technologies.

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References

[1] ElMassah, S., Mohieldin, M., 2020. Digital transformation and localizing the Sustainable Development Goals (SDGs). Journal of Ecological Economics. 169, 106490.
DOI: https://doi.org/10.1016/j.ecolecon.2019.106490

[2] Lopes de Sousa Jabbour, A.B., Jabbour, C.J.C., Godinho Filho, M., et al., 2018. Industry 4.0 and the circular economy: A proposed research agenda and original roadmap for sustainable operations. Annals of Operations Research. 270, 273-286.
DOI: https://doi.org/10.1007/s10479-018-2772-8

[3] BMWi, 2019. Einsatz von Künstlicher Intelligenz in der Deutschen Wirtschaft Stand der KI-Nutzung im Jahr 2019, Studie des Bundesministeriums für Wirtschaft und Energie (German) [Use of artificial intelligence in the German economy Status of AI use in 2019, study by the Federal Ministry for Economic Affairs and Energy]. p. 20. [Internet] [cited 2021 May 6]. Available from: https://www.bmwk.de/Redak-

tion/DE/Publikationen/Wirtschaft/einsatz-von-ki-deutsche-wirtschaft.pdf?__blob=publicationFile&v=8#:~:text=Im%20Jahr%202019%20setzten%20rund,17%2C8%20%25%20erheblich%20h%C3%B6her

[4] BMWi, 2019. Einsatz von Künstlicher Intelligenz in der Deutschen Wirtschaft Stand der KI-Nutzung im Jahr 2019, Studie des Bundesministeriums für Wirtschaft und Energie (German) [Use of artificial intelligence in the German economy Status of AI use in 2019, study by the Federal Ministry for Economic Affairs and Energy]. p. 28. [Internet] [cited 2021 May 6]. Available from: https://www.bmwk.de/Redaktion/DE/Publikationen/Wirtschaft/einsatz-von-ki-deutsche-wirtschaft.pdf?__blob=publicationFile&v=8#:~:text=Im%20Jahr%202019%20setzten%20rund,17%2C8%20%25%20erheblich%20h%C3%B6her

[5] Gomez-Trujillo, A.M., Gonzalez-Perez, M.A., 2021. Digital transformation as a strategy to reach sustainability. Smart and Sustainable Built Environment. 11(4), 1137-1162.
DOI: https://doi.org/10.1108/SASBE-01-2021-0011

[6] Feroz, A.K., Zo, H.J., Chiravuri, A., 2021. Digital transformation and environmental sustainability: A review and research agenda. Journal for Sustainability. 13(3), 1530.
DOI: https://doi.org/10.3390/su13031530

[7] Weber-Lewerenz, B., Vasiliu-Feltes, I., 2022. Empowering digital innovation by diverse leadership in ICT—A roadmap to a better value system in computer algorithms. Humanistic Management Journal. 7(1), 117-134.
DOI: https://doi.org/10.1007/s41463-022-00123-7

[8] Lo, C.K., Chen, C.H., Zhong, R.Y., 2021. A review of digital twin in product design and development. Journal of Advanced Engineering Informatics. 48, 101297.
DOI: https://doi.org/10.1016/j.aei.2021.101297

[9] Ye, Z.P., Yang, J.Q., Zhong, N., et al., 2020. Tackling environmental challenges in pollution controls using artificial intelligence: A review. Journal of Science of the Total Environment. 699, 134279.
DOI: https://doi.org/10.1016/j.scitotenv.2019.134279

[10] Ernstsen, S.N., Whyte, J., Thuesen, C., et al., 2021. How innovation champions frame the future: Three visions for digital transformation of construction. Journal of Construction Engineering and Management (ASCE). 147(1).
DOI: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001928

[11] Leiringer, R., Cardellino, P., 2010. Tables of the expected: Investigating the rhetorical strategies of innovation champions. Journal of Construction Management and Economics. 26(10), 1043-1054.
DOI: https://doi.org/10.1080/01446190802389394

[12] Xue, X., Zhang, R., Yang, R., et al., 2014. Innovation in construction: A critical review and future research. International Journal of Innovation Science. 6(2), 111-126.
DOI: https://doi.org/10.1260/1757-2223.6.2.111

[13] Grunwald, A., Hillerbrand, R., 2021. Überblick über die Technikethik (German) [Overview on technical ethics handbook technical ethics]. J.B. Metzler Publishing: Stuttgart.
DOI: https://doi.org/10.1007/978-3-476-04901-8_1

[14] Grunwald, A., 2020. Verantwortung und Technik: zum Wandel des Verantwortungsbegriffs in der Technikethik (German) [Responsibility and technology: On the change in the concept of responsibility in technology ethics]. Springer Publishing: Berlin, Heidelberg.
DOI: https://doi.org/10.1007/978-3-662-60564-6_13

[15] Jonas, H., 1987. Warum die Technik ein Gegenstand für die Ethik ist: fünf Gründe. Technik und Ethik (German) [Why technology is a subject for ethics: Five reasons. Technology and ethics]. 2, 81-91.

[16] Grunwald, A., 2001. Technikfolgenabschätzung: Eine Einführung (German) [Technical assessment: An introduction]. Sigma Publishing: Rawalpindi.

[17] Holz, H.H., Hubig, C., 2013. Technik-und Wissenschaftsethik. Ein Leitfaden (German) [Technical and economical ethics: A guide]. Nachden-

ken über Technik. Nomos Verlagsgesellschaft mbH & Co. KG Publishing: Baden-Baden. pp. 449-454.

[18] Hubig, C., 2015. Einleitung (German) [Introduction]. Die Kunst des Möglichen I. Transcript Publishing: Bielefeld. pp. 15-36.
DOI: https://doi.org/10.14361/9783839404317

[19] Hubig, C., 2015. Die Kunst des Möglichen III: Grundlinien einer dialektischen Philosophie der Technik (German) [The art of the possible III: Basic lines of a dialectical philosophy of technology]. Transcript Publishing: Bielefeld.
DOI: https://doi.org/10.1515/transcript.9783839428122

[20] Hubig, C., 2004. Ethische Ingenieurverantwortung. Handlungsspielräume und Perspektiven der Kodifizierung (German) [Ethical engineering responsibility. Scope for action and perspectives of codification]. Verein Deutscher Ingenieure: Düsseldorf.

[21] Blankenbach, J., Becker, R., 2020. BIM und die Digitalisierung im Bauwesen (German) [BIM and digitization in construction]. Handbook Industry 4.0: Law, Technic, Society. Springer Publishing: Berlin, Heidelberg.
DOI: https://doi.org/10.1007/978-3-662-58474-3_40

[22] Wieland, J., 2014. Handbuch Compliance-Management: Konzeptionelle Grundlagen, praktische Erfolgsfaktoren, globale Herausforderungen (German) [Compliance management handbook: Conceptual foundations, practical success factors, global challenges]. Erich Schmidt Publishing: Berlin.

[23] Eming, K., 2011. Compliance als Problem der Wirtschafts- und Unternehmensethik (German) [Compliance as a problem of business and corporate ethics]. Interdisciplinary Aspects of Compliance. Nomos Verlagsgesellschaft mbH & Co. KG Publishing: Baden-Baden. pp. 39-64.

[24] Hauschka, C.E., 2016. Corporate compliance. C.H. Beck Publishing: Munich.

[25] Sun, M.L., Zhang, J., 2020. Research on the application of block chain big data platform in the construction of new smart city for low carbon emission and green environment. Journal for Computer Communications. 149, 332-342.
DOI: https://doi.org/10.1016/j.comcom.2019.10.031

[26] Region Stuttgart, 2022. Symposium Zukunft Bauen | 3. Symposium [Video]. [cited 2023 Mar 30]. Available from: https://www.youtube.com/watch?v=fcQDL01kDKE

[27] Schranz, C., 2022. Mit (Digital-) Kompetenz in die Zukunft. Standpunkt (German) [With (digital) competence into the future. Taking position]. Der Bauingenieur. 97(4), A3.
DOI: https://doi.org/10.37544/0005-6650-2022-04

[28] Adam, C., 2020. Mit solider Grundlagenausbildung in eine (bau-) dynamische Zukunft (German) [With solid basic training in a (construction) dynamic future]. Der Bauingenieur. 95(12), A3.
DOI: https://doi.org/10.37544/0005-6650-2020-12

[29] Bundesministerium des Innern, für Bau und Heimat BMWi, 2021. Modellprojekte Smart Cities 2021 Gemeinsam aus der Krise—Raum für Zukunft. Studie des Bundesministeriums für Wirtschaft und Energie (BMWi) (German) [Model projects Smart Cities 2021. Together out of the crisis—room for the future. Study by the Federal Ministry for Economic Affairs and Energy (BMWi)] [Internet] [cited 2022 Mar 15]. Available from: https://www.smart-city-dialog.de/wp-content/uploads/2021/10/BMI-SmartCities_Modellprojekte2021.pdf

[30] ICLEI—Local Governments for Sustainability, 2021. The European Circular Cities Declaration [Internet] [cited 2022 May 6]. Available from: https://circularcitiesdeclaration.eu/

[31] Sarc, R., Curtis, A., Kandlbauer, L., et al., 2019. Digitalisation and intelligent robotics in value chain of circular economy-oriented waste management—A review. Journal for Waste Management. 95, 476-492.
DOI: https://doi.org/10.1016/j.wasman.2019.06.035

[32] Goralski, M.A., Tan, T.K., 2020. Artificial intelligence and sustainable development. The International Journal of Management Education. 18(1), 100330.

DOI: https://doi.org/10.1016/j.ijme.2019.100330

[33] Council of the European Union, 2016. Schlussfolgerungen des Rates zu einer Städteagenda für die EU (German) [Council conclusions on an urban agenda for the EU] [Internet] [cited 2022 May 6]. Available from: https://www.consilium.europa.eu/de/press/press-releases/2016/06/24/conclusions-eu-urban-agenda/

[34] Federal Institute for Building, Urban and Spatial Research, 2021. Smart City Charta [Internet] [cited 2022 May 6]. Available from: https://www.smart-city-dialog.de/wp-content/uploads/2021/04/2021_Smart-City-Charta.pdf

[35] World Economic Forum WEF, 2021. Governing Smart Cities Report. Governing Smart Cities: Policy Benchmarks for Ethical and Responsible Smart City Development. White Paper July 2021 [Internet] [cited 2022 May 6]. Available from: https://www3.weforum.org/docs/WEF_Governing_Smart_Cities_2021.pdf

[36] Braungart, M., McDonough, W., 2014. Cradle to Cradle: Einfach intelligent produzieren (German) [Cradle to cradle: Simply produce intelligent]. Piper Verlag: München.

[37] Jehle, P., 2022. Inkonsequenz bremst Betonrecycling (German) [Inconsistency slows down concrete recycling]. Der Bauingenieur. 97(4), A16. DOI: https://doi.org/10.37544/0005-6650-2022-04

[38] Fajga, K.W., 2022. Ehrgeizige Ziele gesetzt. Interview mit Fred Cortes (German) [Ambitious goals set. Interview with Fred Cortes]. Allgemeine Bauzeitung ABZ. 18, 3.

[39] Giannakidis, A., Weber-Lewerenz, B., Stolze, D., 2021. KI im Bauwesen in Deutschland. Forschungsstudie des Fraunhofer Instituts Stuttgart IAO (German) [AI in construction in Germany. Research study by the Fraunhofer Institute Stuttgart IAO]. Fraunhofer Piublishing: München. [cited 2022 May 6]. Available from: https://publica.fraunhofer.de/handle/publica/300849

[40] Rosha, A., Lobanova, L., 2022. Ethical responsibility of a company in the context of digital transformation of work: Conceptual model. Journal of Sustainability. 14(18). DOI: https://doi.org/10.3390/su141811365

[41] Del Rosario, P., Backes, J.G., Traverso, M., 2022. Level(s)—Eine gemeinsame europäische Methode zur Bewertung der Nachhaltigkeitsleistung von Gebäuden (German) [Level(s)—A common European method for assessing the sustainability performance of buildings]. Der Bauingenieur. 11(3), 385-392. DOI: https://doi.org/10.37544/0005-6650-2022-11-67

[42] Weber-Lewerenz, B., 2022. Thinking otherwise: Integrating existing buildings and monument protection in smart cities—Experience shared from user practice. Impact of Digital Twins in Smart Cities Development. IGI Global Publishing: Hershey. DOI: https://doi.org/10.4018/978-1-6684-3833-6

[43] Razmjoo, A., Østergaard, P.A., Denaï, M., et al., 2021. Effective policies to overcome barriers in the development of smart cities. Journal of Energy Research & Social Science. 79, 102175. DOI: https://doi.org/10.1016/j.erss.2021.102175

[44] Agnusdei, G., Elia, V., Gnoni, M.G., 2021. Is digital twin technology supporting safety management? A bibliometric and systematic review. Journal of Applied Sciences. 11(6), 2767. DOI: https://doi.org/10.3390/app11062767

[45] Kirchschläger, P.G., 2021. Ethische Verantwortung in der digitalen Transformation (German) [Ethical responsibility in the digital transformation]. Journal of Risk, Fraud and Compliance ZRFC. 9(6), 253.

[46] Pilgrim, H., 2017. The dark side of digitalization: Will Industry 4.0 create new raw materials demands? PowerShift e.V. Publishing: Berlin.

[47] European Commission of Regions, 2021. Stellungnahme zum Aktionsplan für kritische Rohstoffe (German) [Opinion on the action plan for critical raw materials] [Internet] [cited 2022 Jul 13]. Available from: https://cor.europa.eu/de/news/Pages/critical-raw-materials-role-future-of-europe.aspx

[48] Elshkaki, A., Graedel, T.E., Ciacci, L., et al., 2016. Copper demand, supply, and associated

energy use to 2050. Journal of Global Environmental. 39, 305-315.
DOI: https://doi.org/10.1016/j.gloenvcha.2016.06.006

[49] DERA Deutsche Rohstoffagentur, 2016. Rohstoffe für Zukunftstechnologien 2016. Bundesanstalt für Geowissenschaften und Rohstoffe BGR (German) [Raw materials for future technologies 2016. Federal Institute for Geosciences and Natural Resources] [Internet] [cited 2022 May 6]. Available from: https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie_Zukunftstechnologien-2016.html

[50] Höfer, T., Bierwirth, S., Madlener, R., 2020. Energie-Mehrverbrauch in Rechenzentren bei Einführung des 5G Standards. Konferenzpapier zur Tagung "Nachhaltige Rechenzentren—Chancen und Entwicklungsmöglichkeiten am Standort Baden-Württemberg" (German) [Additional energy consumption in data centers when the 5G standard is introduced. Conference paper for the conference "Sustainable data centers—opportunities and development opportunities in Baden-Württemberg"] [Internet] [cited 2022 May 6]. Available from: https://www.nachhaltige-rechenzentren.de/wp-content/uploads/2020/03/1-Madlener_5G-Standard-und-Rechenzentren.pdf

[51] Rüttinger, L., 2016. Fallstudien zu Umwelt- und Sozialauswirkungen der Bauxitgewinnung und -weiterverarbeitung in der Boké und Kindia-Region, Guinea (German) [Case studies on environmental and social impacts of bauxite mining and processing in the Boké and Kindia region, Guinea]. Adelphi (Edt.) Publishing: Berlin.

[52] Fiedler, M., 2022. BIM und Baubehörde—ein Erfahrungsbericht. Strukturierte Daten für die digitale Zusammenarbeit im Infrastrukturbau: BIMSTRUCT (German) [BIM and building authorities—a field report. Structured data for digital collaboration in infrastructure construction: BIMSTRUCT] [Internet] [cited 2022 May 6]. Available from: https://www.bsdplus.de/fachartikel/von-einem-der-auszog-das-fuerchten-zu-lernen-bim-und-baubehoerde-ein-erfahrungsbericht.html

[53] Frieske, B. Huber, A., Stieler, S., et al., 2022. Zukunftsfähige Lieferketten und neue Wertschöpfungsstrukturen in der Automobilindustrie (German) [Sustainable supply chains and new value creation structures in the automotive industry]. Project report, Institute for automobile concepts. p. 247. Available from: https://elib.dlr.de/187017/

[54] Gharaibeh, L., Eriksson, K.M., Lantz, B., et al., 2022. Toward digital construction supply chain-based Industry 4.0 solutions: Scientometric-thematic analysis. Smart and Sustainable Built Environment. (Preprint).
DOI: https://doi.org/10.1108/SASBE-12-2021-0224

[55] Tezel, A., Papadonikolaki, E., Yitmen, I., et al., 2020. Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions. Journal of Frontiers of Engineering Management. 7(4). 547-563.
DOI: https://doi.org/10.1007/s42524-020-0110-8

[56] European Commission, 2022. New European Innovation Agenda [Internet] [cited 2022 Jul 13]. Available from: https://www.eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0332

[57] European Commission, 2022. Neue Strategische Vorausschau. Verzahnung von grünem und digitalem Wandel im neuen geopolitischen Kontext (German) [New strategic forecast: Dovetailing of green and digital change in the new geopolitical context] [Internet] [cited 2022 Jul 13]. Available from: https://www.ec.europa.eu/info/files/strategic-foresight-report-2022_en

[58] Building Europe's Digital Sovereignty Conference, 2022. Task Force on Digital Commons [Internet] [cited 2022 Jul 13]. Available from: https://www.presidence-francaise.consilium.europa.eu/en/news/the-building-europe-s-digital-sovereignty-conference/

[59] Weber-Lewerenz, B., 2021. Die unternehmerisch verantwortungsvolle Digitalisierung im

Bauwesen (German) [CDR in construction]. Der Bauingenieur. 96(01-02), 19-25.
DOI: https://doi.org/10.37544/0005-6650-2021-01-02-45

[60] German Ethics Council, 2023. Humans and Machines—Challenges of Artificial Intelligence [Internet] [cited 2023 Apr 6]. Available from: https://www.ethikrat.org/fileadmin/Publikationen/Stellungnahmen/deutsch/stellungnahme-mensch-und-maschine.pdf

[61] Future of Life Institute, 2023. Pause Giant AI Experiments: An Open Letter [Internet] [cited 2023 Apr 6]. Available from: https://www.futureoflife.org/open-letter/pause-giant-ai-experiments/