FYI

Industrial X-ray Inspection: A Guide to Customized Inspection Solutions and Digital Radiography – Part 1
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Introduction
X-ray inspection is a widely adapted technology for quality control of industrial products in many sectors. In particular, safety relevant parts in the aerospace, automotive, and oil and gas sectors are subject to exhaustive tests. A broad and sometimes confusing palette of international, national, and company specific quality standards and requirements has to be closely followed to pass the demanding audits. Additional uncertainty is evolving from the constant technology shift to digital radiography. The quality and variety of digital detector arrays (DDAs) is increasing at a faster pace than ever, allowing their usage in more and more applications.

At the same time as quality requirements increase, companies have to maintain a high cost-efficiency to remain competitive in a globalized world. In many cases the only solution to this dilemma is digitizing and streamlining the inspection process through modern digital radiography technology. Therefore, companies and nondestructive testing (NDT) managers all around the world are analyzing available solutions, which often poses a long-term capital investment. This article gives a brief understanding about the applications, capabilities, certification, and efficiency of complex X-ray systems and applications to inform NDT engineers and managers about the decision process in establishment of new equipment and processes.

To address all points, this article will be published in three issues of The NDT Technician. Each part has a distinct focus while building on each other:

- Part 2: Conception, system design, and investment justification.
- Part 3: Industry characteristics, summary, and practical examples.

Please note that the first part is highly focused on the underlying technical principles and commercial aspects.

The following issues will discuss practical implementations and best practices.

X-ray Technology and Components
It is important to understand that X-ray is by no means a generic inspection technology. X-ray components have to be fine-tuned and handpicked depending on the application. Hard factors are minimum inspection quality, throughput, and budget. Additional soft factors like operation mode, process compliance, company guidelines, operator preferences, and many more have a remarkable influence. This section introduces the available components and their key applications. Please note that this article does not go into detail regarding each technology and principle, as exhaustive literature is already available.

X-ray Sources
- Closed tubes ("mono blocks")
- Mini-focus tubes
- Vario-focus tubes
- Micro-focus tubes
- Panoramic tubes

It is easy to notice that these tube categories are mainly distinguished by their focal spot size. Typical industrial X-ray tubes range from 160 to 600 kV, while most digital radiography applications use focal spots from 0.4 to 1.0 mm (0.02 to 0.04 in.), as defined in DIN EN 12543, Non-destructive Testing – Characteristics of Focal Spots in Industrial X-ray Systems for use in Non-destructive Testing (DIN, 2011). Panoramic tubes, which emit X-ray in 360°, and micro-focus tubes are not discussed here, as they would go beyond the extent of this article.

Image Sources
- DDAs, digital radiography
- Image intensifiers
Computed radiography
- Linear detector arrays (LDAs)
- Film (radiographic testing)

The amount of hardware options on the market is overwhelming. Picking the best choice requires vast experience with the respective devices and technologies. This article focuses on digital radiography as the emerging technology. Image intensifiers have basically been replaced by DDAs, while film and computed radiography are already very mature and often-discussed technologies. LDAs comprise single lines of X-ray sensitive diodes with a high readout speed. This allows generation of X-ray images through constant movement of the LDA or object. DDAs contain up to thousands of diode arrays to allow a direct representation of the X-ray radiation, as defined in ASTM E 2736, Standard Guide for Digital Detector Array Radiology (ASTM, 2010). Most DDAs used for NDT are adapted from the medical sector. This results in standard sizes and technical parameters—the 40.6 × 40.6 cm (16 × 16 in.) models, for example, are originated from thorax inspection. There is a variety of recognized manufacturers for such devices on the market and an even bigger choice of configurations. A typical C-arm setup that is used in digital radiography cabinets can be seen in Figure 1. The C-arm mounts an X-ray tube and DDA. This allows manipulation of the part in five dimensions and ensures a perpendicular setup at all times.

Inspection Concepts

- Visual inspection (digital radiography)
- Automated defect recognition (ADR)
- Computed tomography

At the core of every digital system is the image processing and enhancement software. It allows image acquisition, processing, and archiving in respect to the inspection requirements. Hereby, one has to distinguish between three fundamental solutions: the visual inspection involves manual manipulation of the part, image acquisition, and discontinuity classification by a trained operator. A variation with a higher degree of automation is the usage of programmable computer numeric control sequences to ensure comprehensive coverage, going further towards automation results in ADR (VisiConsult, 2016a). This means that the complete inspection is carried out automatically through sophisticated algorithms. Modern ADR systems can easily detect inclusions or porosities in casting parts and are widely used in the automotive industry. Computed tomography allows 3D reconstruction of the object to perform advanced discontinuity or geometry analyses (VisiConsult, 2016b). All three approaches have their specific advantages and disadvantages. The use of the right inspection concept has to be determined during the project conception phase and is subject to a broad variety of influences. Figure 2 shows a typical digital radiography cabinet and software solution that can be used in a flexible way for many different inspection tasks.

Figure 1. A digital C-arm radiography cabinet consisting of an X-ray tube, flat panel detector, and part manipulator.

Figure 2. Digital radiography systems allow real-time representation, processing, and analysis of the X-ray images: (a) the working principle of the system; and (b) a close-up of the software.
Archiving Concepts

- Digital images
- DICONDE/picture archiving and communication system (PACS)
- Reports
- Video

For proof of quality, inspection results need to be archived. This can be done through conventional and compressed 8-bit images (like Bitmaps) or uncompressed 16-bit images (like TIFF). Inspection parameters are simply placed as overlays and replace the lead numbers used in film radiography. An alternative is to use the DICONDE container format, which holds all process information and inspection results and can be imported to a PACS. This way a DICONDE file works like a specimen dossier and can contain information of multiple NDT technologies and even production information. Modern processing software can export reports in PDF, Word, or Excel formats and are another option. Video recording allows capturing the complete inspection process. Typical applications are real-time inspection for spiral-welded pipes or surveillance of inspection in the defense sector. Every solution has its distinct characteristics, advantages, and disadvantages and should be determined by the requirements.

Introduction of Performance Parameters

The performance of every system or process can be measured in many different ways through key performance indicators (KPIs). Due to the complexity of modern inspection systems it is of the utmost importance to carefully analyze the capabilities and performance of the unique solutions and technologies. This section introduces different parameters from a technical and commercial perspective. All formulas are based on the widely accepted Overall Equipment Effectiveness (OEE) Foundation guidelines (OEE, 2000).

Quality and Failure Rate

Please note that quality herein is not referring to product quality but to inspection and process quality, as interpretation failure is defined as a significant deviation between the operator-determined and real defect class. As this metric alone is ambiguous, it is necessary to differentiate between false positives and false negatives. False positives, also called “false alarms,” are, from a technical point of view, not critical, as there is no danger that products with defects pass the quality control. From a commercial point of view, every false positive is potential scrap and lowers the overall output of the production.

False negatives, on the other hand, are absolutely critical and need to be eliminated, as quality control failed on them. During the project conception phase it is mandatory to set a certain threshold according to industry quality standards and end-customer requirements to avoid false negatives.

Assuming that false negatives are not accepted, the only impacting factor of this metric is false positives. The number of misclassifications can typically be reduced through process changes or more advanced equipment. Responsible persons need to ensure that the investments do not exceed the costs of productivity losses caused by false negatives. Figure 3 explains this correlation and highlights the target with the highest cost-benefit ratio. In the following, $P$ stands for parts.

\[ \text{Quality} = \frac{(P_{\text{total}} - P_{\text{false positive}})}{P_{\text{total}}} \]

Availability

Availability takes all events into account that stop the operation during planned operation time. Typical impacts are operator breaks and changes, X-ray warm-up, detector qualification, and maintenance. In general, it can be concluded that increased process safety and higher degrees of automation or parallelization increase the availability of the system. In the following, $t$ stands for time, differentiated between scheduled and actual operating time.

\[ \text{Availability} = \frac{t_{\text{operating}}}{t_{\text{scheduled}}} \]

Performance

The performance is purely focusing on the throughput. For correct usage of this metric, a realistic mean or ideal cycle time has to be defined. In case the X-ray inspection poses a critical bottleneck for the production output it is highly suggested to introduce some amount of buffer to the ideal cycle time to accommodate unforeseen events. The performance constantly changes based on the daily throughput. Typical impacts on this KPI are operator distractions, slow decisions, inefficient handling, and other unplanned incidents.

\[ \text{Performance} = \frac{(P_{\text{inspected}} \times t_{\text{cycle time}})}{t_{\text{operating}}} \]
Cycle Time
The cycle time describes the complete amount of time for processing a single part. This can include object identification, loading, inspection, archiving, marking, unloading, and many other activities depending on the inspection process. In some cases, the cycle time is predetermined through upstream production equipment or throughput requirements. If the inspection cycle time is not a bottleneck, this value just has to be defined by the technical department for internal labor allocations and performance controlling.

\[ t_{\text{cycle time}} = \left( \frac{t_{\text{scheduled}}}{P_{\text{total}} \times \text{buffer \%}} \right) \]

Overall Equipment Effectiveness
The most commonly used metric for manufacturing success and efficiency is OEE. It is designed to have a generic measurement of the production performance. The OEE cannot be used for financial evaluation, as it analyzes the process itself and is based on the performance targets. All KPIs until this point only measure efficiency and quality. This allows unbiased comparison of different solutions for the inspection task. Please note: the definition of the target is the most important step, as this is the reference every process is compared to. Figure 4 represents the composition of this metric.

\[ \text{OEE} = \text{quality} \times \text{availability} \times \text{performance} \]

Return on Investment
The financial efficiency of an investment can be described in many ways. An easy to interpret representation is the normalization to months. The occurring savings might come from a broad variety of sectors: reduced material costs (for example, chemicals and film), reduced labor costs due to higher efficiency and automation, higher quality leading to less rejects or customer claims, and many more. To determine these costs, it is necessary to do a detailed analysis of the current process and an exact modulation of the future inspection process. Typically, suppliers of inspection solutions provide support and expertise during this process. It is important to note that after the return on investment (ROI) period, the system is “paid off” and only saves money.

\[ \text{ROI} = \frac{\text{investment costs}}{\text{savings per month}} \]

Illustrative Example: Aluminum Casting Manufacturer
All numbers are purely fictive but represent the chosen industry: a casting company produces alloy parts for the automotive industry. The parts have several critical regions, which need to be inspected by X-ray, and the images have to be archived for 10 years. The system is directly embedded in an eight-hour per day operating production line with an output of 320 parts per day.

- \( P_{\text{total}} = 320 \text{ parts} \)
- \( t_{\text{scheduled}} = 8 \text{ h} = 480 \text{ min} \)
- \( t_{\text{cycle time}} = 480 \text{ min} / 320 \text{ parts} = 1.5 \text{ min/part} \)

Example A: Manual Inspection by Film (Radiographic Testing)
- \( P_{\text{false positives}} = 8 \text{ parts} \)
- Quality = \( \frac{320 \text{ parts} - 8 \text{ parts}}{320 \text{ parts}} = 97.50\% \)

Due to uncertainties and cycle time targets, the operator rejects some parts with flaws below the applicable standard thresholds. Exact measurement on film viewers can be challenging. Skilled and trained inspectors can compensate for this effect and therefore a low mean false positive quota of eight parts per day is achieved.

- \( t_{\text{operating}} = 480 \text{ min} - 60 \text{ min operator} - 30 \text{ min X-ray warm-up} - 60 \text{ min film specific downtime} = 330 \text{ min} \)
- Availability = \( \frac{330 \text{ min}}{480 \text{ min}} = 68.75\% \)

Operators need breaks, have shift changes, and are subject to distraction by colleagues or other incidents. The X-ray warm-up has to be performed to prepare the tube for operation. Variations in the film process like overexposed, misplaced, or inconclusive films and replacement of chemicals lead to another excess time of 60 min.

- \( P_{\text{inspected}} = 330 \text{ min} / 15 \text{ min} = 22 \)
- Performance = \( \frac{22 \text{ parts} \times 1.5 \text{ min}}{330 \text{ min}} = 10.00\% \)

As the mean cycle time for one inspection is approximately 15 min, the efficiency in respect to the target cycle time is extremely low. This will result in a critical bottleneck in the production chain. To even this effect, the company will have to invest in multiple X-ray workplaces.

- OEE = \( 97.50\% \times 68.75\% \times 10.00\% = 6.70\% \)

Example B: Manual Inspection Through a Digital Radiography System
- \( P_{\text{false positives}} = 15 \text{ parts} \)
- Quality = \( \frac{320 \text{ parts} - 15 \text{ parts}}{320 \text{ parts}} = 95.31\% \)
Due to uncertainties and cycle time targets, the operator rejects some parts with flaws below the applicable standard thresholds. Increased analysis (measurements and inspection through the American Society of Mechanical Engineers defect catalog) would increase the quality while decreasing the KPI.

- Quality = \( 320 \text{ units} - 5 \text{ parts} \) / 320 units = 98.44%

Through the use of sophisticated inspection patterns and regions of interest, NDT responsible supervisors can decrease the number of false positives. This reduces the risk of false negatives by a huge amount. Automatic systems also eliminate the risk of human error. Due to minor positioning offsets, the system still has a pseudo reject rate of five parts per day.

- Quality = \( 320 \text{ units} - 5 \text{ parts} \) / 320 units = 98.44%

As noted before, operators need breaks and are subject to distraction by colleagues or other incidents. The X-ray warm-up has to be performed to prepare the tube for operation.

- Availability = 450 min / 480 min = 93.75%

Due to reduced human intervention, the operator related downtime is completely reduced. The X-ray warm-up still applies but is of no big influence in practice, as the system cycle time exceeds the target cycle time by a huge amount.

- OEE = 98.44% \times 93.75% \times 99.06% = 91.41%

Comparing the results, it is no surprise that digital radiography outperformed radiographic testing (RT) in terms of process efficiency. Inspection by film consumes a lot of time for film fixture, exposure, development, evaluation, and archiving. Furthermore, all steps can be automated through computer numeric control sequences and executed through a single click on modern digital radiography systems. ADR inspection solutions are the next level in terms of efficiency. Figure 5 shows a typical automated ADR system, which consists of two robots. This allows an installation in the production line and guarantees a short cycle time. Please note that not all applications and inspection requirements allow ADR, but this will be discussed in the second part of this article. The sole purpose of this example is to show how the performance parameters allow the comparison of completely distinct solutions and technologies. The next step is always the commercial analysis to justify the investment. Again, all values are purely for illustration purposes and do not represent real prices.

**Investment Costs**

- Costs_A = no investment, as 10 inspection stations already exist
- Costs_B = $250 000
- Costs_C = $500 000

**Return on Investment of the Transition from Digital Radiography to Film**

- Costs_labor = 9 persons \times 8 \text{ h/day} \times 21 \text{ days} \times $35/\text{h} = $52 920/\text{month}
- Costs_consumables = $8000 films + $3000 chemicals + $1000 storage and others = $12 000/month
- Costs_rejects = –7 units \times 21 days \times $40 = –$5880 (decreasing with operator experience)
- Costs_performance = not applicable as process is running
- Savings per month = $52 920 + $12 000 – $5880 = $59 040/month
- ROI = ($250 000) / $59 040 = 4.23 months
Return on Investment of the Transition from Digital Radiography to Automatic Defect Recognition

- Costs_labor = 6 h/day × 21 days × $35/h = $4410/month
- Costs_rejects = 10 units × 21 days × $40 = $8400
- Costs_performance = 30 units × 1.5 min × 21 days × $50/h = $787
- Savings per month = $4410 + $8400 + $787 = $13 597/month
- ROI = ($500 000 – $250 000) / $13 597 = 18.4 months

The aforementioned calculation is based on fictional numbers but is representative for manufacturers of medium- to high-volume parts like castings. Of course, in the case of industries with a lower production volume, for example, in some aerospace applications, the ROI will be completely different and other factors are of bigger interest. In general, the investment into digital radiography equipment has a relatively short amortization. As traditional RT involves a tremendous amount of labor and consumables, the costs are scaled directly with the production volume. If one compares visual digital radiography and automation (such as ADR), it can be seen that the investment has a longer ROI. Therefore, this technology is rather suitable for long-term production projects with higher volume.

Figure 6 visualizes the costs per part with all three solutions. The film costs have a linear increase based on the production volume. The leaps or ripples represent costs, occurring due to new equipment investments like another inspection room or a new X-ray tube. The visual digital radiography approach is similar but increases at a much slower pace due to less personnel and consumable requirements. The downside is a higher capital investment. The automated system poses a high upfront investment compared to the other solutions. Due to the high reduction in operational costs, the mean price per part gradually decreases over time. If the current setup uses film, an investment in digital radiography is feasible on point A while point B justifies a direct transition to automation. If a digital radiography setup is used, an automation system should be implemented at point C.

Soft factors like reduced human error, lower chance for false negatives, better scalability, and enhanced process stability are not even taken into account for this calculation and are additional benefits of automation. Please note that this section is purely focusing on the commercial point of view. Quality, process, and compliance related perspectives also have a huge influence but will be evaluated in later parts of this article.

Conclusion and Outlook

The previous sections gave an overview on how to compare processes and solutions in an unbiased way through arbitration. As already stated, these calculations are just a simplified example and unique for every industry or application. It is highly recommended to contact solution providers or system suppliers at an early stage of the conception phase for detailed consultation and support.

A basic understanding of these metrics and processes is of special importance for NDT technicians and managers to evaluate and justify new investments. The next parts of this article will focus more on the technical concept and implementation of customized X-ray systems. The next issues will also further go into practical examples and conclusions.

A last note on behalf of the author: when talking about modernization and automation, one perceives a high degree of fear in the NDT industry. Highly skilled technicians have the fear of losing their jobs, the fear of being left behind in digitization, or just a diffuse fear of change. It is important to understand that automation does not destroy jobs, but will generate jobs in the long run. It is the only chance to be competitive against manufacturers operating in low wage countries, which becomes easier than ever through increasing globalization. And even though the digital technology is very complex, the actual inspection and operation itself is very intuitive when using well-engineered solutions. Therefore, it is highly encouraged to embrace the change in technology and see the opportunities for the future.

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REFERENCES


