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# APPLICATION OF ARTIFICIAL INTELLIGENCE FOR PROCESSING DIGITAL ULTRASONIC IMAGES IN THE SHIPBUILDING INDUSTRY

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**Abstract:**

The article describes the completed research and development work conducted for the shipbuilding industry by a scientific consortium from 2020 to 2023, and addresses selected aspects of the commercialization of the developed prototype solutions. The goal of the R&D project was to develop and implement a modern solution for quality control of welded joints and monitoring of the production process. This article focuses on the application of artificial intelligence (AI) to improve the efficiency and rationality of operational processes, such as welding production processes verified by the advanced PAUT ultrasonic method. The prototype UT/PA system is presented synthetically from the perspective of measurement and analytical components, focusing on the processing of ultrasonic images after measurements and their decision-making potential for improving the quality of welded joints. Synthetic conclusions of a methodological, operational, and strategic nature are highlighted. The planned direction for the continuation of the completed research and development work and the finalized commercialization is also presented.

**Keywords:** shipbuilding industry, AI applications, production monitoring, quality control of welded joints, image processing, phased array ultrasonic testing

## Introduction

The Polish shipbuilding industry, as a result of political decisions (both internal and external) between 1980 and 2010, was eliminated from its position as a global power. Currently, it is slowly regaining lost ground. Each of the existing Polish shipyards is developing in its own unique way, although it is a very challenging industry, particularly in light of past economic crises and the "grown" competition from China and South Korea.

This article focuses on the journey taken and planned by Gdansk Shipyard (SG), which currently operates within the Baltic Industrial Group (GPB), and its production profile is managed by Baltic Operator (BO). BO is attempting to build a contemporary image of SG, considering the available workforce potential and production infrastructure, as well as the main tenets of the Industry 4.0 and Industry 5.0 concepts. The workforce potential of SG has "melted" from the level of 15,000 employees to just under 1,000, so the scale of the shipyard's production activity is accordingly smaller. The available infrastructure potential has also been significantly reduced, although it remains substantial and is continuously undergoing revitalization and development efforts. Orders in BO's portfolio are still placed by leaders of the global maritime economy, which confirms the maintenance of SG's esteemed brand.

In the shipbuilding industry, there are many challenges (staffing, technological, and business) that motivate the implementation of artificial intelligence-based solutions, but the priorities of developmental actions always hold significant importance. This article focuses on a production subprocess that incurs substantial costs and supports the core welding subprocesses. Commonly used solutions for quality control of welded joints cannot keep up with the advancements in welding processes, which are largely dominated by automated and semi-automated systems. However, the quality control processes for welded joints in shipbuilding remain conventional, i.e., manual, despite an increasing percentage of required non-destructive testing (NDT). This technological challenge has been recognized as a priority for the development and implementation of artificial intelligence, while also representing a low risk of failure.

## Material, methods and tools

### Methodology and definitions

At BO, initiatives are being undertaken to reconfigure the digital technology of manufacturing welded ship structures, which are components of the world's largest cruise ships like the Independence class, as well as other large-scale structures such as wind power towers and transformer stations. Innovative projects[1] and R&D projects are being implemented, distinguished nationally by winning funding competitions and internationally by the results achieved. BO's strategic approach involves transforming challenges into business opportunities, meaning simultaneously meeting regulatory requirements (national, EU, global), integrating

[1] Project titled: "Establishment of a new production plant for onshore and offshore wind towers under sub-measure 4.5.1 Support for investments in the production sector, action 4.5 Support for investments of major importance for the economy, priority axis 4 Investments in innovative ventures of the Operational Programme Innovative Economy, 2007-2013 (project completion in 2016)."
Project titled: "Development and creation of a prototype of a floating support structure for offshore wind turbines with a capacity of over 10 MW," under Sub-measure 1.1.1 of the Regional Operational Programme for the Pomeranian Voivodeship for 2014-2020 "Expansion through Innovation – Grant Support" (2016).

them into its long-term strategy, satisfying stakeholder expectations, and ensuring access to "financing" for its initiatives.

Methodical generalizations of their own experiences in this area are presented, among others, in: (SALA and TAŃSKA, 2013, 2014, 2015, 2022, 2023, 2024). Selected publications address the complex relationships between politics, science, and economic practice, particularly industrial production. These relationships are direct and indirect causes of disruptions in the functioning of industrial enterprises in Poland and impact the effectiveness of developing and implementing innovative solutions. These experiences were compared with British experiences, which confirmed that the EU mechanisms motivating innovation are fundamentally sound, but they need to take into account the specifics of individual countries. The synthesis of specifically Polish developmental aspects can be summarized into the following issues:

- Information management in Polish industry and the diagnosis of transformation outcomes,
- Determinants of innovation transfer,
- ICT knowledge transfer model and its implementation in the industry,
- Instrumentalization of artificial intelligence in the policy of scientific activity in Poland,
- Methodological aspects of innovation in project and production enterprises,
- Inclusive mechanisms for overcoming technological delays in the Polish economy.

These issues contributed to the creation of a cohesive, authorial methodological approach that is continuously verified in practice. Central to the set of methods used were non-destructive testing (NDT) methods, which are an integral part of production processes in the shipbuilding industry. Quality requirements and safety considerations necessitate the use of increasingly precise and reliable testing of steel structures, including floating units, towers for onshore and offshore wind farms, bridges, and other large-scale constructions. The project mainly employed the following NDT methods: radiographic (RT), eddy current (ET), magnetic (MT), and ultrasonic (UT, PAUT, TOFD, FMC). This research and development project was carried out from 2020 to 2023 and was co-funded by the NCBR, covering approximately 50% of the budget.

The interpretations of the terms and definitions used in this article are widely known and consistent with (Artificial Intelligence for Europe, 2018), (Scoping…, 2019), (Resolution…, 2021). The focus was not on selecting a single definition of artificial intelligence (AI), such as those by (BELLMAN, 1978), (HAUGELAND, 1985), (CHARNIAK and MCDERMOTT, 1985), (McCarthy, 1990), (Kurzweil, 1990), (Rich and Knight, 1991), (Winston, 1992), (Poole and Mackworth and Goebel, 1998), (Nilsson, 1998), or business intelligence (BI) systems (Dudycz, 2012), but rather on the essence of a set of concepts according to two dimensions and four categories, namely processes (thinking and acting) and contexts (performance and rationality) (Russell and Norvig, 2010). A graphical representation of the definitional aspects of AI is presented in Table 1, where the measures of success are the processes and contexts of AI applications in production practice. Most AI definitional approaches can be classified using the referenced exemplary approaches.

Table 1. Two Dimensions of AI definitions according to Russell and Norvig

| Context / Processes | Efficiency | Rationality |
| --- | --- | --- |
| Thinking processes | **Thinking efficiency** [Bellman, 1978] [Haugeland, 1985] | **Rationality of thinking** [Charniak, McDermontt, 1985] [McCarthy, 1990] [Winston, 1992] |
| Action processes | **Action efficiency** [Kurzweil, 1990] [Rich, Knight, 1991] | **Rationality of action** [Poole, Mackworth, Goebel, 1998] [Nilsson, 1998]. |

Source: compiled based on (Russell and Norvig, 2010).

Key factors for reproducing research results and applications of AI in this article include:

- The specificity of large-scale steel structures
- Tooling aspects of developments and their commercialization

**Specificity of large-scale steel structures**

BO's products are characterized as large-scale steel structures. This is custom production, which in rare cases is small-series production. For example, custom shipbuilding results in each product being a prototype in whole or in part, which is very complex, costly, and labour-intensive, and its construction takes a long time (compared to series production), from 6 months to over 2 years. The technology of producing large-scale steel structures involves a hierarchical spatial structure, created by assembling smaller objects called blocks, which are formed by assembling even smaller objects called sections. To illustrate the specificity of shipbuilding products, it is worth mentioning the example parameters of a single section, such as a wind tower, which can range from 18m to 36m in length, up to 10m in height, and weigh from 30 to 40 tons. In the case of ship structures like hulls, completed sections are joined into blocks, typically measuring 20x20m and weighing from 20 to several hundred tons. Example sections and blocks are illustrated in Figure 1.

Fig. 1. Example sections and blocks of large-scale ship steel structures

Source: Own elaboration based on (BERA et al., 2023)

Despite the specificity of custom production of large-scale welded structures, there are framework production processes for individual product groups. An example of a framework process for shipbuilding production is illustrated in Figure 2, with the main assumption being that each hull prototype is a single unit (though there are exceptions to this rule).

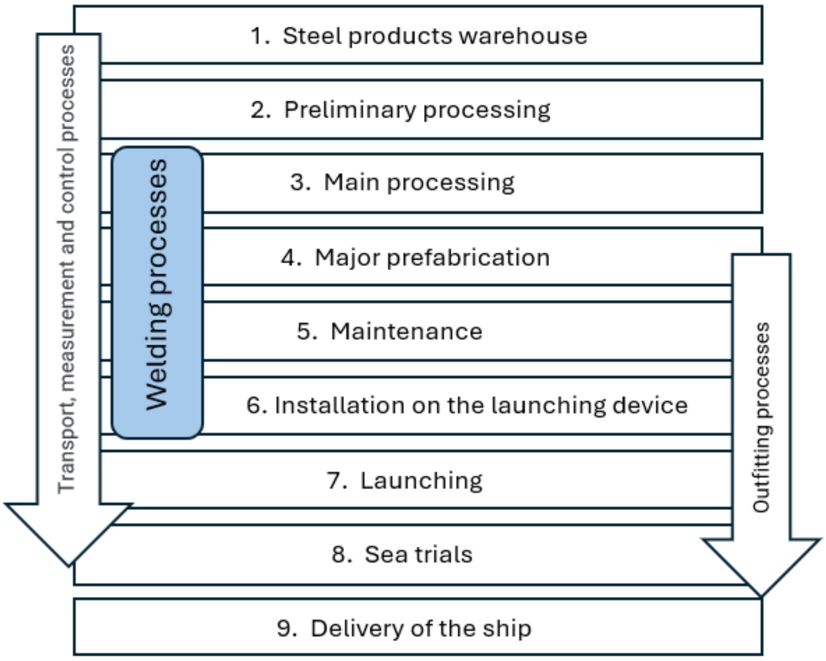


Fig. 2. Framework process of a ship hull construction

Source: Own elaboration based on (BERA et al., 2022)

In light of the above, all sub-processes within each framework process of the product group contain both fixed and variable aspects depending on the requirements of the product-prototype's client. Competitiveness in the international market is dependent, among other factors, on the speed of preparing the variable technological aspects of the framework production process and the quality of execution. Without the application of artificial intelligence solutions, meeting the timing and quality requirements of international leaders is impossible. Currently, the demand for such products in the domestic market is negligible, and it could be generalized that it does not exist. Potential Polish clients opt for significantly lower quality from Asian manufacturers due to lower prices.

**Tooling aspects of developments and their commercialization**

Prototype solutions have been developed using available distributed and integrated tools, including:

1. In the UT/PA System, as illustrated in the schematic (Fig. 2.), the following were utilized:
   - Omniscan X3 flaw detector software for digital recording of measurements, compression, and visualization of ultrasonic images, equipped on mobile testing stations;
   - OmniPC image analysis software (version 5.7.0 and later), constituting the equipment of a stationary analytical workstation;
   - Eclipse Scientific Beam Tool software for developing and simulating scan plans, constituting the equipment of a stationary analytical workstation;
   - The tool potential of the Microsoft 365 platform, including, among others, the OneDrive cloud functionality and unlimited data storage space forming the basis of the prototype UT/PA diagnostic system, as well as statistical chart generators and Power BI.
2. In the model expert system based on the advanced UT/PA system for monitoring the production process and diagnostics of large-scale welded steel structures, the following were used[2]:
   - Python language and its libraries,
   - MS SQL server and SQL language,

[2] The project was carried out in a consortium, inviting researchers from AGH for collaboration in this part.

- Two competitive models for defect recognition and visualization (in the 19-dimensional weld vector space).

This study also refers to the analytical functionality and reporting capabilities at the Power Business Intelligence (Power BI) level (JANISZEWSKI and SALA, 2023), particularly in the areas of:

- Building digital dashboards,
- Utilizing cloud power,
- Integrating important data,
- Using mobile applications,
- Customizing content for different user groups.

It is assumed that the use of Power BI will enable more efficient input, storage, collection, and presentation of quality measurement data for inspected welds. In a broader perspective, this tool will enable the analysis of work at various stages of prefabrication to improve the efficiency and quality of the tasks performed.

## Results and discussion

### Ultrasonic Non-Destructive Testing of welded joints - measurement system

In large-scale steel structures, welding work and the quality of welded joints are of crucial importance [Janiszewski, Dictionary...]. These works are subject to strict requirements from classification societies, such as the Polish Register of Shipping, which are continuously being raised. In the field of NDT (PRS, 2021), conventional methods (e.g., VT, PT, MT, UT, RT) and advanced methods (ANDT) are identified, with hybrids of methods and technologies highlighted among the advanced ones (e.g., digital radiography RT-D). The most significant technological advancements are associated with the UT method (e.g., AUT, SAUT, PAUT, TOFD). The ultrasonic testing of welded joint quality using the advanced PAUT (Phased-Array Ultrasonic Testing) technique is the subject of a commercialized R&D project funded by NCBR[3]. As part of this project, prototype solutions were developed, and their test results were concurrently compared with those obtained using conventional methods. Subsequently, procedures were established to implement and commercialize the UT/PA system for large-scale steel structures. The UT/PA system includes mobile testing stations and a stationary analytical station designed for advanced ultrasonic testing using the PAUT technique, along with a network platform for digital recording, analysis, sharing, and monitoring of the welded joint quality diagnostics processes in BO, as well as testing procedures.

A synthesis of the main components of this project is illustrated in Figure 2, where three components in the form of mobile UT/PA testing stations are dedicated to three product groups: flat sections, spatial sections, and tower sections (Bera et al., 2024). The remaining three components are common and independent of the product group.

[3] The R&D project titled: "Development and implementation of a model expert system based on an advanced UT/Phased-Array (UT/PA) system for monitoring the production process and diagnostics of large-scale welded steel structures for offshore and onshore applications in the maritime industry," conducted from 2020 to 2023 (in collaboration with the AGH University of Science and Technology and the PPT Institute of the Polish Academy of Sciences).

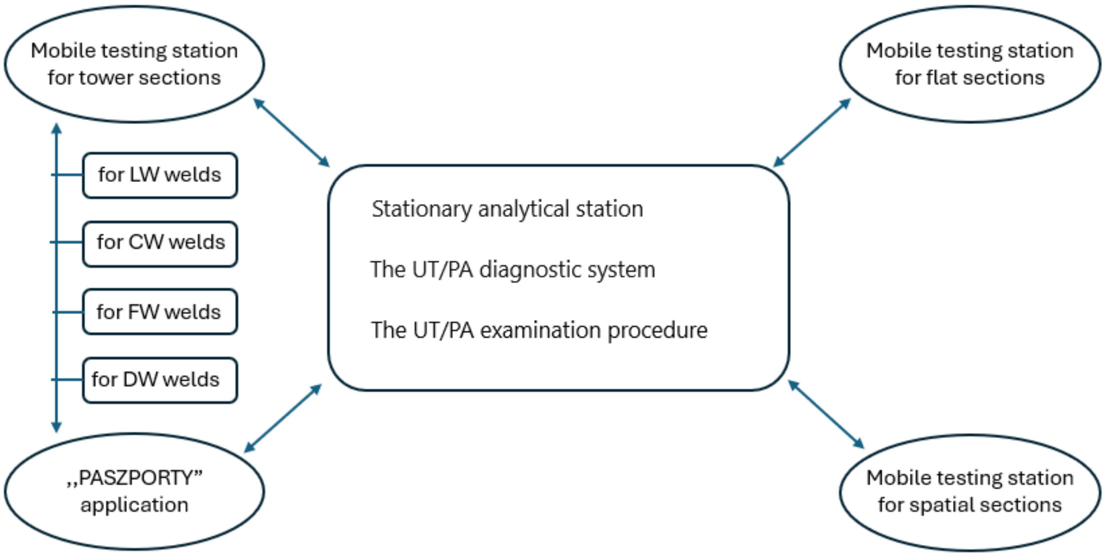


Fig. 2. Main components of the UT/PA system for the commercialization of digital diagnostics of welded joints in large-scale steel structures
Source: Own elaboration

The functioning of the prototype UT/PA system solution fully incorporates artificial intelligence based on the processing of digital ultrasonic images obtained using the advanced non-destructive testing (NDT) technique known as PAUT. The PAUT digital ultrasonic image is recognized in the shipbuilding industry as a more attractive alternative to the digital radiographic image, the acquisition of which generates many hazards. The main commercial benefits of the UT/PA system include a significant reduction in operator working time when using the automated mobile testing station (UT/PA) compared to the time required by costly specialists conducting conventional manual UT tests. The working time of a specialist for inspecting 1 meter of welds has been reduced by over 80%. Conventional UT inspection of 1 meter (including analysis, as UT inspection involves simultaneous analysis with no permanent record of the results) takes about 10 minutes, whereas UT/PA inspection takes only 20 seconds (including automatic digital recording). Consequently, UT/PA digital records are analysed after the measurement is completed, and analysing 100 meters of welds takes on average about 1.5 to 2 hours, depending on the number of recorded discrepancies/defects. Summing up the time needed for analysis with the measurement duration, the total time for inspecting 1 meter of welds using UT/PA, including analysis, is less than 1.5 minutes. These calculations have been simplified by omitting the time required for preparatory tasks. There are various other tasks whose durations balance each other out – for instance, a UT inspector must manually prepare a report for each inspected weld, whereas in UT/PA inspections, the report is generated automatically during the analysis. In 2023, the time saved by Baltic Operator through the use of UT/PA for inspecting 6 kilometres of welds was nearly 900 hours; instead of approximately 1,000 hours required for conventional UT inspections, less than 150 hours were needed with the advanced UT/PA system (in the case of standard welding tasks). From the perspective of AI definitions (RUSSELL, NORVIG, 2010), the developed operational processes are highly efficient and rational, meaning they are based on modern, scientific methods, well-planned, and yield good results (Entry..., 2024), as also defined by the indicators of science and technology from the OECD, EU, and GUS (Main..., 2022), (GUS, 2023).

**Ultrasonic image processing - analytical and decision-making potential**

The operational processes within the AI framework have been implemented in the OECD scheme shown in Fig. 3, focusing on the optimization of sensors and actuators in the context of operational logistics. System efficiency and rationality of AI have been achieved through the integration of several ready-made components, including PAUT probes with 32 UT beams.

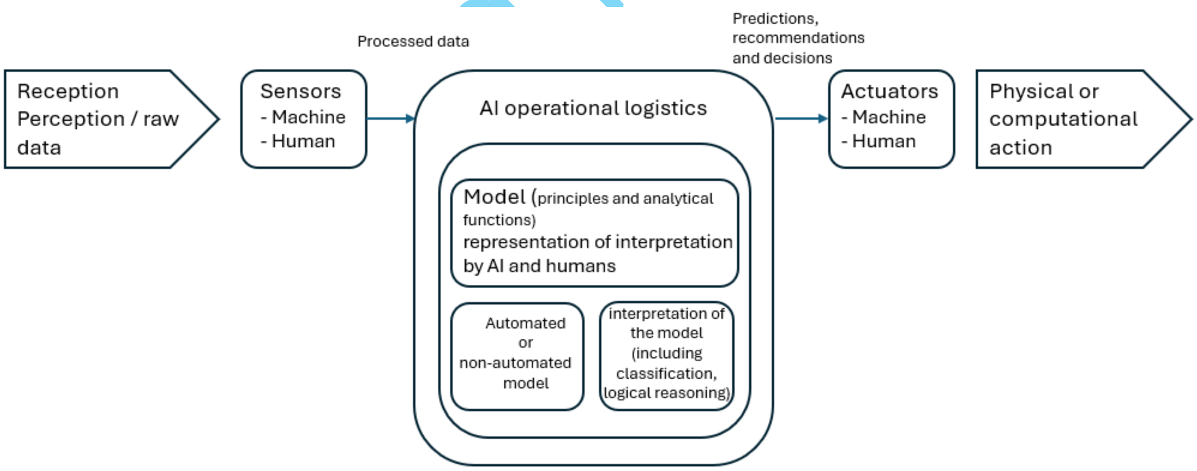


Fig. 3. AI system scheme in the context of digital ultrasonic image processing in the UT/PA system Source: Own elaboration based on (Scoping…, 2019), (Uchwała…, 2021).

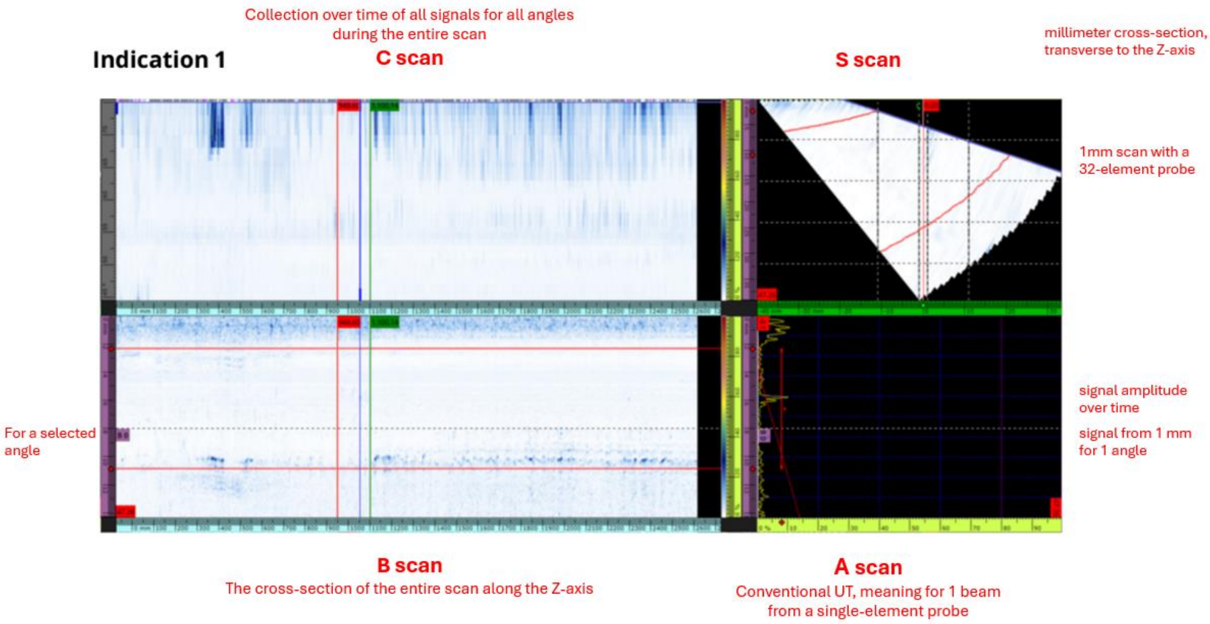


Fig. 4. Explanations for reading ultrasonic measurement images in the UT/PA System

Source: Own elaboration

Each automated mobile UT/PA testing station is equipped with a scanner (with 2 or more sensors, including a PAUT probe and encoder) and a flaw detector for digital recording of measurements, as well as compression and visualization of ultrasonic images, as explained in Fig. 4. The task of the mobile station is to measure the quality of all welded joints on each large-scale steel structure (section, block) from the dedicated product group (wind towers, flat and spatial ship sections) at any location in the production hall and assembly yard. The remaining process from measurement to decision is synthetically presented in Fig. 5.

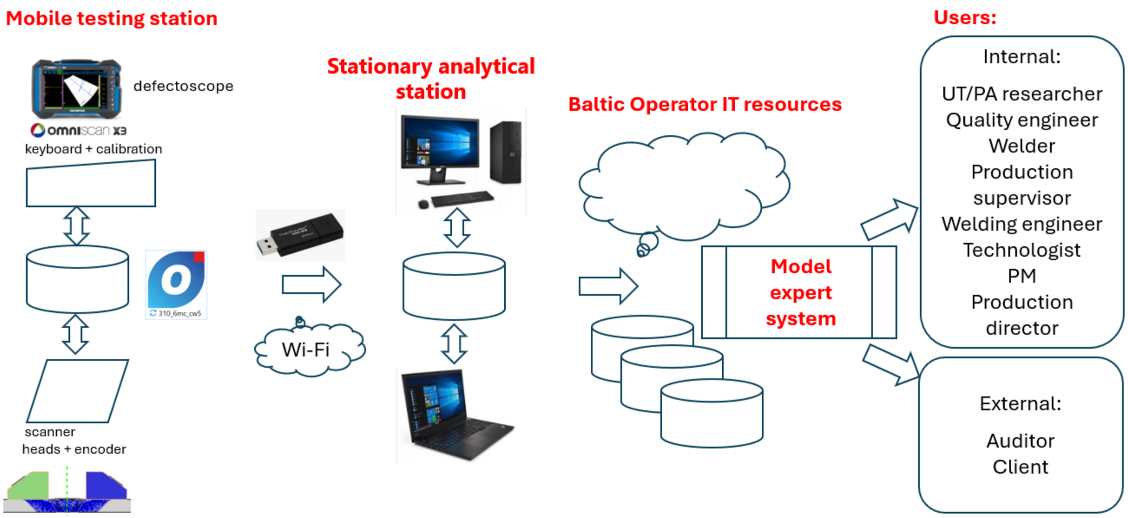


Fig. 5. Path from digital measurement to decision in the UT/PA System

Source: Own elaboration

Experiences from the implementation of the above prototype solutions in shipbuilding for flat sections in BO, and the comparison of these results with those obtained using other methods, indicate their competitiveness, as published in (Bera et al., 2024), while maintaining the confidentiality to which BO is obligated by the NCBR until 2028. The established goals were achieved, including keeping pace with NDT control subprocesses alongside welding subprocesses, which is crucial not only for production logistics. Undoubtedly, they offset the relatively high costs of the main components of the prototypes (mainly flaw detectors and PAUT heads).

## Conclusions and plans for the development of AI applications in BO

It is important to highlight the following synthetic conclusions (of a methodological, operational, and strategic nature):

1. In industrial enterprises, it is essential to have a strong focus on the actual and visibly "obvious" needs of production processes while taking into account the specifics of Polish conditions (e.g., not over-criticizing existing solutions);
2. The results of the R&D project confirm the effectiveness of the proprietary research methodology, which involves collaboration between the team developing the innovation and the team executing the production process under existing principles;
3. In practice, effective segmentation of process and contextual measures of AI success is crucial for motivating employees to collaborate within the R&D project, while also requiring special attention to the processes of action, specifically their rationality and efficiency (of course, without undermining the importance of thinking processes, but their perception usually reduces to the fear of job loss among specialists);
4. At the stage of commercialization of the R&D project results, classic and well-documented implementation barriers for all innovative solutions remain relevant;
5. The commercialization of innovative solutions requires at least intuitive internal marketing actions;
6. Automation of measurement stations (mobile UT/PA testing stations) requires dedicated designs of scanners and guides tailored to the measurement objects (in this case, ship sections/blocks and wind turbine towers), and any attempts at universal solutions do not allow for optimal results;

7. A significant increase in the database of images and reports, as well as the knowledge base in the UT/PA diagnostic system requires continuous improvement of monitoring in qualitative and quantitative metrics such as the number of files, images, and reports, as well as the time and capacity of images. So far, these metrics have reached the following maximum monthly values: 900 files, 430 images, 430 reports, and 60.9 GB of memory capacity. Consequently, the estimated annual increases are expected to be: 10,800 files, 5,160 images and reports, and 730 GB of memory;
8. The UT/PA system represents a huge potential for the self-learning of personnel conducting non-destructive testing, including welders, welding instructors, and welding engineers and also for artificial intelligence, including machine learning, for its improvement;
9. The developed processes of action and thinking within the UT/PA system are very efficient and rational, i.e. based on modern scientific methods, well-planned, and yielding good results and consequently are replicable for the needs of Polish and global shipyards. However, due to the funding obtained, until 2028, i.e. "during the durability period", BO is obliged by the contract with NCBR to ensure that the resulting solution will be intended for internal use and will not contribute to obtaining undue benefits by any private or public entity.

In 2025, BO plans to participate in the National Centre for Research and Development's SMART funding competition for a project aimed at a broader, holistic continuation of AI applications. One of the challenges will be to develop an AI model that mirrors the operational logic of the processes involved in the preparation and execution of unit production. BO intends to take on this challenge in the context of an international network-based business model, which is becoming increasingly dominant in the industry. This model will also be based on the AI system scheme. The main objective is to implement the Industry 5.0 concept, focused on developing effective models, algorithms, and procedures tailored to the needs and capabilities of BO's organizational structures, particularly the technological and design department responsible for production preparation processes, which initiate shipbuilding and have a crucial impact on the entire execution process.

A significant increase in the database of images and reports is anticipated in the UT/PA Diagnostic System. This growth will be monitored through qualitative and quantitative indicators, including the number of files, images, reports, and image size. So far, these indicators have reached the following maximum monthly values: 900 files, 430 images, 430 reports, and 60.9 GB of memory capacity (and consequently, the following estimated annual increases are expected: 10,800 files, 5,160 images and reports, and 730 GB of memory).

In addition to BO's main commercial objectives, the R&D work aims to develop and initiate the process of utilizing the potential of generative AI, particularly in the area of self-learning virtual assistants and virtual experts. Planned experiments on databases of ultrasonic images will utilize methods such as use case diagrams, activity diagrams, class diagrams, neural networks, genetic algorithms, semantic maps (DUDYCZ, 2012), intelligent agents, etc. Work is planned to continue the business rationality of using the FMC method (LEWANDOWSKI, 2022) and the TOFD technique (ŚLIWOWSKI, 2022). However, the efficiency and rationality of action processes are undoubtedly of paramount importance for the planned experiments and the commercialization of their results in BO as measures of the success of AI applications (RUSSELL and NORVIG, 2010), while rational thinking undoubtedly supports BO employees in improving the quality of welded joints in large-scale shipbuilding constructions (BERA et al., 2022).

Of course, alongside R&D plans, the commercial plans of BO in this area are also significant. The implemented prototype solutions require permanent changes (not temporary pilot or experimental changes) in organizational, logistical, and certification structures, including the maintenance of unique equipment (spare parts, servicing, operation). Contrary to appearances, these are not trivial challenges for the future, especially when it comes to their optimization.

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