Abstract
The world around us is changing at a rapid pace. Emerging megatrends like robotics, artificial intelligence, cloud computing and many more are reshaping activities in our personal and professional life. This presentation will address the major drivers of the digital transformation and how it affects our industry. It will identify disruptions, threats and opportunities that professionals, managers and companies have to address in order to be successful in the future. We will also spend some time looking on the impact of the COVID-19 pandemic on NDE and how the New Normal is affecting the way we have been working in the past. This presentation will help NDE experts to understand ‘’the why’’ of the emerging NDE 4.0 transformation. Due to the expertise of the lecturer, the talk will heavily focus on Radiography (RT). To provide a better understanding there will be many practical examples that will illustrate the concepts.

Keywords: NDT 4.0, Automation, Robotics, Digitalization, Radiography

1. Introduction
NDT 4.0 is a commonly established term for a plethora of technologies. As with every innovation it is crucial to understand why companies and managers should implement them for their operation [1]. Therefore, one must understand the underlying economic drivers that lead to the necessity to change the status quo. The fact that NDE 4.0, like Industry 4.0, is a collective term for technologies ranging from Artificial Intelligence (AI), over robotics to Additive Manufacturing (AM) leads to an unclear picture of the relevance for individual stakeholders. Certainly, not all technologies provide value in the same way for every company and situation. Therefore, it is important to explore the technologies combined into NDE 4.0 individually. It is crucial that responsible managers carefully analyze the impact of each aspect on their operation and business. Is there a risk for an external disruption? Is it possible to increase efficiency? Is a fundamental process transformation required? As NDE managers are operating in a commercial setting, it is required to formulate the impact in economic terms. Of course, technical evaluation is also very important, and every responsible person must first check the technical viability and whether an innovation can be certified against industry standards. But finally, the innovation must be assessed in terms of economic viability. This means there must be an assessment of the costs, savings and ultimately Return of Investment (ROI). Otherwise, it is impossible to quantitatively justify the investment to the company’s management or controllers.

2. NDE 4.0 in practice
The concept of NDE 4.0 is simply a subset of change sectors that are driven by the far bigger movement of Industry 4.0. It is important to understand where the term comes from. Figure 1 shows the different phases of industrial revolution and the next section will briefly describe the history of the different NDE industrialization stages on the example of Radiographic Testing (RT) [2].
2.1 The Evolution of Industry 4.0

The first industrial revolution happened between the late 1700s and early 1800s. By using water and steam-powered engines in addition to other types of machine tools manufacturing evolved beyond the manual labor performed by people. In Radiographic Testing this phase is representing the status of using analog film and isotopes.

In the early part of the 20th century, the world entered the second industrial revolution with the use of electricity in factories increasing efficiency and productivity. Mass production concepts such as the assembly line were introduced. In Radiographic Testing the changes of this phase would be to incorporate electric components to improve the process and workflow. Particularly, this goes along with the usage of X-ray tubes that replace the isotopes, simple manipulators and automated film developers.

Starting in the late 1950s, a third industrial revolution slowly began to emerge, as manufacturers began incorporating more electronic and eventually computer based technology into their factories. A shift from analog and mechanical technology to digital technology and automation software started. Within the RT world this phase is characterized by the transition to digital detectors, NC programmable manipulators, digital archiving systems and robotics. This phase is often confused with the fourth phase. It is very important to note that a robot and an ERP connection is not enough to qualify for an NDE 4.0 system.

The fourth industrial revolution is characterized by connected computer systems, cloud utilization, the Internet of Things (IoT), Smart Factories, Big Data, Artificial Intelligence (AI), autonomous robots, predictive maintenance, and Additive Manufacturing (AM). The adoption of these technologies is leading to substantial improvements in productivity. Within the NDE world this results in fully integrated in-line systems, cloud connectivity, usage of AI for interpretation and advanced analytics. High performance gains were realized by the integration of NDE directly into the manufacturing line. Self-adapting systems allow automation to be used even on very small batch sizes. Defects are automatically detected and compared against inspection criteria and Computed Tomography (CT) is used to three dimensionally reconstruct objects and to perform complex analysis.
This means that NDE professionals on the shop floor face fundamental challenges and may have a steep learning curve ahead as the new tools often require a different approach and perhaps even a completely different skill set [3]. Managing this change is the key for future success and competitiveness. Figure 2 shows the different fields of Industry 4.0, which also apply to our sector. This section will assess some of them and should provide a good overview, by introducing real examples where they already impact NDE today.

### 2.2 Robotics

First, we will investigate robotics and simulations, allowing repetitive handling tasks to be automated, allowing higher throughput, lower inspection costs and higher process safety. Figure 3 shows an example solution where three robots work in jointly to inspect airducts and pipes used in the aerospace industry. This team of robots collaborate, sharing the tasks of part handling and inspection. This way, cycle time is effectively reduced from several hours to a several minutes and a healthier work environment is created for operators, where heavy and potentially dangerous tasks are performed by machines [4].

Image quality is always supervised as the system performs automatic long-term performance evaluations according to ASTM E2737. New programs can be programmed offline – including the option to use a CAD/CAM simulation tool so that the system can be utilized 100% for production and does not need to be shut down for engineering purposes, thereby significantly increasing system utilization and throughput. To further optimize the process X-ray technicians can simulate the X-ray images digitally before even loading the part into the system. This allows to easily check the inspectability of the part and enables operators to establish the right X-ray parameters very early in the process. Systems these days have to communicate with the factory or enterprise management software (ERP/MES) and many other systems in the shop floor. The advantage of automated systems grows exponentially if generated data can be used in real-time to fine-tune the manufacturing process.
2.3 Artificial Intelligence, Big Data and Automated Quality Control

Another significant focus of Industry 4.0 includes Artificial Intelligence (AI) and Big Data. These concepts are realized for example as Automated Defect Recognition (ADR) in Radiography [5]. The R&D driven company VisiConsult X-ray Systems & Solutions GmbH for example, is currently developing an AI platform to detect defects even more reliably and more automated than in the past. X-ray technology is always used in non-destructive testing. Unlike optical processes, internal defects like pores, inclusions or geometries can also be tested. By replacing analogue film with digital detectors the data is available in real time and can be be evaluated and processed immediately.

For 20 years, the company has been delivering ADR systems, which detect errors automatically after a human did a component-specific parameterization. Specialists from VisiConsult predict that by using artificial intelligence, this effort could be reduced massively. Initial tests with available AI frameworks already achieved detection rates of up to 90% in a blind study compared to the conventional procedure.

Crucial for the success of an AI is the number and quality of the underlying image data. For this reason, VisiConsult has developed a cloud solution into which cooperation partners can upload evaluated image data. These are anonymized and used to parameterize the AI. The higher the quality of the data, the better the AI can become. VisiConsult’s defect database includes multivalued multi-user records with marked and classified errors. As a specialist for fully automated inspection systems, VisiConsult has developed a patent for automatic robot positioning: Through the combination of robotics, 3D sensors and image registration a high positioning repeatability can be achieved without additional components. This system will now be combined with the new AI solutions, reducing the ramp-up process from several days to a few hours.
2.3.1 Defect Recognition

Typical applications for defect recognition are casting parts. The ADR software should automatically classify typical casting defects like porosities and inclusions. Figure 4 shows the result of such a classification. On the left side is the evaluated part and defect list, while on the right one can see the original X-ray image. Different parts of the image allow different error thresholds. This can be defined by the Level III through inspection Region of Interests. Depending on the inspection guideline criteria for classification different parameter such as defect depth (contrast), distance to surface, defect size or defects per area can be calculated.

2.3.2 Geometric Evaluation

Even though most applications in NDT are looking for typical defects in produced parts it might be important to check for geometry, alignment, completeness or other aspects inside complex parts. Dedicated ADR software allows to perform these checks automatically. Figure 5 shows automatic evaluation of a flash-bang grenade. Checks performed are presence of the safety pin, length of the fuse delay, homogeneity of the explosive material, alignment of internal structures and much more. X-ray is the only technique allowing to perform these checks in a non-destructive manner.
2.4 Additive Manufacturing andComputed Tomography

Additive manufacturing (AM) offers new possibilities in manufacturing and designing products. The aerospace and automotive industry is a main driver because of the possibility to manufacturing lighter structures that reduce weight and save fuel. During the manufacturing process different discontinuities or defects can occur, depending on the applied AM technology. To ensure constant manufacturing quality of the parts it is required to perform a regular sampling or 100% inspection using non-destructing methods. Currently CT is the leading technology that is suited to sufficiently inspect complex AM parts to qualify them for safety critical environments [6]. By acquiring substantial amounts of digital radiographs and computing them into a 3D model, as can be seen in figure 6(a), we can gain information about parts like we never have before [7]. It is also possible to do advanced analyses like actual-nominal comparison, porosity analysis and metrology. With increasing computational power, we currently see CT moving from a lab environment to the shop floor. This allows to implement inline CT systems that perform a 100% inspection of parts while at the same time checking geometric tolerances.

The AM technology is growing unrestricted but there are some limitations include the standardization of the process, qualification of the parts and optimization of the manufacturing process. The motivation to use the opportunities of AM promote the development of qualified inspection techniques. CT offers a wide range of analysis methods to evaluate such complex structures depending on the application. In many places different institutes and organisations working on a standardisation for AM products and their qualification.
2.5 Digitalization – Cloud and Connectivity

With today’s technology it becomes possible to connect nearly everything – system to remote viewer, systems to other connected systems, systems in different factories, and if desired even complete connected factories around the globe. Today it is possible to have image acquisition locally, computer scientists call it “the edge”, and interpretation centralized in an excellence center. This could be a solution to compensate for the lack of qualified personnel that many companies face or temporary imbalances of workloads. Standardized interfaces on machine communication like OPC UA allow systems to interact, while standardized data formats like DICONDE [8] allow interoperability between devices from different manufacturers. Currently, NDE is often only seen to ensure quality, but it can provide so much more information.

VisiConsult offers a solution that can link systems and even global sites into a single inspection platform. It allows evaluations to be performed from remote locations or even from home office. This drastically reduces the need for highly skilled personnel at each individual system and at the same time it ensures a baseline for inspection quality. Figure 7 shows an exemplary setup using different modalities.

All data is archived in a local data center, and an AI is constantly trained in the background. The smarter the system gets, the more help the interpreters/inspectors get, which further improves the image evaluation quality, while the goal is to statistically prove that the probability of detection of the AI algorithms is good enough to be implemented. This simple scenario shows the powerful impact that robotics, cloud connection, system integration and AI can have on our industry.
3. The Impact of NDE 4.0

It is important to note that the value potential will differ between industries and individual companies [9]. In this section we will explore the different ways that NDE 4.0 can have a positive economic impact through improvements of efficiency and effectiveness. Additionally, we will also evaluate the possibility of disruptive innovations that create a completely new paradigm to value creation derived from NDE [10].

3.1 Incremental Innovation: Efficiency

Increasing the efficiency of processes has been the common theme of the past industrial revolutions. Moving from manual labor to steam powered machines (1.0) to manufacturing lines (2.0) to robotics, each industrial revolution has increased the efficiency of manufacturing and inspection processes. NDE 4.0 is also offering a huge potential for further efficiency increases.

The economic value of automation, and thereby efficiency increases, depends on the required investment costs and the operating cost reductions. To achieve the optimum cost the different factors must be carefully balanced. Ultimately, investments into process efficiency are most of the time depending on simple cost and volume considerations. The question is mainly, does the volume justify the investment and how will it influence the unit costs. It can very well be that a higher efficiency will indeed reduce the operating costs significantly, but the investment is spread out over so few units that it is not possible to recoup them over a reasonable period. There are many examples for efficiency increases: Implementation of process automation and robotics, digitalization of the data acquisition process and many more.

3.2 Incremental Innovation: Effectiveness

Innovations focused on increasing efficiency are quite straight forward. They take an established process and optimize it using process improvements or new technology. In some cases, the rigid quality process requirements in NDE make efficiency increases the only option to innovate. But often enough there is the possibility to also work on the process itself – to make it more effective. Typically, this type of innovation us is much harder to achieve as it requires to rethink the process and potentially
also to perm a new process qualification. A reduced effective throughput might be caused for example by fluctuations in part throughput, unscheduled breaks, and other factors. In case of a X-ray imaging an aggregation of all images into a central data storage in the cloud and connect review stations from several locations might be considered to improve the effective throughput as shown in figure 7. Also, it can be assumed that more aggregated data leads to better trained ADR systems, which will further drive down the false reject rates and thereby saving costs. Increasing effectiveness follows the same economic principle as efficiency. Responsible managers must carefully analyze their operations to understand the composition of their cost curves. Where do costs come from (e.g. labor vs. consumables vs. CAPEX)? How easy can certain things be changed? What are the lowest hanging fruits and which levers have the biggest impact? When looking at the hard facts, it is very important to never forget the additional value that is added through soft factors. But even more important is to assess the risk that is associated with the innovation and whether the organization has the capabilities to implement it.

3.3 Disruptive Innovation: Paradigm Shift

The data-driven trends of Industry 4.0 and NDE 4.0 are fueled by information provided from industrial sensors – also called the Industrial Internet of Things (IIoT) [11]. These sensors are omnipresent and range from discrete data points such as temperature, time, position, etc. to the most complex sensors that provide a much higher depth of information. One such sensor found in NDE are for example CT systems – arguably a sensor that has the potential to deliver a high level of information regarding a company’s product and processes. In manufacturing in general, one of the hottest technologies with high potential is the concept of digital twins, which are considered as virtual copies of manufactured products or equipment. What people sometimes do not realize is that NDE can supply a lot of information that can be used to build this digital twin! Imagine the possibilities when you have all the as-built data for every component combined with ever-advancing simulation capabilities. This is a paradigm shift for our industry, transforming NDE from a pure quality step to a full industrial sensor in the manufacturing process. So we must ask ourselves what else can we learn from the hundreds and thousands of images that we are generating? The possibilities are vast, and the NDE world can be proud to provide that information. The step to see NDE not only as a Quality Assurance (QA) and Quality Control (QC) process, but as a comprehensive process sensor, is a revolutionary paradigm shift [9].

4. Conclusions

This paper has shown some of the key-aspects of Industry 4.0 within NDT. It shows that we are already on the journey towards implementation in our industry. Are we there yet? For sure not. The main challenges are that we do not have a complete conversation from analogue (film) to digital operation principles. This third industrial revolution is still ongoing – in some industries faster in others slower.

Another challenge is training and education. The new technology requires a completely different skillset than the technology of the past. It is highly suggested to start early to train the needed skills to responsible operators. We can typically see a level of rejection and fear if automation is in discussion. Even the best AI or automated systems will not replace trained and skilled operators.

When assessing the potential of innovations, it is recommended to take a step back and to assess the effectivity (“Are we doing the right things?”) and efficiency (“Are we doing things right?”). Then one should proceed to analyze on which dimension the innovation will have an impact. This will help a lot
to determine the right way forward and what it will take to get implemented. To perform an orderly risk assessment, it is helpful to classify whether it is an incremental or a disruptive innovation. Performing these analyses early will help to identify all stakeholders and parties that must get involved at an early stage [12]. Only when all stakeholders bought into the idea and the economic feasibility has been confirmed, one should take it to management for consideration.

To put it in a nutshell, NDT 4.0 is the movement of our century. Even though we have many challenges to overcome the benefits and gains of this technology will be massive. It will also be an enabler technology that will increase the added value of NDT to the production.

References