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Digital Transformation, Applications, and Vulnerabilities in Maritime and Shipbuilding Ecosystems

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Abstract

The evolution of maritime and shipbuilding supply chains toward digital ecosystems increases operational complexity and needs reliable communication and coordination. As labor and suppliers shift to digital platforms, interconnection, information transparency, and decentralized choices become ubiquitous. In this sense, Industry 4.0 enables "smart digitalization" in these environments. Many applications exist in two distinct but interrelated areas related to shipbuilding design and shipyard operational performance. New digital tools, such as virtual prototypes and augmented reality, begin to be used in the design phases, during the commissioning/quality control activities, and for training workers and crews. An application relates to using Virtual Prototypes and Augmented Reality during all the design and construction phases. Another application relates to the cybersecurity protection of operational networks that support shipbuilding supply chains that ensures the flow of material and labor to the shipyards. This protection requires a holistic approach to evaluate their vulnerability and understand ripple effects. This paper presents the applications of Industry 4.0 for the areas mentioned above. The first case in shipbuilding design is an example of how the virtual prototype of a ship, together with wearable devices enabling augmented reality, can be used for the quality control of the construction of ship systems. For the second case, we propose developing an artificial intelligence-based cybersecurity supply network framework that characterizes and monitors shipbuilding supply networks and determines ripple effects from disruptions caused by cyberattacks. This framework extends a novel risk management framework developed by Diaz and Smith and Smith and Diaz that considers complex tiered networks.

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Keywords: cybersecurity; shipbuilding and repair; risk analysis; supply network; virtual prototype; augmented reality

1. Introduction

The entry of shipbuilding to the level imposed by the paradigms of Industry 4.0 sets new challenges for a sector strongly linked to tradition. Therefore, the current fundamental mission is to unleash new methods and tools capable of managing both the design and construction of ships, which remain the most complex vehicles ever built by man. Undoubtedly, this revolution passes through the massive exploitation of intelligent digital technologies available on the market. Hence, developing a Digital Transformation (DT) process consisting of, among others, information technology implementation projects and organizational factors and changes

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is necessary. DT principles include the use of new technologies (e.g., virtual and augmented reality, machine learning, and big data analytics) and changes of key business elements/models/processes and strategies [1]. When discussing product design, all these factors contribute to developing digitized approaches and services.

In this framework, the present paper aims to provide methodologies and case studies based on technologies belonging to the DT trends. This can significantly impact ship design and production processes and revolutionize the traditional approaches adopted in such a strategic and fundamental industrial sector, highlighting the limitations and threats such technologies may face during their application.

Since the ship is a complex system, the first step to ensuring a high-quality product consists of the use during the different design phases of tools capable of elaborating a detailed virtual prototype (VP) of the whole ship. The next step foresees the extension of the use of VPs also during the construction of the ship as interactive documentary support to the workers. Finally, by elaborating lean manufacturing, digital twin, and virtual and augmented reality logic, the entire supply chain and end-users (shipowner and crew) can be integrated into the process. As regards the use of VPs in ship design, what had been prophesied in previous works [2-4] has been detailed and structured at a methodological level in more recent works [5-7] and then validated by experiences in the field [8-9]. The principle that was followed to define Shipbuilding 4.0 aims to create/adapt "smart and digital" shipyards that are characterized by adaptability, resource efficiency, ergonomics, and close integration among shipowners, shipbuilders, and suppliers [10].

The first step of this revolution was the identification of methodologies and tools to create the VP of the ship. The VP or "digital mock-up" is a digital simulation of a physical product that can be presented, analyzed, and tested concerning aspects of its life cycle, such as design, engineering, maintenance, and recycling, such as if it were an actual physical model [11]. Using these technologies, based on parametric 3D models of the products and carrying out tests, we can simulate their behavior in the real world [12]. It is possible to predict the performance of the products before realizing the physical prototypes. This allows designers to explore many design alternatives without investing time and money in manufacturing. By carrying out tests on many different options, it is thus possible to improve the quality of the project and arrive on the market with a product that satisfies the requirements in a significantly reduced time. Furthermore, shipbuilding industries are constantly under the pressure of global competition. They must search for solutions able to reduce the time to market and enhance the characteristics of their products while ensuring reliability and high performance. In this context, Quality Management tasks are paramount and can benefit from applying the innovations mentioned above.

Recently besides VP and thanks to the availability of wearable devices, the use of virtual (VR) and augmented reality (AR) was also introduced as a solution to the problem of translating the information received by the digital system to make it clear and concise reading by all users [13]. In particular, AR is a technology that allows virtual objects to be superimposed on the physical world to provide users with more information and make them easier to read and interact with the digital world. Within shipbuilding, onboard systems' design and quality control during construction and commissioning were the first cases of joint use of VP, VR, and AR [14-16]. It is worth noting that the adoption of VR and AR in ship design and construction phases is now a consolidated reality, as some of the most productive shipyards worldwide have been implementing these technologies in their processes. This underlines their importance as disruptive technologies in the sector and their increasing development. In this work, the authors propose a detailed methodology based on an advanced design tool to exploit VR/AR capabilities at their best and apply it to a practical case involving ship system design.

Then, several questions related to the robustness of the new processes and tools remain open. First, ensuring adequate data storage space through the Cloud for virtual simulations and prototypes is necessary. This virtual space must be fed by stable internet connections that allow seamless integration among all levels of the supply chain and the analysis of Big Data from design and production. Clearly, data and connections are increasingly exposed to the risk of violations and interruptions that can have disastrous effects on all industrial processes related to shipbuilding. Therefore, issues related to cybersecurity become of utmost importance.

Cybersecurity is a significant concern to the U.S. Department of Defense [17-19]. Shipbuilders and suppliers handling any U.S. Government technical information must comply with cyber-security requirements cited in the Defense Federal Acquisition Regulation System (DFARS 252.204.7012 and 252.204-7020). However, this compliance only relates to 20-30% of materials used in a shipyard. The remaining 70-80% of the material and supplies used in shipbuilding originate in the commercial sector, not requiring compliance. Accordingly, shipyards generally consider that the impact of a cyber-attack on firms providing commercial supplies to shipyards is of significant interest to the industry. Overall, estimates a one-week delay caused by a project's critical path disruption due to a late or incorrect component might have an approximate cost impact of $50,000 per ship (2020 U.S. Dollars).

Cybersecurity threats to supply chains and industrial systems are growing drastically. This has been attributed to the rapid rise in computing power [20]. As the frequency of remote working becomes prevalent in new digital ecosystems, workers, suppliers, operations, and manufacturers become increasingly exposed to cyberattacks [21, 22]. Cyberattacks may further decelerate or halt port or shipbuilding and repair activities, generating shortages in labor and sparking interruptions through supply chains [19]. Cyberattacks on critical industrial sectors related to maritime supply chains and shipbuilding suppliers are rising [23]. A cyberattack on the 5,500-mile pipeline system that carries about 45% of the fuel used on the East Coast (Colonial Pipeline) was perpetrated on May 7, 2021 [24]. This, and other disruptions, affect suppliers differently, suggesting the necessity of an approach that carefully quantifies the impact of cybersecurity breaches on shipbuilding supply networks. Ripple and bullwhip effects propagate backward and forward simultaneously throughout supply networks [25], negatively impacting suppliers and amplifies distortions [26]. These fluctuations are especially harmful to small and medium-sized businesses, constituting roughly 62% of active suppliers to the shipbuilding and repair sector (Newport News Shipbuilding [27]).

2. Digital Transformation in Ship Design

2.1. Design Methodology based on Augmented Reality for Quality Management

Nowadays, the global competition within the shipbuilding sector has reached very high levels due to several players involved. Characteristics like reduced time-to-market and high quality are the key performance indexes for shipyards to establish their leadership. At this aim, the introduction of Industry 4.0 technologies is a crucial aid: tools such as virtual prototypes, digital twins, virtual and augmented reality represent exploitable solutions able to impact the whole production processes of ships and improve shipyards' efficiency and economic value. In this context, we can talk about "Shipbuilding and Shipyards 4.0", for which digitalization represents a fundamental requirement.

With a specific focus on quality management, the opportunities and related advantages offered by virtual prototyping combined with augmented reality can increase shipyards' incomes and importance in a remarkable way. Indeed, Cyber-Physical Systems such as augmented reality glasses combined with 3D virtual prototypes can allow the organization of an integrated, flexible, efficient, and green production process, with real-time quality control thanks to self-optimized and autonomous systems able to combine availability, exchange, and processing of relevant data and information.

The design and production of onboard ship systems and their consequent quality control are one of the sectors in which tools such as VPs and AR may give the best advantages. Indeed, they allow checking the correct position of components and machinery and their integration with structural elements even before their installation onboard. With these aims, the authors implemented a design methodology for ship systems that merges the classic procedure with digitalization technologies. In such a way, the possibility of errors and interferences are reduced; furthermore, the methodology favors a more straightforward and more fluid design development, facilitating both the communication between shipyard and designers and the dialogue with the customer.

For this study, the authors selected the software Cadmatic®, which has a suite dedicated to Marine Engineering that can be used for the digital design of onboard systems in a 3D interface and the generation and exportation of all the necessary 2D drawings. Cadmatic® allows the creation of a parametric model, in which each component presents both geometric and functional characteristics and is stored in a library; all the components can then be used to assemble the 3D virtual prototype of the ship equipped with the proper systems in the Plant Modeller interface. Furthermore, Cadmatic® allows the users to inspect the digital model by exploiting AR and VR applications through the use of wearable devices such as AR glasses: through the dedicated tool, it is possible to identify and easily check details on any object, get dimensions, and even create the markup for project coordination and change management. During the construction of a ship, all the supply and production data, and inspection, operation, and maintenance data can be constantly monitored. All these activities can be performed while ensuring a constant sharing of data between the parties involved and allowing consultations and interventions from the design office.

The methodology implemented by the authors is schematically reported in Figure 1 and extensively described below.

The first step for creating the 3D virtual prototype consists of the setup of the new project and of the working space within Cadmatic® Plant Modeller. Here, the ship's main dimensions are inserted to specify the volume occupied by the model and the best working views.

Once the working environment is created, the user must implement a series of preliminary actions necessary to start the modeling phase. The reference coordinates of the ship must be defined through the input of transversal and longitudinal sections and decks. Then, the program requires the definition of *systems*: these are work levels characterized by different names, colors, and transparency, in which all the model elements should be properly attributed. Examples of the system could be "structure," to which the hull is associated, and "machinery," to which the various machinery (e.g., pump, valves, etc.) are attributed. Each designed system should create and distinguish a work level from the others. Then, the user is called to define different categories for pipelines, cable trays, and duct lines based on their *specifications*: these represent their main characteristics regarding construction material, curvature radius, and shapes. Based on specifications, pipelines, cable trays, and duct lines may be created within the correct system.

After defining the ship's coordinates and systems, the pre-modeling phase can begin. Initially, the ship structure must be defined: the common practice is based on importing 3D structure blocks modeled through external tools within the Plant Modeller. Once the hull and the structures are completed, the equipment pieces defined in the component library (i.e., machinery, pumps, switchboards, etc.) can be inserted and properly located. At this point, the user can set up all the connections between the various components using the pipelines, cable trays, and duct lines previously created by characterizing the type of junctions (e.g., through flanges, sleeves, fillets, etc.).

Finally, once the coordinate plan of the selected space is finished and the characteristics for the drawing dimensioning and symbology are set, the user can export the 2D coordinate drawings by sectioning the 3D virtual prototype as desired. On the other hand, the 3D model is now available for inspections, analysis, and quality control through VR and AR technologies. In order to validate the proposed methodology, the authors selected the chiller space of a RoRo-Pax ship as a case study. The selected ship is 206.6-meter long, has a total cabin capacity equal to 947 beds subdivided in 870 beds for passengers and 77 beds for crew members. As regards the cargo, the selected ship has a trailer linear capacity of 2559 meter and a car capacity of 149 cars.

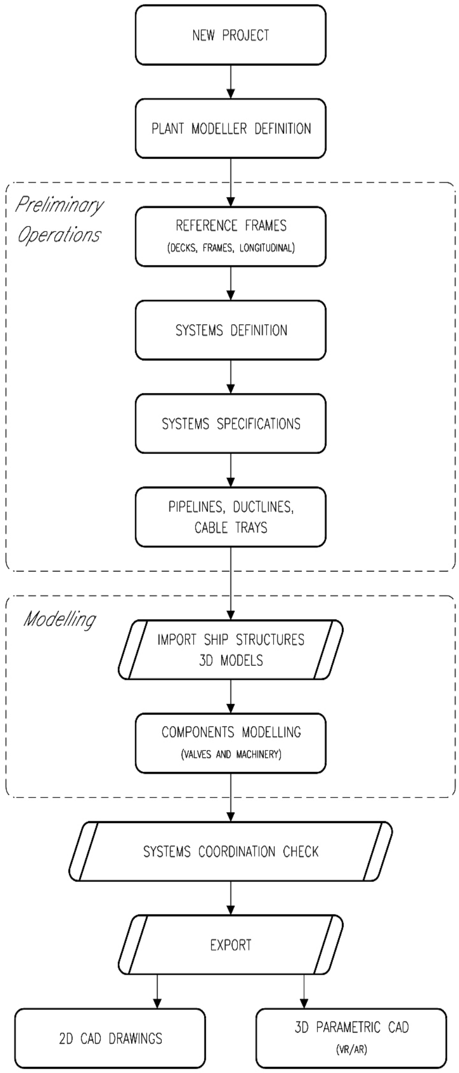


Fig. 1. Design methodology for ship systems based on VR and AR.

This space is equipped with the main machinery and auxiliary equipment necessary for the cooling of water, whose 3D model is shown in Figure 2 and which can be summarized as follows: (a) Chiller machinery and chilled water pumps; (b) Thermal heater, tanks, and pumps for "hot chilled" water to be sent to the HVAC system; (c) Salt-water pumps; (d) Electric heater, tanks, and pumps for potable water; (e) Hi-Fog tanks and pump unit; and (f) Electric switchboards.

After the completion of the 3D virtual prototype of the chiller space, VR was applied through wearable glasses. The model was inspected using specific manual controllers that also allowed interaction with the components present in the space, as shown in Figure 3. By exploiting the potential of AR, the 3D model of the systems was saved in the same wearable devices and could be visualized onboard the ship still under construction (Figure 4). In such a way, the systems were checked in the real environment through the elaborated model. This step allowed the corrections and modifications of possible design errors before installing the system itself. Through AR, users could interact with the model without controllers but simply using their hands. After the alignment of the model with the actual space, distances onboard could be measured by tracing the aimed quantity (Figure 5), and component details could be viewed by pointing at those. Furthermore, technical documentation was associated with equipment and visualized through AR glasses directly onboard.

Through the application of VR and AR technologies, the authors tested the possibility of developing an advanced interaction between humans and the virtual prototype in two different ways:

- By VR: using the wearable device, the digital model could be inspected. This allowed the evaluation of the spaces available for passage and maintenance and a visualization of the systems and components located in the room, also ensuring the possibility of ascertaining the correct realization of the coordinate plane by verifying the presence of possible interferences;
- By AR: with the wearable device, the digital model of the systems could be aligned with the real structure of the ship, thus allowing an analysis of the correct onboard implementation of the systems themselves and performing the quality control even before the physical outfitting of the space.

2.2. Cybersecurity as a Potential Threat to AR in Ship Design: Risks and Solutions

The evolution of shipbuilding supply networks toward digital environments increases operational complexity and requires reliable communication and coordination to regulate information exchange. As workers and suppliers transition to digital platforms, interconnection, information transparency, and decentralized decisions become prevalent [28, 29]. These digital platforms' appearance and extensive use inexorably increase their exposure to cyberattacks. Unfortunately, the effects of a systematic cyberattack on one or more nodes belonging to the shipbuilding supply network (e.g., Colonial Pipeline [24]) are unknown. This collectively may represent a substantial source of disruption [30]. Cybersecurity protection of these networks requires a systemic approach to evaluate their vulnerability and understand ripple effects [25, 30, 31]. However, current evaluation technologies and techniques are primarily applied to individual nodes or firms (if they are applied at all) and commonly lack systemic perspectives [43] that consider overlapping risks and tiered hierarchies [32], as presented in Figure 6.

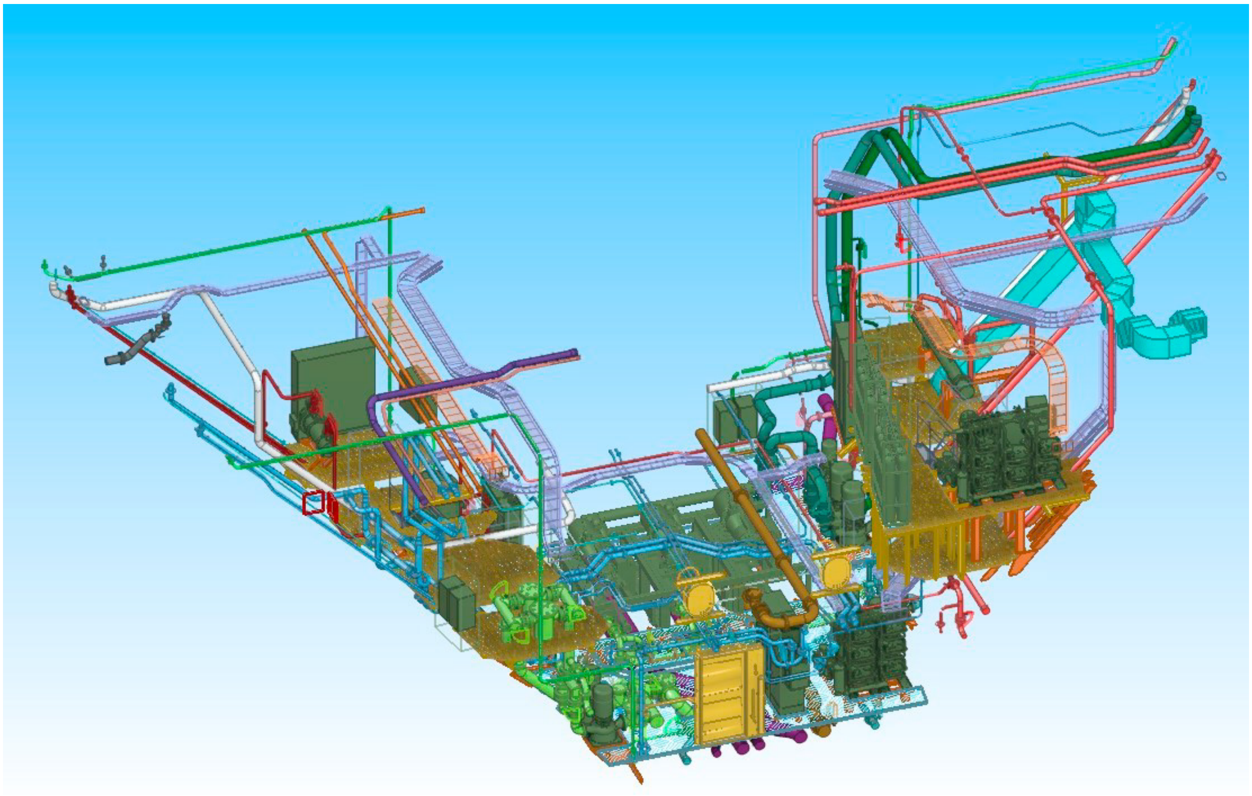


Fig. 2. 3D virtual prototype of the chiller space main machinery and equipment.

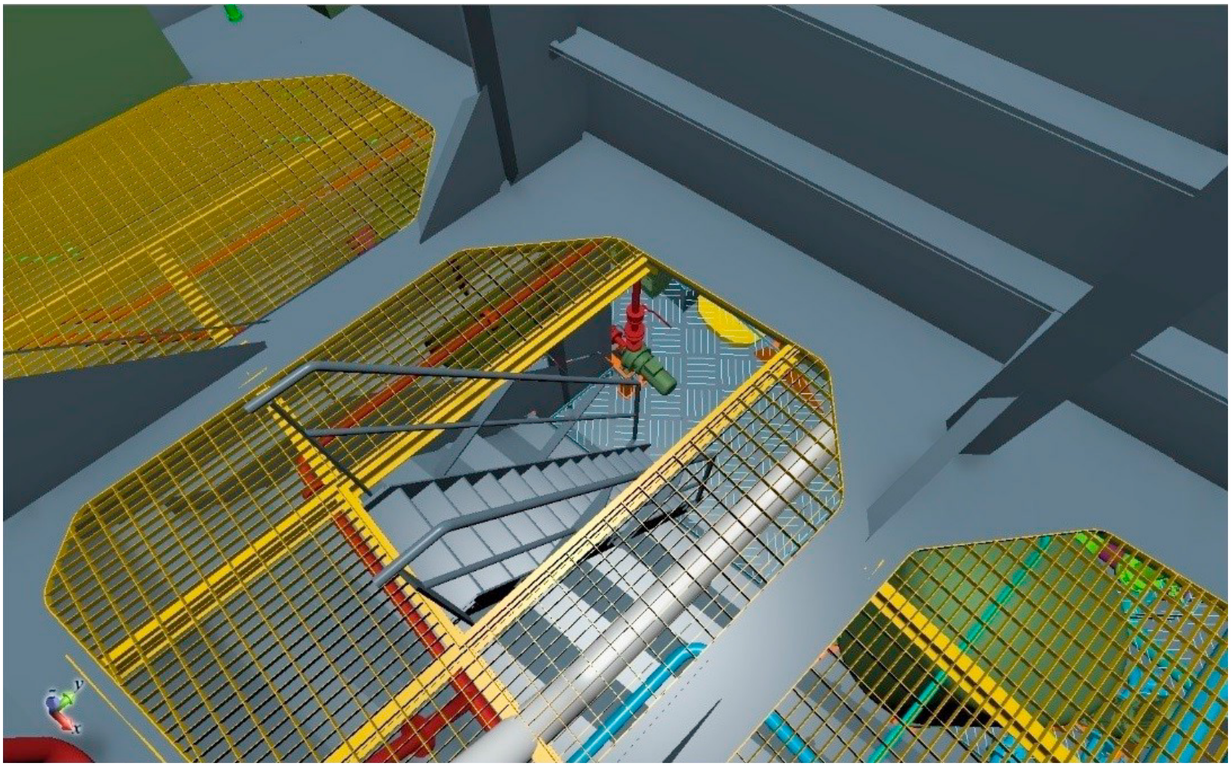
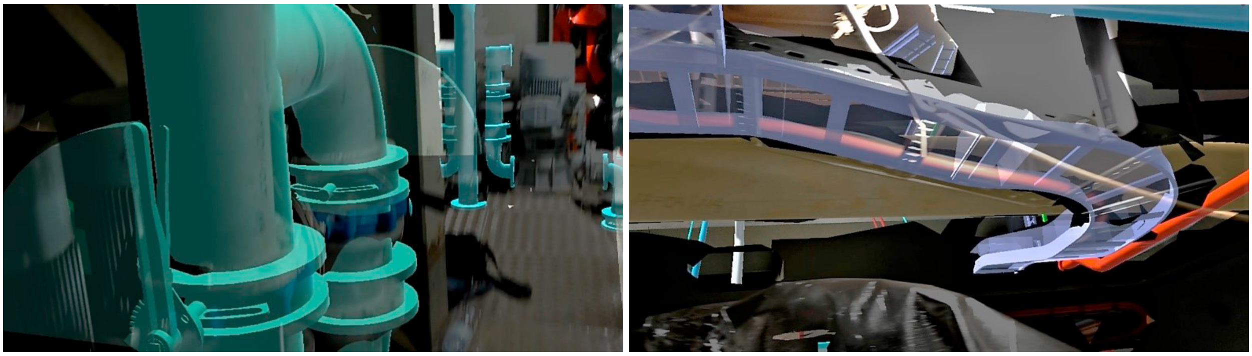


Fig. 3. 3D virtual prototype inspection through the VR wearable glasses.



(a) Pipe lines (b) Cable tray

Fig. 4. Superimposition of the 3D virtual prototype and the system installed onboard through the AR wearable device.

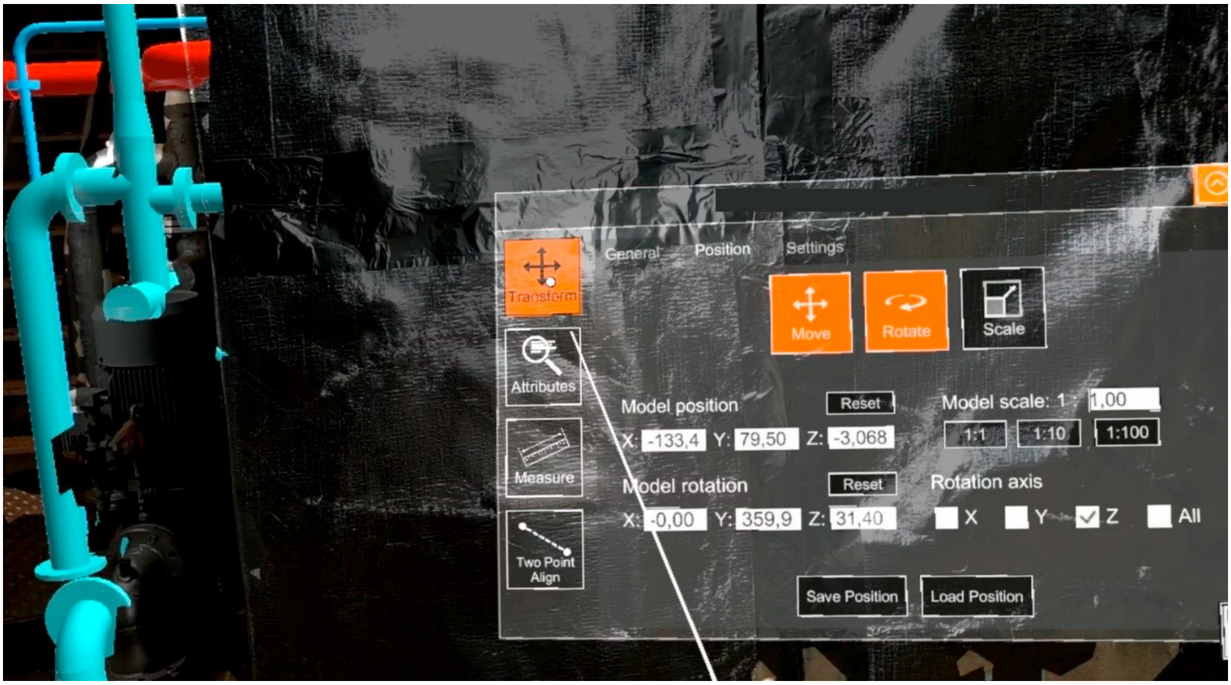


Fig. 5. Measurements and quality control of the system installed onboard through the AR wearable device.

Current tools fail to quantify ripple effects and subsequent delays in the defense of shipbuilding sector [31]. We argue that without that knowledge is not possible to develop a timely understanding of the impacts of cybersecurity disruptions on schedules, adjust a response (e.g., reconfigure operations), and prevent significant losses. As trends in cyber-attacks suggest using intelligent actors to learn from systems vulnerabilities [33], supply chains may conceal more dire plans to disrupt long-term operational effectiveness, including supplying goods during periods of critical need [17].

To overcome these limitations, we propose developing an Artificial Intelligence-based cybersecurity supply network framework that characterizes shipbuilding supply networks and determines ripple effects from disruptions caused by cyberattacks to the supply network. By representing and replicating the collective behavior of relevant shipbuilding supply network nodes, shipbuilders can monitor and measure the effects of cybersecurity disruptions and test the reconfiguration options that minimize the detrimental impact on the supply network. It also enables the study of individual and simultaneous failure of one or more nodes and propagation effects across the network as a whole. This framework extends a novel risk management framework developed by Diaz and Smith [30, 31] and Smith, Diaz [34] that considers complex tiered networks and systemic hyper-vulnerabilities and is currently under development in the port security cyber-physical setting.

The definition of the intrinsic vulnerabilities of the systems entails undermining their security [35]. We employ a systemic perspective based on extensions to the Functional Dependency Network Analysis (FDNA) that considers: cyber threats [36, 37]; systems vulnerabilities [38, 39]; the risks associated with the cyber-attacks; security risks related to the loss of confidentiality, integrity, or availability (C.I.A. triad) of information [40]; and the countermeasures to deal with cybersecurity issues [39]. The cybersecurity evaluation framework proposed in this work seeks to extend Diaz, Smith, et al (2021) by examining emergent behavior and vulnerabilities to assess the effects of cybersecurity breaches on suppliers. The new method, Adaptive Risk Network

Dependency Analysis (ARNDA), is an extension of the so-called Systems Operational Dependency Analysis (SODA) [41]. SODA improves FDNA [42, 43] by enabling partial dependency analyses, progressive absorption, tiered structures, and embedding risk profiles.

Both FDNA and SODA fail to consider hierarchies such as those observed in the shipbuilding multi-tier supply network and the simultaneous propagation effects that may lead to hyper-vulnerability. Hierarchical structures and hyper-vulnerable dependencies [44] are two critical components prevalent in supply networks [30, 31]. Figure 7 presents a hypothetical supply network for a watertight door on a naval vessel. Figures 7(a)-(c) show a high-level modeling process in which nodes (suppliers) are identified, connected, analyzed, and scored.

Our method allows for combining a probabilistic, graphical, real-time Bayesian Network with functional dependencies leading to lower computational costs and integrating parameters with intuitive meaning to tiered suppliers [41]. Figure 8 presents the application of ARNDA to a hypothetical functional dependency network that represents port operational nodes' operability in the context of a cyber-physical space. In the shipbuilding context examined in this paper, the extension of ARNDA will capture risk events, embed node risk profiles and interdependencies and determine ripple effects in the shipbuilding supply network space. Thus, stakeholders can prioritize investments [30] and analyze supplier reconfigurations that minimize the cyberattack disruptions via optimization.

3. Summary and Future Endeavors

The introduction of digitalization technologies in the industrial world is never straightforward. Still, for shipbuilding, this represents a more significant challenge due to the traditionally employed approaches for design and production. However, the necessity of reorganizing production processes and increasing product quality requires adopting innovative tools to support the development of a new industry concept. In this framework, the most disruptive technologies belonging to the Industry 4.0 notion are those based on the interaction between humans and virtual reality. The possibility of creating 3D virtual prototypes that can be both inspected as real environments and verified on the actual ship was at the base of the methodology proposed in the present paper, implemented by exploiting one of the most modern design tools. The 3D VP of the selected systems was verified through the use of VR and AR wearable devices, highlighting all the advantages of such methodology. These consist of early identification of design errors and necessary modifications, rapid and efficient quality control performance, and the importance of simultaneous data sharing between all the parties involved in the ship design and production.

Applying Industry 4.0 technologies mentioned above could also lead to a reduction in design and production times. This may also lead to a cost reduction, with increased attractivity for the company. Besides, customer satisfaction could also benefit from adopting such technologies. Indeed, he may be involved during the design phase by either presenting the project development status or proposing alternative construction solutions that could be verified through the Virtual Prototype to achieve a high level of customization of the final product. On the other hand, it is important to take into account the potential limitations of the VR and AR technologies. These limitations may include the reduced comfort of wereable AR glasses and devices, the battery runtime and the adequate lighting conditions in both the shipyard and on-board, as well as the personnel lack of experience in using and fully exploiting the technologies. Speaking about the risks related to data management and treatment coming from the application of VR and AR technologies in naval shipbuilding and repair domains, it is also crucial to consider that the benefit of using a real-time data-driven approach to constantly evaluate supply network disruption risk due to a cyberattack on suppliers and sub-tier suppliers. We have proposed the refinement of a framework that combines a stochastic, real-time Bayesian Network with functional dependencies. This approach extends the Systems Operational Dependency Analysis (SODA). The extension creates a multi-layered approach that enables modeling backward and forward risk propagations. The method allows aggregating granular behavior under a node that represents collective behavior. More importantly, the technique overcomes limitations in modeling absorbing states from binary [0-1] to broader ranges representing progressive transitions instead of abrupt state changes. The new approach, ARNDA, allows the embedding hierarchical structures and risk profiles. It identifies dynamic potential emergent systemic hyper-vulnerabilities prevalent in real-world operational systems by its ability to capture high levels of activity and exposure of nodes simultaneously.

Risk analysts and managers must identify their supplier portfolio's hidden risks. In general, managers are expected to gauge these risks as an individual or a sub-sample of suppliers might cause undesirable risk levels that may make operational integrity vulnerable. Likewise, these tools facilitate the anticipation of actions that makes the firm resilient, as vulnerability might develop if risks are not timely recognized and adequately mitigated. Future research endeavors include adapting ARNDA to the shipbuilding context and building a prototype that follows the conceptual model lines described in this paper. Also, granular firm-to-firm connectedness to model degrees of dependency among nodes.

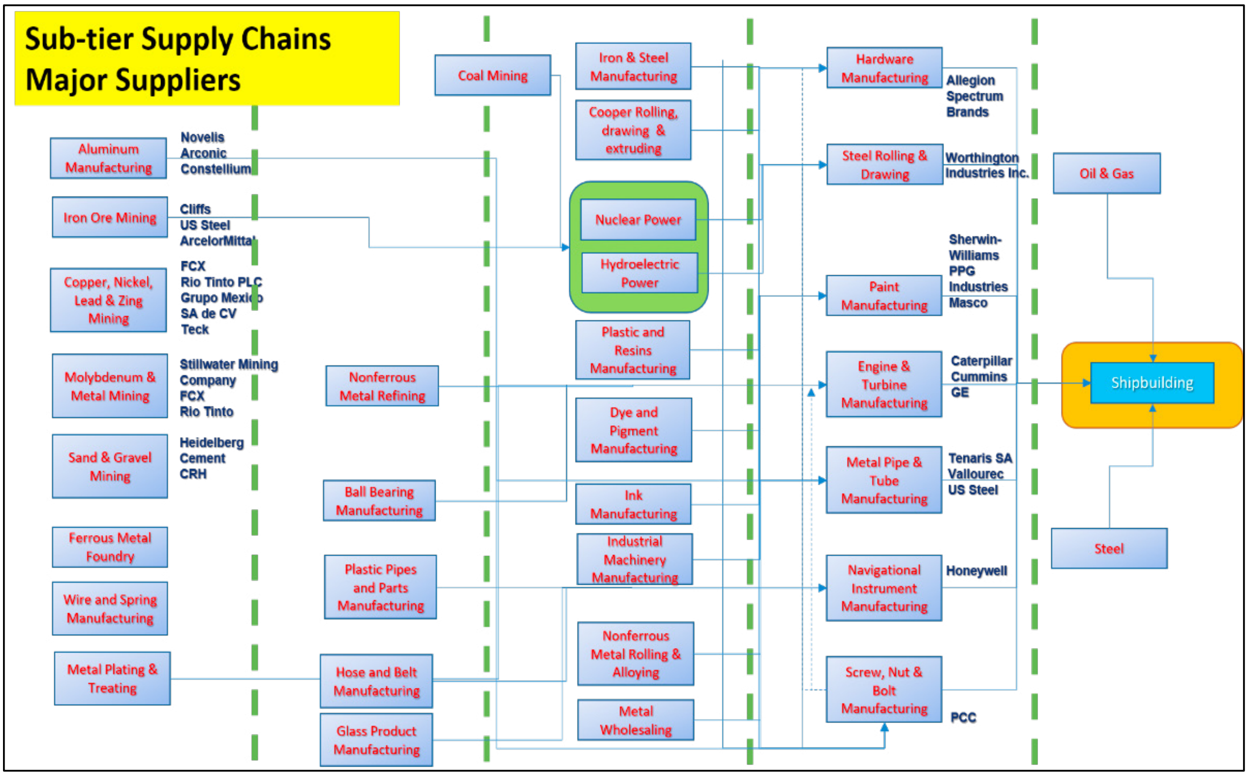


Fig. 6. Overlapping industry sectors that converge in shipbuilding supply chains.

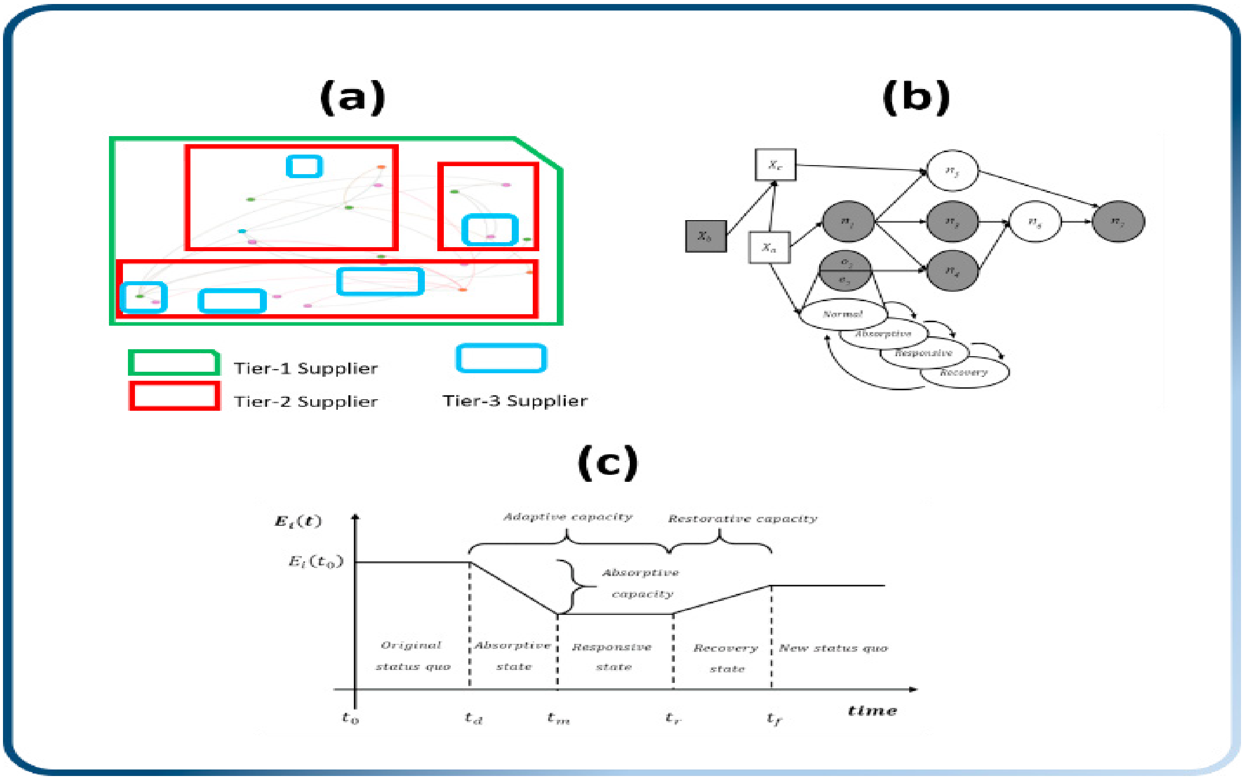


Fig. 7. High-level modeling process in which suppliers(nodes) are labeled, connected, and analyzed.

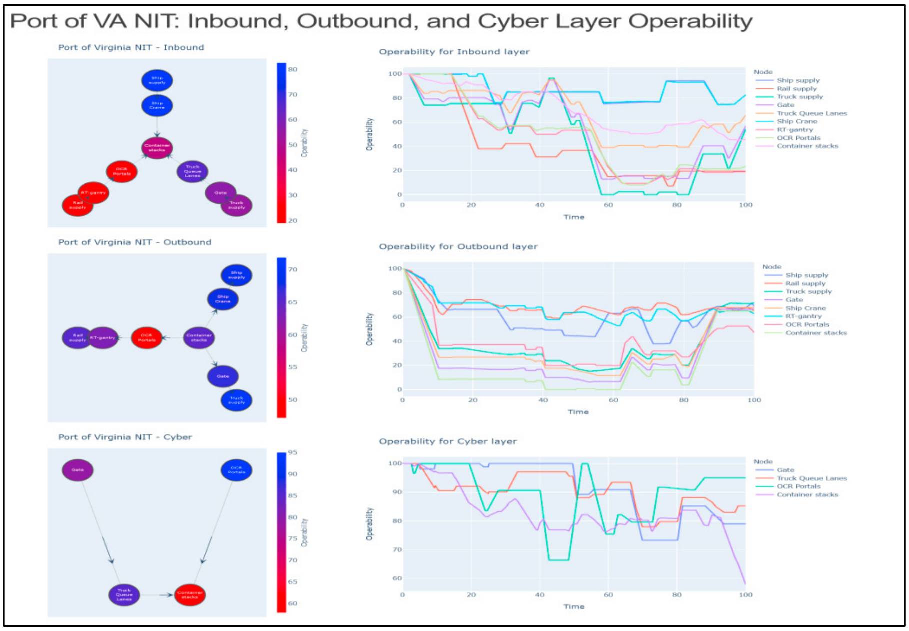


Fig. 8. Application of ARNDA to a hypothetical port cyber-physical space and different operability levels changing dynamically.

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