

Article

Development of Augmented Reality Technology Implementation in a Shipbuilding Project Realization Process

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Abstract: The technology of Augmented Reality is taking on an increasingly important role in the digital (and green) transformation of industry, including shipbuilding. Upgraded to the three-dimensional ship model in the form and content of a Digital Twin, (industrial) Augmented Reality contributes to the activities of sale and marketing, development, and design, as well as production and maintenance. Recognizing its leading potential in creating the configuration of Shipyard 4.0, research on the further applicability of Augmented Reality in shipbuilding processes, with an emphasis on outfitting activities, was initiated in collaboration between industry and universities. This paper describes the course of the research, i.e., the development of an Augmented Reality application supportive of the shipbuilding process. The authors emphasize the possibility of achieving savings in shipbuilding project realization by implementing the Augmented Reality application according to the conducted proof of concept, thus contributing to shipbuilding system competitiveness improvement.

Keywords: augmented reality; digital twin; Shipyard 4.0; shipbuilding; competitiveness



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1. Introduction

The transformation from a traditional to a smart shipyard, “Shipyard 4.0”, is the primary response to the requirements of sustainable, environmentally acceptable, and, above all, competitive business. The “smart factory” is the response to the highlighted challenge of the shipbuilding industry’s low productivity, with an emphasis on the European as being projected oriented, with prevailing individual (prototype) production [1]. In addition, the European shipbuilding sector is, for the most part, present precisely in the market niches of highly complex types of new builds [2]. Such market orientation makes the industry more labor-intensive, with a high demand for a specially qualified workforce, and exposed to a large number of alternation requests from clients, which extends the already initially long project implementation deadlines [1]. All the above results in an additional increase in costs, and European shipyards, despite the high added value of their products, are under constant pressure of the continuous business improvement necessity.

Fraga-Lamas et al. [3] recognize the main drivers of Industry 4.0 in “ubiquitous sensorics, massive growth in data volumes, growth of computing power and connectivity, growth in analytics, business intelligence capabilities, and cloud computing”; in addition, they also point out “new forms of human-machine interaction through Augmented Reality (AR) systems, and advances in the transfer of digital instructions to physical reality”, such as robotics, three-dimensional (3D) printing, Cyber-Physical Systems (CPSs), and the Internet of Things (IoT). The last two drivers of Industry 4.0, along with Big Data and the IoT, are also recognized in the research by Stanić et al. [4].

According to Rivas [5], the introduction of digital technologies into traditional shipbuilding systems enables business improvements by integrating (i) processes, (ii) stakeholders in processes, and (iii) functions in processes in three directions—vertical, horizontal, and cyclical. The mentioned forms of integration respond to, according to Stanić et al. [4], the main problems of the shipbuilding industry today, i.e., the realization of a ship with the highest degree of safety, energy efficiency, and environmental protection both in shipbuilding processes and in the exploitation of the ship, as well as the cost efficiency in the construction, exploitation, and dismantling of the ship.

The digitalization of production machines and lines, radio frequency, collaborative robots, the IoT, and Additive Manufacturing, i.e., the general wide application of sensors and actuators in processes and products, enables the vertical connection of business processes. Vertical connection spreads from the workshops to all business functions up to administration in the way of data exchange between virtual reality (such as a digital model of the production line or the product itself) and physical reality, in real time. Such integration creates not only the CPS of the product realization [1,5] but also a product that communicates with reference systems during its production, management, and maintenance, as well as with other vessels in the exploitation phase (“Smart ship”) [3]. Savings in shipbuilding through vertical integration are achieved in the number of working hours and labor resources, as well as energy, thereby contributing to environmental protection [1,6]; additionally, the quality of working conditions in a safe and environmentally acceptable way also improves significantly [1,3].

The horizontal unification of all creators of added value through innovation activities, diversification of roles in product realization, and implementation of Cybersecurity [1], Big Data Mining (BDM), Cloud Computing, IoT, Virtual and Augmented Reality (VAR), i.e., Digital Twin (DT) [5], creates a highly interrelated supply chain in terms of stakeholders. With this kind of integration, the interests of all parties involved in the chain of creating added value are harmonized in such a manner that the expectations of each individual stakeholder in the project realization process are met [1]. This includes, for example, the customer’s modification requests and all of those fulfilled in the shortest possible time [3]. This new generation of value creation networks [3] is the basis for shaping new connections between stakeholders in the form of partnerships on some new projects in the same or another market niche, but again, by meeting individual interests. Moreover, it can result in far better recognition of opportunities for cross-stakeholder mergers and acquisitions [3].

Industry 4.0 technologies such as VAR, Artificial Intelligence (AI), 3D or 4D printing, and remotely controlled or autonomous vehicles (drones, robotic transport vehicles), along with remote sensing and monitoring networks (“remote sensing”) and robotics, in general [1,3], enable the monitoring and analysis of given or read data in real time throughout the product’s entire lifecycle, that is, of each of its relevant parts. With such a cyclical or end-to-end digital integration of owners/operators, designers, suppliers, shipyards, and service providers throughout the entire value chain, i.e., from the product development process activities to its disposal, amongst others, the following conditions are realized:

- Optimization of technical–technological project solutions for the purpose of cost reduction during both construction and exploitation of the ship, to the owner’s satisfaction;
- Definition of project improvements by data monitoring through ship exploitation, applicable on the same or newly ordered (sister) ships;
- Effective ship maintenance throughout the exploitation period.

However, as explained by Sánchez-Sotano et al. [1], smart transformation does not only imply the introduction of digital technologies and trends but also includes organizational and infrastructural changes and revisions of management doctrines. The prime motivation of the authors to initiate this research was to affect the perception of the management of business systems regarding the possibilities of improving the productivity or competitiveness of processes by adopting digital technologies—in the example in this research, AR technology upgraded to a virtual 3D product model.

The authors recognize the scientific contribution of this article in showing the possibility of achieving savings in the process of building and outfitting a ship by a timely detection or prevention of production errors, as well as shortening the duration of their repairs by applying AR technology upgraded to the digital prototype of the ship. The practical contribution of this research is in the achievable integration of two different kinds of production management systems that utilize all the advantages of the “old” system (robustness, the use of open standards like OpenGL) with new computer graphics technology (AR), which results in less time and documentation necessary to update the shipbuilding processes. Furthermore, as the shipbuilding information, such as work recording and completion status, are then processed only through the AR software application system (therefore, documents are not printed or delivered verbally), the truthfulness of the reports can be fully preserved.

As a novelty, this study presents AR technology as a tool for possible improvement in the procedure of planning production hours in the process of realizing shipbuilding projects.

After reviewing the literature, the Section 3 presents the research questions as well as the research methodology, along with a description of its main steps. In the same section, the selection of methods, i.e., technologies and programming tools used in the development of the AR software application implemented in this research, are also presented. The Section 4 describes the steps of AR application development, and the relationship between its system and the existing Enterprise Resource Planning (ERP) IT system of the observed business entity; also, the section describes how to use the application. In the Section 5, the results of the first-level functionality testing of the AR application are presented to prove the innovativeness of its concept; further on, the section describes the experimental functionality of the application upgraded with a higher level of program logic. The rest of the section presents the possibilities of achieving savings in the expenditure of working hours for the elimination of errors created in the process of outfitting, as well as in the duration of the process of their repair. In addition, the possibility of improving the procedure of planning production working hours by using the AR application in the process of recording work, i.e., reporting on the completion of outfitting activities, is discussed. Finally, in the Section 6, the observations from the conducted research on the overall possibilities of improving the productivity and competitiveness of shipbuilding processes are presented. This article ends with the authors’ recommendations for the continuation of the analysis according to the conclusions of this study, as well as suggestions for conducting new, follow-up research.

2. Literature Review

A great amount of research emphasizes the DT, a virtual replica of a physical product, or, for example, a manufacturing system [7], as the backbone of Industry 4.0, i.e., its supply chain [2,5,8]. However, for DT implementation, a previous coherent exchange of data among all functional units of the business system is necessary, regardless of the hierarchical structure [9]. Digital 3D modeling, through the stages of vessel development and design, enables the definition of optimal technical–technological solutions in order to achieve lower construction and maintenance costs, i.e., more energy-efficient ship systems as well as their form, and thus, lower exploitation costs [2,10]. However, although the digital prototype of a ship is developed in parallel with its development, design, and construction [9,10], its degree of integration with the physical entity (from creation to delivery) is assumed to be complete, which distances it from Building Information Modeling (BIM) [11,12] or Digital Shadow concepts [13]. Namely, the daily exchange of data between the virtual and physical entity (communication among client representatives, shipbuilding departments and facilities, and subcontractors) is implied [2], and thus, the continuous implementation of improvements and/or changes—both in the project and construction. In addition, within the focus of ship optimization through 3D modeling is also the definition of project solutions that assume simpler and thus safer activities in the construction or exploitation of the product, thereby ensuring a high level of health and occupational safety [2,14]. The aim to eliminate or at least minimize the possibility of injuries places workers at the

center of attention, which is one of the main characteristics that distinguishes DTs from BIM [14,15]. Thus, through the 3D model of the ship even before its delivery or exploitation, the concept of a DT is realized; moreover, when upgraded with the implementation of AR technology—which results in real-time bi-directional data flow between the physical and digital ship—the DT concept is achieved even according to the strict categorization of virtual models suggested in the work by Singh et al. [15]. With the assumption that the product is equipped with sensors, its DT also represents the backbone of Product Lifecycle Management, since by collecting data during exploitation, it predicts the ship's maintenance steps, i.e., its timeliness [16]. Moreover, analyzing the data improves the design of future similar or identical products in the series [16].

According to Wang [17], DT technology, i.e., the processes of modeling a real entity with digital technology, is the core of the creation of CPS—multidimensional integration of computing, communication, network, and the physical world. As described by Dhinnesh [18] in his work, CPS architecture consists of a network of sensors, controllers, and actuators interacting with people and machines. As expected by Giering and Dyck [16], a new generation of the digital industry will be formed, in addition to DT, specifically by CPS together with IoT, two technologies with, according to Dhinnesh [18], closely related concepts. Namely, as Dhinnesh further explains in his work, the role of CPS is crucial in the automation environment—the operation of robots and autonomous vehicles, i.e., smart (production) devices in general, which intercommunicate, i.e., perform work operations together thanks to IoT technology; combined, these two technologies fully collect and process data from the system, enabling the user to manage, i.e., interact with it in real time [18]. As a further level of upgrading the smart factory concept, and in terms of remote work support, Deac et al. [19] research the development of a platform for the real-time assignment of parameters to machines, i.e., the control of autonomous mobile robots through the virtual environment of a DT, while emphasizing the growing importance of VR technology in the visualization of production processes. To achieve low latency (below 100 ms), the authors propose a web-based approach to the physical system instead of telemetry data-based communication [19].

DT, VR, and AR technologies, along with the Hybrid method, are presented by Mourtzis [20], in his research, as the most advanced tools for the simulation of products and production systems, which, with low risk and cost, enable quick analysis of optional development or configuration solutions during the process of their design and exploitation. However, while, for example, VR technology enables experimental simulation and the integration of AR technology into a product or production system for its continuous improvement, the application of DT technology provides the possibility of precisely predicting their “behavior” [20]. Such prediction, though, is possible only with the prerequisite of integrating relevant technologies such as machine learning, monitoring systems, and reference Big Data, and, in addition, ensuring that all are connected to Industrial IoT (IIoT) [20]. Furthermore, in their article, Rabah et al. [21] elaborate on the proof-of-concept application of AR in combination with the industrial system DT developed for its predictive maintenance. Qiu et al. [22] extend the application of AR and DT technology to the product assembly process simulation, emphasizing the importance of the role of digital assembly in improving the efficiency and quality of the physical one, especially considering products of high complexity. In addition to real-time synchronization with the physical model through AR technology, their research also highlights the exceptional potential of applying DT technology for simulation purposes, considering the possibility of highly accurate prediction of assembly performance in a real environment [22].

Achievements in the development of wearable or portable AR technology devices are increasingly expanding the possibilities of its industrial application, thereby improving productivity and working conditions [23]. With an emphasis on the latter, De Pace et al. [24] highlight the use of AR interfaces for the realization of safe human–robot collaboration, enabling the user to understand the robot's intentions—its movements, the trajectory of the robotic arm, as well as the force that the arm will apply in the planned action. In addition to

the industry domain, the technology of combining virtual computer-generated information with the real environment finds its application in art, medicine, archaeology, or in “search and rescue” operations; in tourism, for example, by using the cameras of mobile devices, AR technology completes the experience of visiting historical sites by overlaying their digital models with physical remains [25].

VAR technologies are applicable throughout the entire vessel life cycle, improving innovation solutions applied both in shipbuilding processes and in the development and exploitation of products, contributing to the competitiveness of the shipbuilding system [26]. Virtual Reality (VR) makes a primary contribution to the quality of interaction with the client (already) in the negotiation phase since it enables the client to take a virtual “walk” through the interior and thus possibly make the desired modifications in the spaces or systems or, for example, on the exterior of the ship, immediately during its development [26]. VR technology is widely used for educational purposes, so ship crews are trained, among other things, on a VR-based simulator connection of the bridge and a digital 3D model of the ship in various scenarios of combinations of sailing conditions and situations on board [26,27]. Simulation of, for example, complex assembly operations in a virtual environment enables the optimization of their execution procedures, thus achieving savings in the ship construction process as well as more precise planning of production capacities [26]. The upgrade of AR technology to the virtual environment of the 3D model, i.e., the DT of the ship, provides opportunities not only to train workers before performing assembly activities but also to provide remote assistance of experts during their execution, thereby optimizing the shipbuilding and equipping processes [28,29]. In their work, Vidal-Balea et al. [29] test the possibilities of improving the production and maintenance processes that can be achieved by applying the most powerful technologies of Shipyard 4.0—(Industrial) AR and Mixed Reality (MR), previously integrated with IIoT. For this purpose, the authors develop a demo application that uses the Microsoft HoloLens 2 smart glasses device and the DT system to virtually practice and physically perform the work operations of assembling or maintaining ship components and systems [29]. Fernandez-Carames and Fraga-Lamas [30] point out the importance of AR and MR technologies in improving the efficiency of shipbuilding processes, considering the possibilities of facilitating the performance of work activities provided by the application of human–machine interfaces created by AR/MR hardware devices. Thus, the AR welding helmet can project to the worker which welding parameters need to be applied and indicate the error in the procedure and how to correct it, while, for example, AR glasses in combination with a software application-adapted paint gun can faithfully simulate the painting process, enabling the worker to train without actual waste of materials—paint and plates [8,30]. In addition to training purposes and guiding workers through the phases and steps of production tasks, as well as predictive maintenance [24,31,32], the application of AR (and MR) technology in the environment of a smart shipyard can facilitate work in a wide range of cases. The process distinguishes the following activities [30,33]:

- Quality control;
- Warehouse, tools, and machinery management;
- Locating (semi)products and tools;
- Visualization of ship installations “hidden” behind ceilings, decks, and partitions;
- Mutual communication among employees (with an emphasis on remote assistance).

Furthermore, it can facilitate activities of interactions with advanced software for the management of business processes, such as ERP or the Manufacturing Execution System [30,33]. The frequent problem of misalignment of the ship’s hull sections or blocks during their joining, with an emphasis on pipeline segments, can be prevented by the application of Industrial AR (IAR) in simulating the joining, i.e., by projecting the digital model of the assembly unit onto the already built one with which it is to be joined, thus correcting the ship’s DT in real time [34,35]. To increase productivity, i.e., the timely construction of offshore facilities, Choi and Park [36] propose the development of an AR system not only for guiding workers through the assembly process but also for guiding them to quickly

find the reference location of work. The accuracy of positioning and alignment in real space using the camera of a hardware device is a key factor in the successful implementation of AR; therefore, in their paper, the authors present an improved method of marker registration, adapted for application within complex buildings [36]. The success of using IAR applications generally depends on the appropriate communication architecture of the shipyard—one that enables low latency response or real-time rendering, thereby reducing the intensity of computational load and network traffic common to traditional, cloud computing systems [33,34]. In [34], a three-layer fog-computing architecture is proposed, in which IAR hardware devices from the node layer communicate with single-board computers, physically distributed in workshops and ships under construction, which form the second or middle fog layer (the cloud represents the third, upper layer), while in [33], a more advanced, edge-computing architecture of the future is proposed, in which the middle, edge layer is structured from a fog sub-layer upgraded with cloudlets—high-end computers that perform extremely demanding computing and rendering tasks.

3. Methodology

The purpose of this paper is to explore the possibility of the (future) contribution of AR to an improvement in shipbuilding processes. In this endeavor, the authors take into consideration the research on the applicability of AR in industry (with an emphasis on the maritime sector) analyzed in the previous section. With the intent of fulfilling its purpose, the authors seek answers to the following research questions through this study:

- Q1: To what extent does the application of AR technology contribute to reducing the number of errors in ship outfitting process activities?
- Q2: To what extent does the application of AR technology contribute to the reduction in repair costs in ship outfitting process activities?
- Q3: How can an improvement in the process of planning working hours for the execution of ship construction and outfitting activities be achieved by applying AR technology?

Given the negligible number of research studies on the implementation of AR technology for the purpose of improving the process of realizing shipbuilding projects, and since this study is based on collected statistical and empirical data, the latter is still insufficiently developed for this research to qualify for the (full) rank of quantitative, the authors deemed the case study research methodology as relevant. Also, considering that the research field in itself does not have the opportunity to control the course of ship outfitting, the identical choice of methodology was made by Leonardo et al. [37]. Furthermore, the correctness of the methodology choice stems from the umbrella research strategy itself, that is, the strategy of formulating theoretical conclusions and proposals based on the given case [38].

Among the three types of case studies represented by Yin in his work [39]—descriptive, exploratory, and explanatory—the authors of this study choose the last one stated for reasons of its applicability to the research of processes within the business system. Furthermore, the model of single-case study design is applied, since there is no similar process within the scope of this research that would allow for repeating this study.

From the perspective of paradigms that characterize research of information systems, as described by Hevner et al. [40], the authors initially applied a behavioral-science approach due to the intention of this study—to explain, i.e., predict, organizational and human phenomena in the shipbuilding process and, therefore, make the process more efficient. However, during the course of this study, the design-science research approach became more dominant and prevailed. Namely, as our proposed innovative system includes a change in the procedures and methods in the current information system and the introduction of new IT artifacts (DT), i.e., protocols (mobile application (for AR utilization)), the objective could not be accomplished without constructs, techniques, methods, and models used in the design-science research.

Figure 1 shows the main steps of the research methodology used in this study, and its content is presented in more detail below.

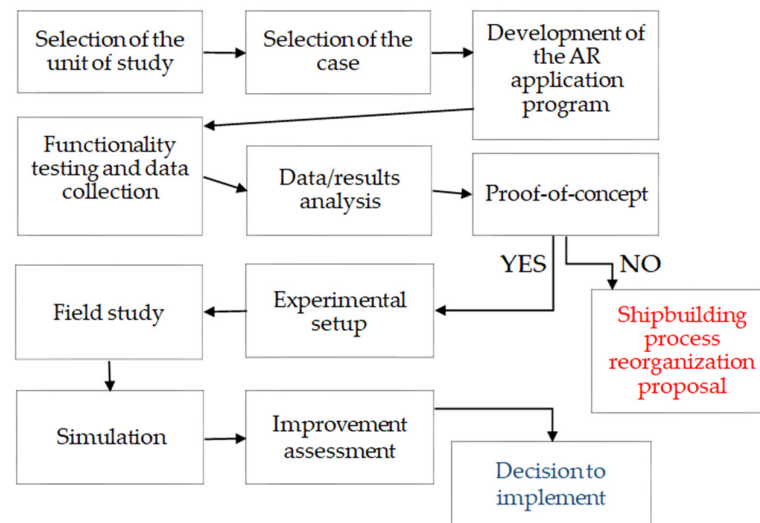


Figure 1. Research methodology/case study steps.

The shipbuilding system in the process of transformation from traditional to smart or green that was chosen as the unit of study is from a group of larger European ones and has been oriented over the last decade towards the construction of passenger ships, cruise ships, mega-yachts, military ships, and other vessels or special purpose and high-added-value objects. The observed business system provides the entire scope of shipbuilding services, from “concept” design, development, and initial design, to planning, construction, and furnishing (including luxury interiors), and finally, to handover and maintenance during the life cycle of the product.

Within the organizational structure of the shipbuilding system, all necessary departments and workshops are included for the unified provision of services for the implementation of shipbuilding project realization activities—from administrative functional units (with an emphasis on the Sales and Marketing Sector with integrated the Initial Design Department, Project Management Office, Design Department, and Planning and Technology Sector) to technical–technological (especially highlighting the Hull Construction Department and outfitting workshops according to specialties: locksmith, piping, machinery and electro). The project is implemented in the observed shipyard by a parallel development of three prevailing shipbuilding processes as follows: design and construction of the hull and its outfitting, by using the 3D model or the digital ship prototype as the backbone of the project realization process, and, therefore, the Shipyard 4.0 in general.

The 3D model of the ship is created with the activities of establishing the ship, using the most modern software programs—such as NAPA 2022.1 and version 5 of Rhino—in the initial design phase. In the later phases, that is, from the basic design phase to the delivery of the ship, the virtual prototype is modeled by applying CAD software tools such as version 12.1 of AVEVA Marine, which consists of various modules, like Stability, Material Planning, Assembly Planning, Engineering, and Diagrams, all having the possibility to interconnect with shipyard’s ERP system. Ship development in virtual reality enables clients, shipyards, suppliers, and servicers to define optimal technical and technological solutions with the aim of reducing costs in the process of its realization (primarily by performing outfitting activities in the earlier stages of the building process—advanced outfitting), exploitation and maintenance.

Design solutions through the development of a virtual prototype of the ship are optimized (also) to improve the safety of the working environment [2]. Namely, outfitting the ship at an earlier time achieves the conditions of reduced risks of injuries at work—a more open outfitting area with more natural light and ventilation and thus fewer obstacles from temporary energy installations [2]. Furthermore, during the process of building the ship, the production facility provides feedback on the state of completion in the outfitting

areas, as well as observed actual and possible errors in the design, comparing it with the currently executed state. The subject enables timely corrections or changes in the 3D model achieving a two-way communication between the physical product and its digital replica. Following the aforementioned characteristics of the 3D model, it is evident that its development in the observed shipbuilding system actually simultaneously develops the DT ship.

Figure 2 shows the correlation between the development of the 3D model, that is, the DT ship, in the stages defined by Giering and Dyck [16], and the stages of design documentation development. Three-dimensional modeling has greatly improved the level of processing technological requirements for the assembly of machines and systems, i.e., equipment in general, in terms of their positioning, requirements for connections, intersection/inter-block passages, etc. Hence, the selection and procurement of equipment—with an emphasis on the key equipment—is enabled already at an early stage of design, and thus, the preparation of planning documentation with a high level of accuracy. Consequently, by completing the second phase of the virtual ship prototype development (the “Digital Twin ship prototype” phase), workshop documentation (drawings) is extracted and entirely defined in detail, including lists of all materials and equipment necessary for the execution of production and outfitting activities.

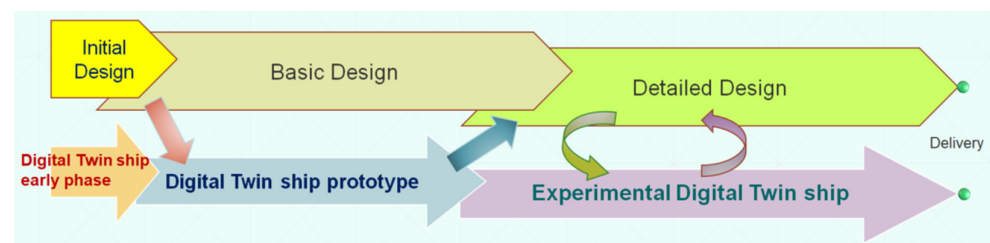


Figure 2. DT ship development phases [18].

In every single position from the workshop drawing, the Documentation Technologist (employee in the Planning and Technology Sector) assigns, through the ERP system independently developed by the observed shipyard, a technological place of work. The technological place of work is defined by the code of the specific workshop, the number of the corresponding work order, and the designation of the activity per the work execution plan. Thus, by selecting the activity label in the software application, it is possible to see all the workshop drawings necessary for the realization of that activity, as well as all production functional units (workshops) that participate in its implementation. Furthermore, the technologist enters the realization sequence of a particular activity into the application by connecting all workshops involved in its implementation, whereby the connections are defined based on the material and equipment components found on each workshop drawing.

In the next step of planning the necessary production capacities, the Technologist “standardizer” (also an employee of the Planning and Technology Sector) takes over the workshop drawing and, according to the shipyard’s standards, standardizes the work required to perform all technological operations resulting from the activities on the drawing and creates worksheets in the software application. A worksheet is opened for each technological operation containing labels for the location of the cost (the specific workshop), work order, and the specific activity. Furthermore, a worksheet contains the number of standard hours for its execution, the planned start and end date of its execution, and the amount of its value. Finally, the Technologist “standardizer” concludes the planning of the working hours required for the production by handing over the worksheet and the corresponding drawing to the workshop manager, who is first in line for the activity realization.

Previous analyses, although few, of the concept of early outfitting point to its important role in contributing to an improvement in the competitiveness of the process of realizing shipbuilding projects. This is why the process of outfitting a ship was chosen as the case of

this research. Although Lamb argues in his study [41] about the effects of advanced outfitting on cost reduction in the process of building navy ships or cruise ships, most shipyards today have adopted the concept of carrying out installation activities for (sub)assemblies of ship systems, equipment blocks, machines, piping, and others in the earliest possible stages of the shipbuilding process, as this will result in shorter construction periods as well as increased productivity [42]. Namely, empirical data from world practice followed by theoretical research indicate a ratio of working hours spent in the outfitting process to perform the same assembly activity from 1:3:5:7 [43] to 1:3:7:11 [44]. The subject ratio depends on the shipbuilding phase, i.e., whether the particular assembly activity is carried out in the outfitting workshop or on the panel/2D section, in the block in erection, in the ship on the slipway/berth, or after launching on the outfitting quay [43,44]. Considering the shipbuilding initial phase as the most cost-effective in terms of carrying out outfitting activities, the research analyses the possibilities of optimizing shipbuilding processes by redirecting as much of the assembly work as possible from the later stages of construction to the phase of modular outfitting [43], i.e., on-unit advanced outfitting [41]—assembly of individual parts of ship's equipment and systems in outfitting workshops into equipment assemblies, equipment blocks, or the largest equipment modules [43]. Thus, Fafandjel et al., in their paper [43], present an algorithm for measuring possible improvements in the shipbuilding and outfitting processes optimized with the concept of modular outfitting. Furthermore, Rubeša et al., in their article [45], develop a procedure for assessing the reduction in labor costs in the shipbuilding process resulting from the application of the modular outfitting concept compared to the “traditional” one. However, defining the phase of shipbuilding as the most favorable in terms of cost and time for carrying out early outfitting activities depends, to a large extent, not only on the production program of the shipyard but also on the layout and size of the halls or workshops of the production facility, the capacity of production lines (panels, 2D sections), and the possibilities of horizontal and vertical transport. Hence, Kunkera et al., in their paper [2] concerning the characteristics of an analyzed shipbuilding system and its processes, present the block erection phase as being recognized as optimal for the performance of (advanced) outfitting activities. In the phase in question, favorable working conditions are still achieved (natural light and ventilation) and disruption of the work in the pre-assembly production lines of the hull construction process is avoided. Namely, depending on the production plan, the excessive scope of performing outfitting work on panels and 2D sections risks the congestion of production lines considering their dimensioned permeability. The research emphasized the significant improvement in the level of outfitting in the earlier stages of the ship's construction achieved by applying its virtual 3D model in the form and content of DT and presented the resulting savings in energy and consumption of working hours, as well as the reduction in the number and severity of injuries at work [2].

Figure 3 shows the newbuilding outfitting process relevant to the observed shipbuilding system.

The process of hull construction in the observed shipbuilding system, to the greatest extent, takes place simultaneously with the subsequent process of ship outfitting. Technologically, the ship's hull is divided into blocks—assembly units defined in dimensions that enable the implementation of outfitting activities to the highest possible degree, but at the same, time coordinated with the shipyard's transport capabilities, the size of the assembly halls, and the load capacity of the berths/slipways. The block is usually erected out of four sections in the pre-assembly phase. The construction technology defines the number and sequence of connecting blocks on the slipway.

The selection of the methods used for the development of the Augmented Reality (AR) software application for implementation in the ship outfitting process [46] was based primarily on the working conditions in the ship's environment. Therefore, technology for recognizing and registering quick response (QR) codes was used, as QR codes serve as a link when the real and virtual worlds overlap. Algorithms for the detection of QR codes were selected, taking into account the characteristics of the working environment, which

are usually low lighting, obstruction of equipment and segments of the ship's systems from structural elements of the hull, weak Internet connection, and the like. A QR code can additionally contain values that form a link between the 3D CAD model and currently available information about the model (e.g., a link to digitized technical documentation or a time plan). The AR display, regardless of whether a mobile or a computer software application is being developed, is created with the help of one of the available tools for software development—Software Development Kit (SDK)—in the case of this research, Unity Editor 202.3.16f1 —game engine SDK software for the development of computer games—was used.

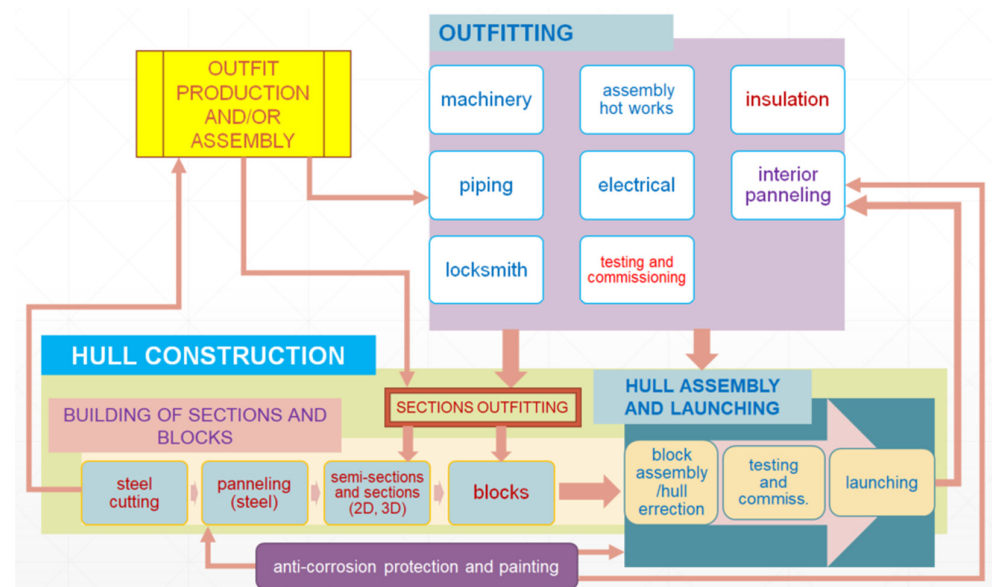


Figure 3. Newbuilding outfitting process [2].

Besides the methods for generating and detecting a QR code, various packages of software tools were additionally used within the Unity framework to create an AR application; primarily, the AR Foundation software package [47] was used. AR Foundation, together with AR Core extensions, represents a special program plugin within the Unity environment that enables the creation of AR applications on different operating environments (Android, iOS, Unreal, Web, etc.). AR Plane and AR Raycast Manager [48] are some of the more significant extensions or available pre-prepared algorithms used in the creation of an AR environment. Using the AR Plane algorithm, commands are executed to detect flat surfaces in the physical environment via the camera of the hardware device being used, and according to the performed detection, to create a virtual surface on which virtual objects will be projected. Next, the AR Raycast Manager algorithm enables testing the correctness of the projection of virtual models by projecting a (laser) ray from the hardware device used (e.g., tablet, smartphone) onto a specific object in the physical world, while also enabling the automation of that entire control process. Other additions include script packages for creating an application in user interface (UI) design, such as raycasting (converting a 3D perspective into a 2D map), the display of textual content, manipulation with objects in an AR environment (Lean touch), and detection and control of input via the devices used (keyboard, mouse, joystick, . . .), screen touches, or gesture usage.

Assuming an already implemented ERP IT system, and previously implemented software programs for 3D modeling, the basic cost of developing an AR software application should not exceed the amount of approximately EUR 10,000 for software tools, and approximately EUR 2000 for the purchase of the necessary hardware devices (tablet, smartphone). The investment in the implementation of an AR software application mainly depends on the number of users.

The results of this study are based on empirical data, that is, conclusions derived from numerous conversations and brainstorming sessions held with employees of the observed shipbuilding system during this research, direct observations of researchers, analysis of relevant technical–technological and planning documentation, and collected statistical data from the archives of the observed business entity.

4. AR Software Application Development

Constituent parts and functions within the system of the developed AR software application, and their link with the current key processes of the ERP IT system (the “Web Sphere Application Server” (WAS) system, independently developed by the observed business entity) are shown in Figure 4.

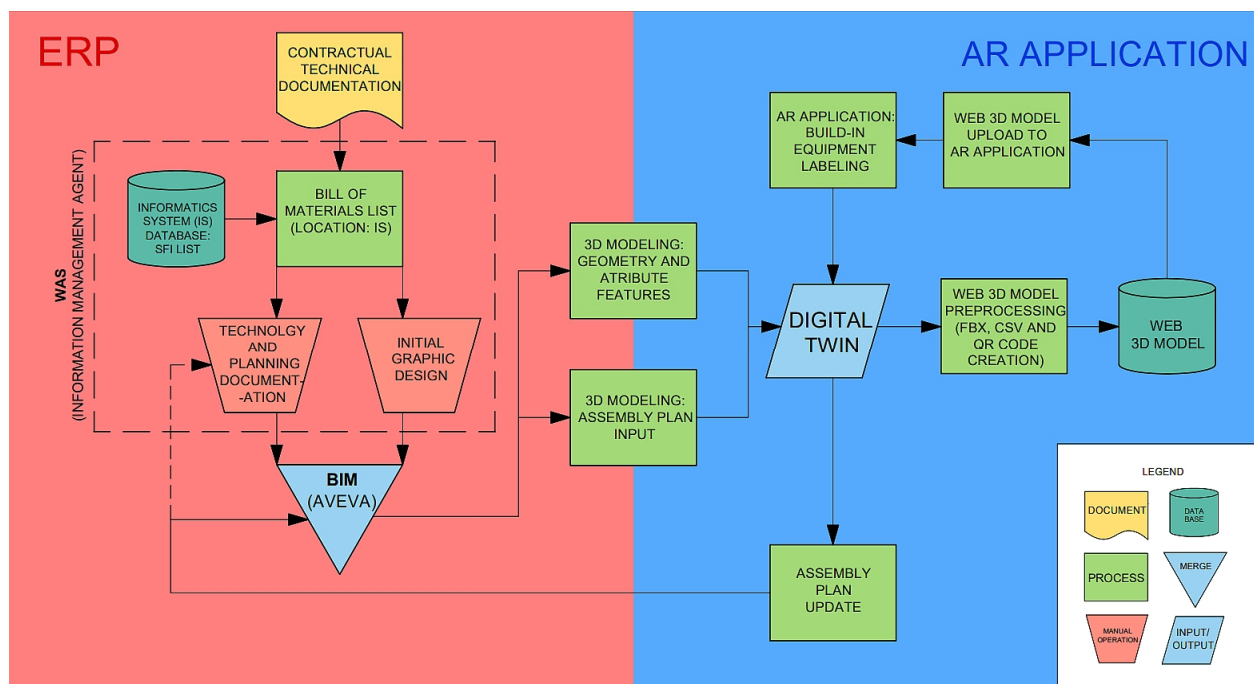


Figure 4. Process flow diagram within the AR application system and functional connection with the ERP system.

At the outset, it is important to note that there is currently no central place in the WAS system to which all information about the process of building and outfitting the ship is transferred and collected, but rather, it is dispersed within it—by upgrading the existing 3D model of the ship with the AR software application system, shown on the right side of the diagram (Figure 4), the properties or content of the DT ship are significantly improved.

The left side of the diagram represents the process of creating information according to the (daily) plan for installing elements of ship systems and equipment, which is an integral part of the current ERP system of the observed shipyard. After the technological, planning, and preliminary graphic processing of the information generated from the contractual technical description of the ship, it is necessary to transfer it to the software for 3D modeling—AVEVA E3D (AVEVA), formerly commercially known as AVEVA Marine—and connect them to create a virtual prototype of the ship in the form and content of the DT.

The designed AR system in shipbuilding uses the outputs from WAS and AVEVA as its basic inputs, and it contains the following steps:

1. Selection of outfitting elements with associated attributes as well as the outfitting area according to established procedures from the AVEVA software tool—selection of outfitting professions (locksmith, electro, piping, machinery) and the outfitting area (group/zone/room) will depend on the adopted installation schedule. The output is

a 3D model in Industry Foundation Classes (IFC) data file format, or RVM data file format (RVM is a proprietary file format created by AVEVA Plant Design Management System), and a text file in Comma Separated Values (CSV) data file format, along with element attributes;

2. Model processing for Unity and AR application—from the basic format (IFC/RVM), a FilmBox (FBX) 3D file format is generated for a previously defined outfitting profession or area;
3. Space identification with the help of a QR code—for the purposes of the application, ship areas (zones/groups) are divided into smaller spatial units—rooms—which are instantiated in real space with the help of a QR code. In this step, a QR code is assigned to each spatial unit in FBX format. QR code generation is performed with the help of QR libraries available online (e.g., <https://webqr.com/create.html>, accessed on 31 August 2023);
4. Saving the documentation of the 3D model for the AR application—the result of the previous step is a large number of FBX and related CSV data files and QR codes, which will be accessed with the help of the database.

4.1. Using an AR Application

4.1.1. “Completion Marking” Function

The procedure consists of the following steps:

- Downloading the appropriate files (FBX with corresponding CSV) and QR codes from the database, depending on the outfitting area or profession and the time schedule for delivery of the ship systems and equipment;
- Loading a specific file into the application;
- Going to the appropriate outfitting area;
- Placing the QR code in a pre-defined place for this purpose;
- Instantiation of the selected equipment as an extended representation of reality on the screen of the applied Android device;
- Checking the overlap between the virtual display and the real world;
- Entering data on completion (“built-in” yes/no) and saving it in a CSV data file;
- Sending information about the completion of the equipment assembly to the database.

As Figure 4 shows, further activities would include the steps of entering data on the outfitting completion in the DT and updating the equipment installation plan. These are outside the scope of AR application development; however, they are implied as the future integral parts of the ship’s DT.

4.1.2. Function “Attribute View”

This function is procedurally identical to the “completion marking” function, but instead of entering the completion of installation, the action of inspecting the attributes of the ship’s systems and equipment components is performed in such a way that by touching the equipment elements of interest, a transparent box appears with information about the touched element (e.g., outside dimension size, weight, manufacturer, etc.). In addition to displaying the attributes, it is possible to add a comment on the observed equipment, which is recorded in the previously mentioned CSV data file.

5. Results and Discussion

5.1. AR Application

5.1.1. Proof-of-Concept

The first tests of the AR software application were carried out in June 2021 [46]. The tests were focused on the functioning of the application, especially on the part of instantiating the virtual display of objects and how the environmental conditions of the outfitting area affect the operation of the application. The position of the QR code is predefined, and the tolerance for the area where the code should be detected is given. The “joystick” and “slider” functions were added, which enable the translation and rotation of objects for more

precise adjustment. These functions were made exclusively for the development phase of the application to allow for more precise positioning (Figure 5) due to expected minor deviations. Objects were successfully instantiated in the first test, and then the function of hiding objects with the help of check marks was also successfully tested.



Figure 5. Positioning of the displayed equipment with the help of slider and joystick.

5.1.2. Experimental Level

For the higher-level AR application prototype, the programming logic for the development of functions on the installation of components of ship systems and equipment and the display of their attributes, described in the previous section, was elaborated. In order to enable the operability of the functions within the AR software application, it is necessary to have an accompanying Graphical UI (GUI) for interaction. The existing GUI needed to be adapted concerning visibility—the existing selection buttons were not readable, so scaling was performed (Figure 6).

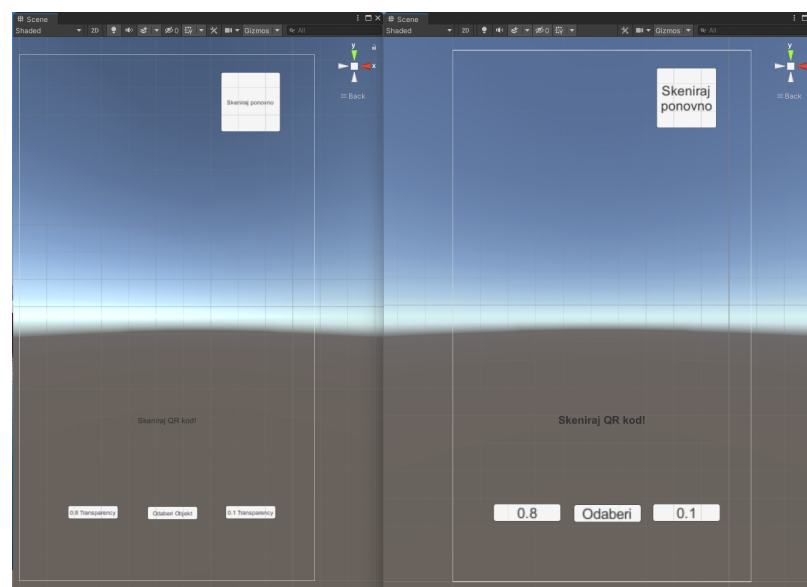


Figure 6. Changing the font size in the Unity programming environment.

Since the current IT system of the observed shipyard does not allow communication with the help of wireless technology, the AR software application system was adjusted so that the communication between the 3D model of the ship from AVEVA and WAS takes place with the help of a CSV data file, i.e., a text file. Using this file type is a sufficiently robust and understandable way of transferring information across different operating systems and platforms. The basic function of the CSV data file within the AR application is the transfer of information about the attributes of the equipment elements and the role of the input/output file in recording the state of the equipment assembly completion.

The entry of the state of installation completion is made in such a way that after selecting an element of equipment, a checkmark is placed in the checkmark field to the left of the text (in Croatian) “Završeno?” (in English: “Completed?”)—shown in Figure 7b as “Completion input”. These data are then directly “inserted” into the CSV data file and saved in the network database with the associated FBX data file. The equipment elements shown in the FBX data file are selected with the help of the offered menu with a hierarchy tree. For the hierarchy tree, a function was set for selection by individual subgroups, which is currently visible through the inscription (in Croatian) “1. Objekt” (in English: “First Object”) positioned to the right of the corresponding check mark field (shown in Figure 7b in the position in the upper left corner of the picture). In addition to selection, a function was added to display the attributes of equipment elements that appear after selecting an individual displayed element with a touch gesture. The number and type of displayed attributes depend on the type of the outfitting profession and the type of equipment, so as a result, a survey was conducted among future users of the application to determine the procedure for “retrieving” attributes from AVEVA and ultimately automating the entire process. Finally, the option to enter a comment was added (Croatian text “Dodaj napomenu...”—English: “Add a remark...”), as shown in Figure 7b in a position on the left in the middle of the picture) which, together with information about the degree of completion of the equipment assembly, is returned to the basic 3D model of the ship. For now, this option serves as a place to record observed errors when reviewing equipment installation accuracy. All the mentioned options and functions together form an innovative way of communication between the 3D ship model and the IT system in terms of improving the content and properties of the DT as the only real representation of the physical product (“one true model”).

5.1.3. Obstacles and Limitations

Obstacles that the authors ran into during the AR software application implementation were mainly related to the following:

- Communication between the “old” and “new” software systems;
- Signal quality (inside enclosed outfitting areas—“metal compartments”);
- Conditions of the working environment—e.g., insufficient lighting and intensive presence of dust make the initialization and tracking slower and more difficult;
- Size of the digital 3D model (“congestion” due to a large number of equipment types and systems, i.e., elements with numerous associated attributes);
- Employees’ “resistance” towards changes in work procedures.

The main technical limitation of this AR application prototype is recognized as the impossibility of establishing continuous web connectivity in enclosed ship spaces. Another significant error in the AR application prototype is that the information input (“completed”/“not completed”) is not always correctly connected to the related virtual 3D model of a ship system component.

The main risk of AR technology implementation in shipbuilding processes is the possibility of sending incorrect data from the ERP system, that is, the digital 3D model to the AR software application, due to, for example, errors in 3D modeling.

Future work considering AR technology implementation in the shipbuilding project realization process will include back propagation programming, to ensure each element

position is defined by the AR method, and that definition should be communicated and updated in a virtual 3D ship model.

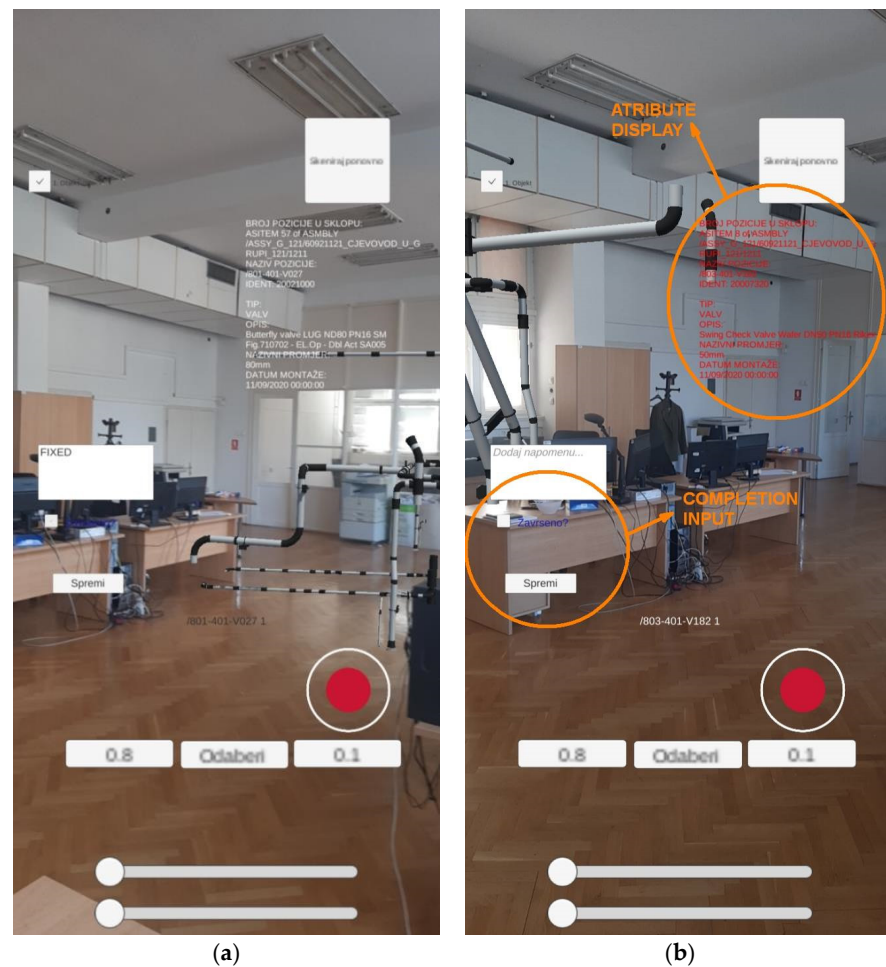


Figure 7. Adding a framework for equipment attributes, changing the attribute colors, and adding a window for entering text: (a) before GUI changes and (b) after GUI changes.

5.2. Errors in System and Equipment Assembly Activities

Based on statistical and empirical data collected from the observed shipyard system, Kunkera et al., in their paper [2], explored the importance of performing ship outfitting activities in the earlier stages of construction to achieve savings in the process of project realization. Their research was based on the comparison of data concerning the hours of work spent on outfitting activities and the ratio of the outfitting duration in the block erection phase compared to the post-ship launching phase. The data were compared using an example of two newbuildings from the passenger or cruise ship market niche, by standardizing the parameters of their volume or complexity by converting the gross tonnage unit into compensated gross tonnage as a unit of measure. The only significant difference in the process of their realization relates to the design process, since in one of the cases, the 3D model of the ship was developed in the form and content of the DT. Their research defined its contribution to science through the promotion of the importance of early or timely outfitting of a ship concerning the realization of possible improvements in the building process, which the authors ultimately presented in the study. Namely, in the case of a newbuilding based on the development of its DT, as much as 70% of the activity of the total outfitting of the ship with piping, cable routes, ventilation ducts, key equipment, and other outfits was realized before the lifting phase, i.e., the assembly of the ship's blocks on the slipway. Thus, depending on the specialty of the assembly work (machinery, piping, locksmith,

or electro), a saving of up to 30% was achieved in the number of working hours on outfitting activities (machinery assembly), and productivity in the shipbuilding process in general was improved by approximately 20% (which includes the already achieved approximate reduction of 14% in the total number of welding hours during the building of the ship).

The research in [2] further shows that by performing outfitting activities in the early stages of shipbuilding, the share of the number of working hours spent on repairs during assembly compared with the total hours spent on outfitting significantly decreased, from approximately 48% for electrical works to as much as 92% in case of locksmith works. The described saving in the number of working hours spent on correcting the errors in systems and equipment assembly was also achieved because of the two-way communication between the physical product and its virtual prototype (in the “Experimental Digital Twin ship” phase). Feedback to the Design Department, i.e., the 3D model of the ship, and other relevant functional units of the shipbuilding system is based on (weekly) reporting of the production facility, i.e., the outfitting workshops on the following:

- Outfitting work status of completion;
- Observed irregularities in the workshop drawings in relation to the completed status of assembly;
- Observed irregularities in the previous stages of production (of system components, equipment, equipment blocks, etc.);
- Procurement of material and equipment inadequate for installation;
- Definition of inapplicable assembly technology.

Table 1 shows the distribution of working hours spent on repairs according to the cause of errors following the categorization of the observed shipyard, while Table 2 shows the working hours spent, structured according to professions covering outfitting.

Table 1. Consumption of working hours for assembly repairs according to the error cause, for the example of three newbuildings.

Outfitting Process		Cause of Error							
		Documentation		Outfit		Technology		Fabrication	
New Build	Man-Hours for Repair Activities	(h)	(%)	(h)	(%)	(h)	(%)	(h)	(%)
1	6257.5	4105	65.6	1236.5	19.76	916	14.64	0	0
2	20,396.5	12,706	62.3	483	2.37	6725.5	32.97	482	2.36
3	24,092	20,273.5	84.15	770.5	3.2	2814	11.68	234	0.97
Total	50,746	37,084.5		2490		10,455.5		716	
Average			70.68		8.44		19.76		1.11

Table 2. Consumption of working hours for repairs according to outfitting professions, structured by error cause categories.

Outfitting Profession	Man-Hours for Repair Activities	Cause of Error			
		Documentation (h)	Outfit (h)	Technology (h)	Fabrication (h)
Assembly—machinery	3679.5	2600.75	310.63	727.22	40.9
Assembly—piping	25,305.5	17,886.49	2136.33	5001.42	281.26
Assembly—locksmith	7414	5240.38	625.9	1465.31	82.4
Assembly—electro	14,347	10,140.78	1211.2	2835.56	159.46
Total	50,746	35,868.39	4284.06	10,029.52	564.03

The collected data are based on archival records of the observed business entity from the period between 2012 and 2022 and refer to three newbuildings from the shipyard’s production program (passenger or cruise ships), of similar parameters, and realized consecutively over three years; in the process of their realization, a total of about 960,000 working hours were spent for the execution of the outfitting activities, which is approximately 43% of the total spent during construction. Feedback from the production facility is analyzed,

together with Project Management Office, by the error “causative factors”, i.e., the referent units of function (Planning and Technology Sector, Key Material Sourcing Department, Design Department, Purchasing Department, workshops). The analysis of feedback enables the prevention of new assembly errors and also the prompt correction of existing ones at the stage of detection, which in relation to their removal in the later outfitting stages, achieves significant savings in repair costs, i.e., reduces the engagement of working hours (with an emphasis on assembly and welding professions), as well as provision of temporary energy, i.e., energy consumption in general.

Although the number of errors created during the outfitting activities is reduced primarily thanks to the application of the DT of the ship in the process of its realization, the cost of the work required to eliminate them is still significant. Through direct observation of the ship outfitting process during this research, including the interviews with engineers and managers in the production facility, it was concluded that more frequent and not only current one-week reporting to the administrative and production units of the business system involved in the ship realization process, would increase the savings in the number of hours spent in repairs. Furthermore, it was noted that it would be of additional importance for the achievement of the savings in question, to also report, besides the status of assembly activities and observed possible errors during the outfitting process, any possible deviations in the positioning of equipment and/or ship system components in the outfitting areas in relation to the design documentation. However, reporting the progress and quality of outfitting works on a wider scale and at more frequent time intervals (preferably daily) in an up-to-date manner would result not only in a significant increase in working hours for monitoring and reporting activities but also in the need for the engagement of an additional number of foremen or production engineers.

By analyzing the possibility of improving the reporting procedure with the technologies and trends in Industry 4.0, the technology of AR was recognized as the best applicable for this purpose, which would enable two-way communication with the digital prototype of the ship by overlaying virtual 3D models of objects with physical reality in each area of outfitting. In addition, considering the already daily visits to the outfitting areas by the production engineers/foremen in charge, communication using AR could be performed on a daily basis, as it “only” takes a loading of a virtual model into the physical space via a tablet or a smartphone. This method of operational reporting would probably result in a corresponding reduction in the number of working hours since instead of more engineers or foremen—according to the current procedure, each workshop reports separately—a smaller number of employees could visit the outfitting areas. However, the latter should be the subject of additional research.

This is the reason why, for the purpose of improving the reporting process, i.e., analyzing the status of (outfitting) works in progress in a timely, quantitative, and qualitative sense, the AR software application, described earlier in this paper, was developed. After multiple brainstorming sessions of researchers and relevant representatives of functional units involved in the process of ship outfitting, and based on the empirical data gathered through many years of observations of operations engineers and project managers in the shipyard, approximate sizes of theoretically possible improvements in the process of project realization using the application in question were adopted. All such improvements are in the sense of reducing the number of working hours for assembly repairs. Thus, for the elimination of errors caused by irregularities in the documentation, a conservative assumption is made of a 24.3% reduction in the consumption of working hours, and 17% for assembly errors caused by the impossibility of procuring specified equipment and materials or their inadequacy. Furthermore, in the case of technology being incompatible with the outfitting activities, a reduction of 34.3% in the number of working hours for repairs is assumed, and 13% because of errors in the production of an equipment block or installation sub-assembly, such as a piping segment, which is prepared for assembly by one of the shipbuilding system workshops. Table 3 shows the example of three realized newbuildings, i.e., statistical data on the working hours spent on repairs and theoretical

reductions in the number of working hours by the percentages according to the premises of this study, structured according to assembly professions, that is, the category of the cause of error occurrence.

Table 3. Reduction in the number of working hours for repairs in the outfitting process according to assembly skills and error causes, achievable by applying AR technology.

Outfitting Profession	Reduction in Man-Hours in Relation to the Cause of Error				Reduction, Total (h)
	Documentation (h)	Outfit (h)	Technology (h)	Fabrication (h)	
Assembly—machinery	632.85	52.81	249.68	5.32	940.65
Assembly—piping	4352.38	363.18	1717.15	36.56	6469.27
Assembly—locksmith	1275.16	106.4	503.09	10.71	1895.37
Assembly—electro	2467.59	205.9	973.54	20.73	3667.77
Total	8727.98	728.29	3443.47	73.32	12,973.06

The results show that the application of AR technology is expected to save an average of 26% in the number of working hours required for repair activities in the outfitting process, in the usually planned dynamics of shipbuilding from the production niche of the observed shipyard system over a three-year period.

5.3. Repairs in the Outfitting Process

During this research, direct observation of the production activity implementation revealed significant time consumption with the high engagement of employees, with an emphasis on production engineers and foremen, in carrying out removal activities of errors that occurred in the construction and outfitting process. It was noticed that the above is especially evident in the case of an error of the lack or failure to open cutouts through elements of the ship's structure for the purpose of inter-section or inter-block passages of pipings, cable routes, ducts for heating, ventilation, and cooling systems (HVAC), and the like. The procedure for repairing the error of not opening the cutout is time- and cost-intensive, regardless of the stage of the process in which the error was detected. Figure 8 presents examples of situations where the error in question was discovered in various phases of shipbuilding; however, its repair duration as well as the frequency of engaging employees in the process of repair execution is particularly pronounced if it occurs during the execution of ship outfitting activities.

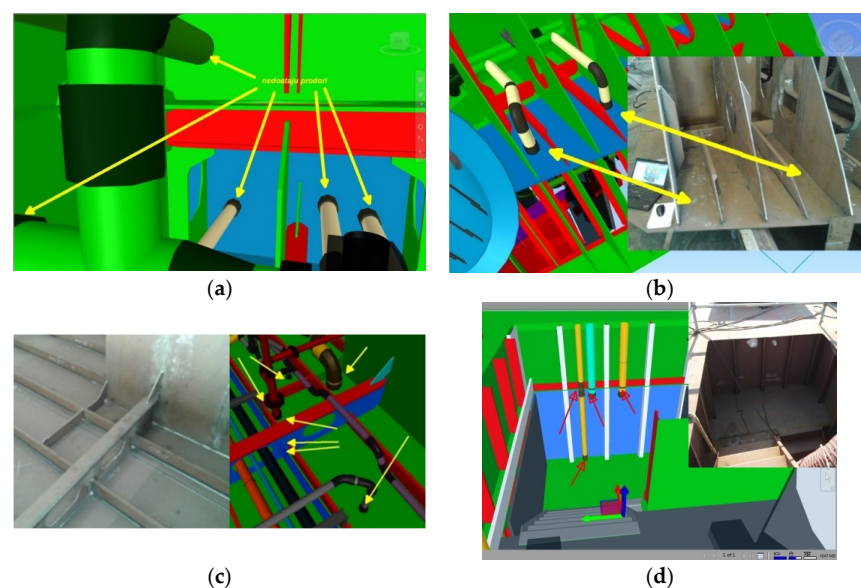


Figure 8. Examples of detecting missing cutouts in the phases of (a) sheet metal cutting, (b) erection of sections, (c) erection of blocks, and (d) outfitting in the ship while on the slipway.

Based on the analysis of the repeated processes of repairing the error of not opening the cutout, from the moment of its detection to its removal, the authors of this paper described its current general repair procedure. The course of the procedure as well as the description of the steps in its implementation are shown in Table 4, where the average values of time spent and distances traveled for each step are applied, taking into account the possible combinations of the relationship “cutout size–construction phase–position of repair work”.

Table 4. The procedure for repairing the error of not opening a cutout.

No.	Step	Duration (min)	Cumulative Duration (min)	Distance (m)	Number of Persons/Steps
0	Lack of cutout established				
1	The worker rechecks the drawing	5	5	0	1
2	The worker calls the foreman	2	7	0	1
3	The foreman arrives at the scene	20	27	100	1
4	The foreman rechecks the drawing	3	30	0	2
5	The foreman calls the production engineer	2	32	0	1
6	The production engineer arrives at the scene	20	52	100	1
7	The production engineer controls the drawing	2	54	0	2
8	The production engineer goes to the office	20	74	100	1
9	The production engineer writes a Change Request	5	79	0	1
10	From the Change Request to the Change Order	1920	1999	0	
11	Going to the change point	15	94	150	1
12	Checking and securing the work area	5	99	0	2
13	Opening of the cutout	5	104	100	1
14	Cooling the cutout	5	109	0	1
15	Grinding the cutout	5	114	0	1
16	Dismantling the equipment and cleaning the workplace	5	119	100	1
	Cumulative (production facility)		119		
	Total	2039		650	

It is evident from the table that several employees are involved in the implementation of the procedure—workers, foremen, and engineers in the production facility—and in some steps, out of as many as 16 of them, from the moment of detecting the lack of a cutout, up to 2 employees were engaged. Their total average distance traveled during the implementation of the steps of the procedure is 650 m. The duration of the activity of step number 10 is particularly noteworthy, with an average of 1920 min recorded. If step 10 is excluded from the analysis of the procedure, which is not even under the authority of the production facility but of the administrative functional units of the observed shipbuilding system, an average of 2 working hours are spent to repair the error. However, the duration of the activity from the submission of the “Change Request” (which considers the change in the workshop documentation) to the issuance of the “Order for change” prolongs the duration of the error removal, from its detection to cleaning the workplace after repair, by 4 days. Consequently, if the error in question is part of the construction and outfitting process activity, which is on a critical path, the deadline for the realization of the project is also prolonged by 4 days. In the case of discovering new errors of the same type and in other activities of the project implementation process, which are also on the critical path, an additional 4-day extension of the ship’s delivery deadline is multiplied by the number of such activities. The resulting extension ultimately causes an increase in the cost of financing, insurance, and possibly those resulting from the contractual penalties for delay. It is implied that the delay in the realization of the project can be reduced or completely canceled by replanning work capacities (engagement of new employees to work in additional shifts); however, the same will result in a significant increase in labor and energy costs.

With the focus of this research on the ship outfitting process, a theoretical analysis was undertaken of the possible improvement in the procedure for removing the error of not opening a cutout in case of the implementation of the AR software application described in this paper. As already emphasized earlier, the application makes it possible to detect any

inconsistencies in the workshop documentation in relation to the existing and planned state of assembly works by visiting the outfitting areas on a daily basis while communicating with the 3D model of the ship in real time. Thus, as empirically analyzed by detecting errors in the earliest stages of the process, i.e., low-level outfitting of the area, savings are realized in the number of work hours and the energy required to eliminate them. In addition, by projecting virtual objects from the digital prototype into the image of the physical environment of the outfitting area, along with communication with the ship's DT in real time, it is possible to redefine the procedure for repairing the error of not opening a cutout, but also of repairs in general, with the realization of significant savings. Namely, the first 10 steps in the procedure of the recorded actual error repair process, including the most time-consuming, the tenth step, can be replaced with only four new steps using the AR application. This reduces the repair time from registering the error to clearing the workplace, from the current up to 4 days to approximately only 1 h, also reducing the total distance traveled by the engaged employees during the repair process by 150 m.

The flow and content of the redefined error correction procedure are shown in Table 5.

Table 5. Procedure for fixing the error of not opening a cutout in the case of using AR technology.

No.	Step	Duration (min)	Duration Cumulative (min)	Distance (m)	Number of Persons/Steps
0	Completed hull part of work				
1	Mounting the QR code holder and the QR code itself in the room	1	1	100	1
2	Control of the outfitting area (room) with AR technology	10	11	100	1
3	Recording all the missing cutouts in the area	5	16	0	1
4	Recording defects into the system (DT)	1	17	0	2
5	Going to the change point	15	32	100	1
6	Checking and securing the work area	5	37	0	2
7	Opening of the cutout	5	42	100	1
8	Cooling the cutout	5	47	0	1
9	Grinding the cutout	5	52	0	1
10	Dismantling the equipment and cleaning the workplace	5	57	100	1
	Cumulative (production facility)		57		
	Total	57		500	

5.4. Man-Hour Capacity Planning

The estimation of the optimal number of (production) working hours required for the project realization is one of the critical preconditions for the realization of a competitive shipbuilding system [49]. However, the high complexity of shipbuilding projects represents a major challenge in production planning and scheduling of working capacities [50,51]. Furthermore, due to the traditional one-way hierarchical link between long-term production planning and mid-term scheduling, changes in mid-term plans, in terms of redistributing work capacities to preserve production deadlines, are not timely updated in long-term plans [52].

As described in Section 2 of this paper, the process of planning the required production working hours per the standards of the observed shipyard ends with the activity of handing over the Worksheet by the Planning and Technology Sector to the production facility. During the performance of production activities, including final commissioning tests, the foreman of each functional unit registers workers daily according to the activity they were engaged in that day. Records about the engagement of workers are delivered in physical form by the foreman to the administrator in the workshop, who supplements the reference Worksheet with the employee codes accordingly. In addition to employee codes, in each Worksheet, the administrator also records the realized start and end of work on the activities, as well as the number of working hours spent on their implementation. The administrator of the workshop completes the Worksheets with data through the appropriate software application of the ERP system, from which, on a weekly basis, on the last day of the week, reports on the consumption of working hours are generated for each workshop, newbuilding, workshop drawing, or activities. After calculating the employee salaries,

the reports are supplemented with the amount of monetary value according to the same review categories.

Reporting the completion of activities in the observed shipyard system is carried out by entering completion into the corresponding ERP software application based on the assessment of the activity completion percentage or according to the completion of the positions on workshop drawings. The evaluation method is used by workshops engaged in the fabrication and painting of hull sections and blocks, and, in general, by production functional units that perform activities for which the workshop documentation is not planned—for example, an electrical workshop when installing electrical cables. Entering the degree of completion of the activity according to the completion of the works by positions on the drawings is applied by the outfitting workshops, both in the stages of the outfitting process in sections or blocks (advanced outfitting) and in the stages of outfitting in the vessel on the berth/slipway, i.e., after launching (on the outfitting quay). On a daily tour of the work zones, i.e., the outfitting areas, the operations engineers of each profession involved in the process of ship construction and outfitting estimate the percentage of completion of the activity or mark the completed positions on the physical drawings. The data are then entered into the ERP, whereby the percentage of completion of the activity is calculated by software based on the completed positions. Entered/calculated data on the degree of completion are generated on a weekly basis (on the last day of the week) by the appropriate software application in reports on the realization of the production plan for each project in the process of realization.

Based on the reports, a (weekly) analysis of the completion of works (construction and outfitting) is carried out, and, if necessary for the purpose of maintaining the planned realization deadlines, replanning of the working hours required for the progression of the observed shipbuilding system production process.

Table 6 shows the current average duration of procedures for recording work, i.e., reporting the degree of the completion of activities during the ship outfitting process for the four basic assembly professions (piping, machinery, electro, and locksmith) and the Advanced Outfitting Department throughout the two-year production period and the optimal dynamics of shipbuilding.

Table 6. Consumption of working hours for reporting activities (record and completion of work) during the outfitting process over a two-year period.

Activity	Dynamics	Executor	Time/Day (h)	Number of Employees Engaged per Day (Four Assembly Professions + Advanced Outfitting Department)		Total Time (h)
				Outfitting in a Hull Section or Block	Outfitting in the Ship (Slipway and Outfitting Quay)	
Registration of workers according to the activity in progress	Daily	Foreman/head of department or workshop	1	5	4	3182
Delivery of employee records to the workshop administrator	Daily	Foreman/head of department or workshop	1	5	4	3182
Completion of the Worksheet in the ERP with the codes of engaged employees, start and end of work, and the number of hours spent on activity	Daily	Administrator of the production functional unit	8	5	4	25,456
Entry of activity completion in the ERP	Daily	Head of department or workshop/engineer in operations	1	1	4	1766
Total						33,586

By analyzing the work recording and completion reporting procedures, as well as by understanding the already developed and possible functions of the AR software application, the possibility of automating the procedures is perceived. Such automation could be accomplished by digitizing the work registration directly in the areas where the activities are performed and by adding appropriate attributes to elements of ship systems and equipment (such as standard hours of assembly work by position for each necessary outfitting profession and the attribute of the complexity of the work, i.e., the required level of expertise of the worker).

With the digital registration of the worker's assigned activity start and finish, along with uploading requests and/or instructions for mounting equipment positions on the screen of a smart device via the corresponding QR code, it would be possible to automatically record the work in full (who, when, how much) with daily report generation on the completion percentage of a certain position assembly by comparing the number of hours spent and the standard hours of work.

The use of the AR software application in daily tours of the outfitting areas, i.e., automatic detection of the completion of positions by overlaying virtual 3D objects onto the image of the real environment, enables a "control" review of the activity completion degree and generates real-time reports regarding the realization of the plan according to each project. This would ultimately fulfill the prerequisites for the production working hours daily (re)planning, that is, the (re)allocation of workers according to projects in the process of realization; with appropriate software upgrades, it would be possible, on a daily basis, to automatically inform or assign a worker to the subject and location of work for the next day through smart devices, according to the required outfitting profession or expertise of the employee. The latter is certainly the subject of further research.

The application of AR technology in the process of completion reporting, i.e., work recording, enables the substitution of the activities described in Table 6 only with the activity of setting elements for the digital daily registration of workers, i.e., uploading the assigned work activities in each outfitting area. Naturally, at the same time, the additional engagement of employees of the Design Department or Planning and Technology Sector is required for the activities of defining and entering additional attributes of positions, as well as creating QR codes according to outfitting professions or areas, with the need to redefine their content even on a daily basis. An additional study is needed for further analysis of the same, along with an estimate of the consumption of working hours.

6. Conclusions

The application of AR technology was chosen as the topic of this article based on the analysis of, up until now, only a few research studies with promising conclusions, and, above all, because of the recognized possibilities of improving shipbuilding processes concerning the following two features of performance in design, construction, and outfitting: completion and accuracy [24,53,54]. Furthermore, considering the importance of advanced outfitting on labor and energy cost reduction, as pointed out by previous research and also confirmed by earlier analysis of collected statistical data on the realization of two shipbuilding projects in the observed shipyard, the outfitting process was chosen as the case of this study. The operation of the AR application applied in this research is based on the use of QR codes, primarily due to the complexity of the working conditions in the outfitting areas (e.g., low lighting). The application was developed in the environment of Unity software tools, with the use of the AR Foundation software package, and the development concept was proven by testing the application operation in a physical environment.

Through direct observation of the performance of ship outfitting activities and the collection and analysis of archival and empirical data, affirmative answers were given to all the research questions, i.e., this study confirmed the further possibility of improving the process of project realization, in addition to those already achieved using the 3D model of a ship with DT features.

The applied AR application enables reporting the status of completion and accuracy of assembly works by projecting virtual 3D objects into the image of the real environment/outfitting room, in real time and on a daily basis, and with the same or even less involvement of employees responsible for monitoring the progress of the outfitting process compared with the current one. Given the above, the authors of this study expect the possibility of reducing the expenditure of working hours for repairs by at least an average of 25%, considering the four analyzed possible causes of errors in outfitting activities (irregularities in documentation, production, technology, or procurement). This would increase the productivity in the outfitting process by approximately 1.4%, observed over the three-year period of building ships.

Furthermore, the properties of AR technology upgraded to the ship's DT enable not only the detection and prevention of assembly errors in the earliest stages of the outfitting process, thus significantly reducing repair costs, but also shortening the procedure for their repairs. Namely, in the example of not opening the inter-section or inter-block cutouts, one of the frequent mistakes in ship construction and outfitting phases, this research theoretically established the possibility of a 97% reduction in the repair procedure implementation period by applying the AR application in relation to the recorded current time of the process of removing the error in question. Since this study did not include the analysis of the average number of detections of missing cutouts in the construction of a typical ship from the production niche of the observed shipbuilding system, the authors propose an extension of this study in this sense, and thus, a conclusion about the total time savings based on the example of a single project realization.

Finally, this research determined the possibility of shortening the time of recording work and reporting the completion of outfitting activities using the AR application by up to, theoretically, approximately, 30,000 h during the two-year production period of building typical ships from the shipyard's program. Furthermore, reporting the realization of the production plan in real time enables a daily revision of the required working hours plan, thereby improving the management of working hours, i.e., better redistribution of workers according to the projects in progress. This implies not only the possibility of preserving the contractual construction deadlines but also the possibility of shortening them, and, together with this, increasing the competitiveness of the shipyard. The authors therefore propose the implementation of additional research related to the planning procedure of working hours with the application of AR technology in shipbuilding processes.

It is important to additionally emphasize that the mentioned possibilities for improving the project realization process were ascertained only by research in the scope of outfitting process activities. The authors note the same substantive possibility of contributing to savings in the working hours and energy consumption also in the process of building the ship's hull, from the production of panels to the assembly of blocks on the slipway, and in this sense, recommend conducting further studies.

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