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Using Digital Twin in a Shipbuilding Project

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Abstract: Three-dimensional modelling software tools enable the creation of a digital replica of the product—"Digital Twin"—a representative of "Virtual Reality" as one of the prominent trends of Industry 4.0. The development of the Digital Twin can start simultaneously with the development of the product, primarily for the purpose of selecting optimal technical and technological solutions prior to and during physical construction, and, ultimately, with the intention of managing the entire product life cycle. The Digital Twin, as one of the key technological achievements in the implementation of the business system transformation from traditional to smart, should also be recognized as the cornerstone of the "Shipyard 4.0" model, i.e., its "Cyber-Physical Space." This paper is based on statistical and empirical data of the observed shipyard with the aim to represent the significance of the Digital Twin ship in preserving and improving the competitiveness of the shipbuilding industry. Namely, with the emphasis this article places on the contribution of "advanced outfitting" in achieving savings in the shipbuilding process as well as its role in attaining high standards of environmental protection and workplace safety, the importance of its further improvement is an obvious conclusion—with Digital Twin being one of the recognized tools for this purpose.

Keywords: Digital Twin; Virtual Reality; Shipyard 4.0; Cyber-Physical Space; advanced outfitting

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1. Introduction

The European shipbuilding industry nowadays already faces competition from the Far East in a shipbuilding niche of passenger and cruise vessels and special purpose ships. Furthermore, it also faces the problem of the extremely high share of the shipping industry in terms of the rates of environmental pollution through greenhouse gas emissions and noise as a threat to living beings in waters [1]. Therefore, the shipyard is expected to find solutions to build safe, energy-efficient and environmentally acceptable vessels with high operational and maintenance autonomy (Smart ships) constructed in a sustainable business environment [2]. The market niches that the European shipbuilding industry is oriented to mostly have a demand for individual vessels or smaller serials of vessels, which additionally emphasises the shipbuilding company's profitability risks concerning the high complexity of the shipbuilding process, the high ratio of working hours in the cost structure of the process and the high portion of working capital [3]. The subjected challenges to competitiveness point to the necessity for improving shipyard's production process [4], management process [5], as well as developing technical–technological solutions during a vessel's design phase, thereby defining the efficient shipbuilding technological process [6]. Adopting Industry 4.0 doctrines is part of the strategy that most countries with a tradition and influence in the shipbuilding and maritime industrial sector in general have taken on [2], knowing that the digital technologies, development, research and innovation, are recognised as the most efficient tools for maintaining and, as expected, improving the competitiveness of the shipbuilding business systems [3]. Some of the previous research has defined and recognised Artificial Intelligence (AI), the Cloud, Big Data analytics (BDA) and the Internet of Things (IoT) as leading technologies in transforming traditional shipyards into Smart businesses, i.e., Shipyard 4.0 [3], while, for example, a Shipyard 4.0 case study by the Navantia shipyard in Spain emphasises Digital Twin or "ship zero" as the axis of the shipyard's digital transformation [7].

Digital Twin was initially introduced through the concept of monitoring the life cycle of the product ("Product Lifecycle Management") and defined by joining three "entities", i.e., (i) the physical product, (ii) its virtual equivalent and (iii) its data link (which actually represents digital technology, i.e., IT components) [8,9], which can be, according to its original definition, considered as "Digital Twin technology", the core technology in realising Cyber-Physical Space [10]. Digital Twin, as a common notion, represents the virtual replica of the product, process, manufacturing system [11–13], object and other physical entities; such a replica is, with various sensors and software applications, connected to the physical entity, and with the data collected, it monitors the physical entity's performance parameters in real time throughout the entire lifecycle [10,14,15]. Figure 1 shows the Digital Twin conceptual model.

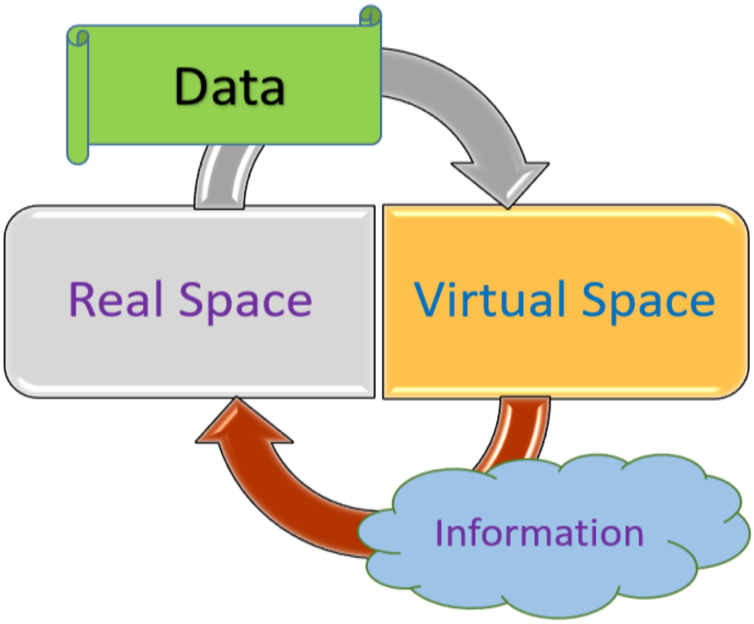

Figure 1. Digital twin—conceptual model.

A Digital Twin is either created as the replica of the already realised physical entity [16] or is developed along with the entity's design process by using 3D modelling technology [17]. In this study, the authors approached 3D modelling of the entity as the development of its Digital Twin, the same as has occurred in other researches on the topic of Digital Twin implementation in the shipbuilding processes [1,15].

Modern software applications enable 3D modelling from the early beginnings of an entity's development, i.e., the initial design phase, as well as interconnectivity with various software modules such as Assembly Planning or Material Planning, all as a prerequisite for prototyping the vessel in Digital Twin form and content; such a 3D model, i.e., Virtual Reality (VR), with the future upgrade to Augmented Reality (AR), enables all stakeholders involved (horizontal integration [3,7]) to define the best possible technical–technological solutions aiming to optimise the construction, exploitation and decommissioning of the entity [9,18]. A further precondition for creating a Digital Twin is the existence of an appropriate IT communication infrastructure (digital thread) that enables uninterrupted data flow, i.e., managing the same when integrating the virtual and real surroundings [19,20].

Due to the lack of quantitative research related to the improvements in shipbuilding processes by implementing digital technologies, and with accepting the thesis of Digital Twin's primary importance of its role in Shipyard 4.0 [7], including to the marketing and sales activities [18], the main interest of this research is aimed towards the analysis of the impact of Digital Twin's implementation to productivity in the process and contribution to the green transformation of the shipbuilding system.

Furthermore, there are very few analyses and researches considering the advanced outfitting in shipbuilding [21]: very few discuss the approach of shipyards in different market niches towards outfitting activities' distribution through the shipbuilding process [22–24], whereby only a few investigate the potential advantages of implementing advanced outfitting in the earlier stages of ship construction, though they have analysed only a particular type of new builds [25]. Following the subject gap that is shown after reviewing the literature, the main purpose of this study is to further research the eventual accomplishments in terms of the shipbuilding processes' cost deductions by improving the advanced outfitting in the shipbuilding system within the market niche of cruises, i.e., passenger vessels.

Shipyards in general are looking to improve their competitiveness primarily by reducing supply and labour costs as well as construction time; in that respect, the advanced outfitting could offer a significant reduction in the number of man-hours engaged for the outfitting activities, as well as a decrease in the various types of costs, such as insurance, financing, energy, consumables and sickness leave. That being said, the authors' intention is to respond, through this research, to the following questions:

- Q1: Does the outfitting of new builds in earlier stages of construction improve the competitiveness of the shipbuilding system acting in the niche of passenger ships, i.e., cruise vessels?
- Q2: Does the 3D modelling of the vessel in the Digital Twin form and content enable a larger scope of outfitting activities to be performed in earlier stages of construction?

The methodology of the research is based on a case study, i.e., the collection of statistical and empirical data gathered by one European shipyard, investigating distinctions in the realization of two new build projects considering the building duration between main events, the total number of man-hours spent on welding and outfitting activities, the electric energy consumption, as well as the injury frequency and severity rates; the basic difference in the realisation of subject vessels is that one is designed and built by using a 3D model but in the Digital Twin form and content.

This paper presents the improvements achieved through implementing Digital Twin in the shipbuilding process of the observed shipyard due to the accomplishment of outfitting activities at a higher magnitude within the early stages of ship building. The article contributes scientifically through the aim of initiating the additional awareness of scholars and industry professionals considering the benefits of advanced outfitting applied at the highest applicable level at earlier stages of the shipbuilding project realization process, and thereby of the importance of its constant improvement. As a novelty, this study introduces Digital Twin (in the concept as accepted by authors) as the tool of the advanced outfitting improvement.

The stages of the Digital Twin ship observed for the purpose of this research were limited to those developed simultaneously with the design and construction processes of the physical entity, as described by Gierin et al. [1], until the delivery of the vessel. Therefore, in order to avoid any doubt, the 3D ship model was not utilised as the Digital Twin, as it is commonly known, and in any case, it could not have been due to the fact that the vessel was not outfitted with sensors, actuators and related software tools that would enable data exchange between the physical entity and its virtual replica during the sea trials, operation and maintenance of the vessels. Nevertheless, data flow between the physical entity and its digital prototype during the construction process was bi-directional and not one-way in terms of the type of communication, i.e., the level of integration that refers to Digital Shadow and not Digital Twin [16,26]. Namely, the status of the entity's outfitting spaces were reported by the production and technology departments on a daily basis, also for the purpose of ensuring eventual changes in the 3D model's design were achieved in a timely manner, thereby avoiding potential repair activities that could occur due to, e.g., changes in the outfit caused either because of obstacles in supply or because of the client's modifications.

In the first part of this paper (second chapter), the realisation process of the shipbuilding projects in the observed shipyard is presented, with an explanation of the applicable shipbuilding and outfitting technologies. Furthermore, in the third chapter, the concept of advanced outfitting is explained, along with the impact on the shipyard's production process. The fourth chapter describes the development of the Digital Twin and its contribution to increasing the scope of the advanced outfitting in relation to the scope of the outfitting after launching. Improvements achieved in the shipbuilding process by implementing the Digital Twin are presented and discussed through the fifth chapter. The sixth chapter, i.e., the conclusion, is dedicated to the findings and suggestions for further development, i.e., the research of Digital Twin's implementation through the shipbuilding project's realisation process.

2. The Process of Realizing Shipbuilding Projects

The observed shipyard, according to the production surface area, is among the largest shipyards in Europe, and in terms of business organisation and the number of employees, is considered a large company. Among others, it offers design services, including 3D modelling by "up-to-date" program tools. During the second half of the 20th century, this shipyard had a leading position in Europe and the world for producing cargo vessels. However, due to Far East competition, in the last 15 years or so, it has pivoted into designing and constructing passenger and cruise vessels. The shipbuilding project realisation process is conducted mainly by the simultaneous implementation of the activities of design, hull construction and ship outfitting.

2.1. Design

After signing a Letter of Intent with the client, the ship's development begins with the initial design activities, the scope of which partially overlaps with the content of the design documentation required by the relevant ship classification society. After signing the shipbuilding contract, the basic design is prepared (the majority of it is required by the ship classification society) as well as the detailed (workshop) design documentation. The ship development process, i.e., the initial (precontractual) design documentation preparation of the medium complexity passenger vessel takes nearly four months, while the basic design documentation is completed within twelve months from the shipbuilding contract signing date. Activities related to the detailed design documents last until the delivery testing and inspections. The general schedule for composing the design documents is shown in Figure 2, whereby the coloured bars represent design stage activities duration.

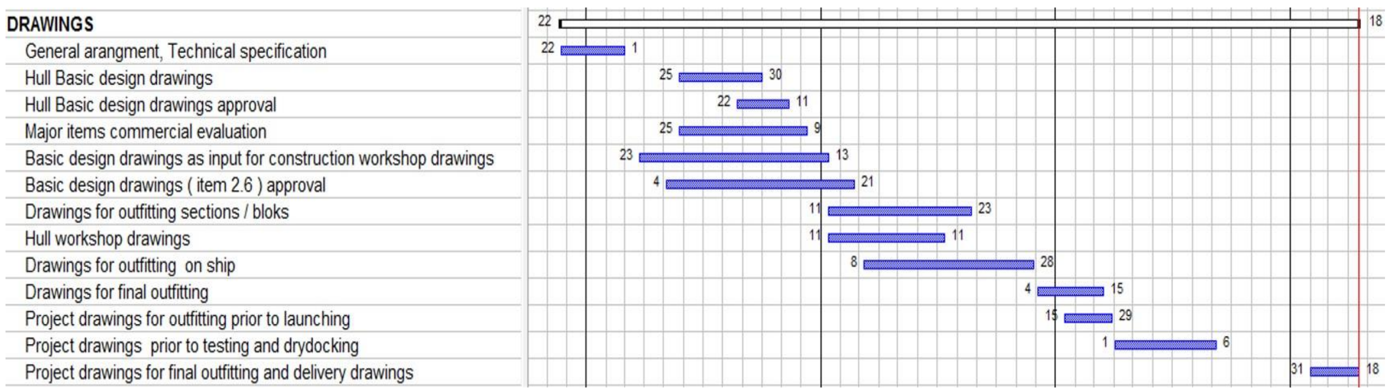

Figure 2. Design process: deliverables dependencies.

2.2. Hull Construction

The ship's hull, in technological terms, is divided into basic groups (stern, engine room, cargo area, bow and superstructure), all of which are further subdivided into smaller assembly units—blocks. The dimensions, volume and weight (in the pre-outfitted stage) of blocks are predetermined by horizontal and vertical shipyard transport capacities, the size of pre-assembly and painting hulls, dimensions and bearing capacity of the building berth for the blocks assembly into the hull before launching, and the possibility of advanced outfitting of the block spaces. Therefore, due to the last reason mentioned, it is necessary to make the 3D ship model in the early design phase by suggesting the positions for the preliminary-defined key outfits and the main ship systems. Everything must align with the process of defining (hull) construction technology to redirect the same towards block modelling in the size that enables the highest level of advanced ship outfitting. Blocks are assembled of (usually four) sections. Sections are smaller assembly units, the size of which depends on the pre-assembly line parameters, and the level of the pre-outfitting of which depends on the throughput of these lines. Figure 3 shows the technological division of the hull into blocks with the schedule of their assembly on the building berth (number on the right side of the block label).

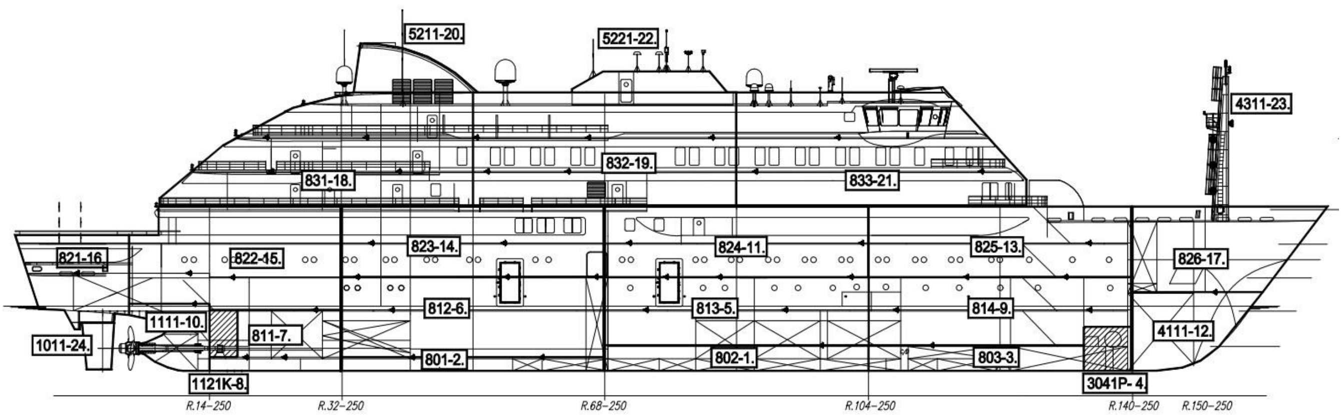

Figure 3. Technological division of the hull.

2.3. Outfitting

Ship outfitting activities with the outfit, outfit assemblies, propulsion machines, ship system elements, interiors, etc., are conducted in different stages of the shipbuilding process, depending, among others, on the level of completion of the (acquired) outfit assemblies, subsystems, propulsion set and the like, the permeability of the pre-assembly lines (panel fabrication, erection of 2D and 3D sections), as well as the defined block dimensions and possible weight in the outfitted stage before its lifting (positioning) onto the building berth (slipway).

Ship outfitting before launching takes place according to the following technological schedule: (i) building of outfit assemblies, (ii) sections outfitting, i.e., on-block outfitting with the outfit adjusted for installation before painting, (iii) painting of blocks and outfit that is applicable for painting, (iv) further on-block outfitting after painting and before lifting and joining blocks together on the building berth, (v) installing outfit of large dimensions and masses in the spaces (outfitting zones) of the ship on the slipway and before closing the same, and (vi) assembly of the outfit after closing the ship spaces. After launching, further technological outfitting phases continue: (i) outfit installation in corresponding outfitting areas (zones), (ii) painting of the ship and equipment designated for painting, and, eventually, (iii) the final outfitting. Figure 4 shows the new build outfitting process.

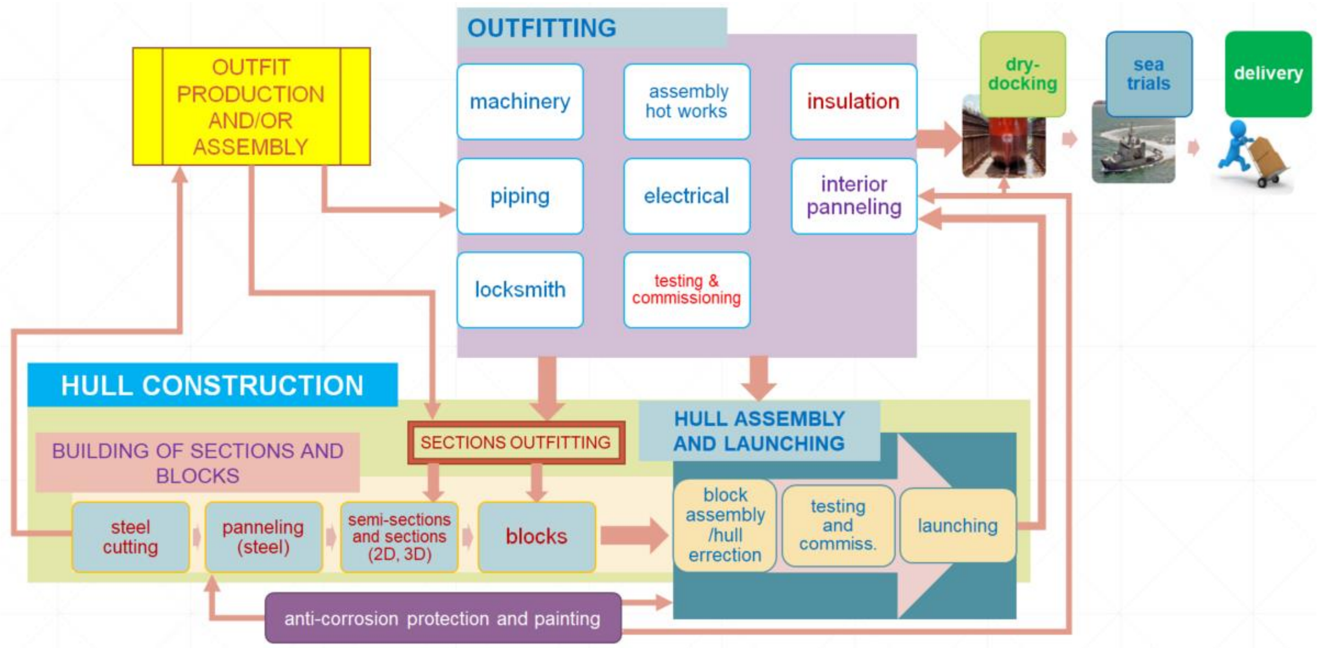

Figure 4. New build outfitting process.

3. Advanced Outfitting

According to the practical information of some international shipyards and professional literature sources, the work–cost ratio for the identical outfitting activity, depending on the shipbuilding construction stage where outfitting is implemented, varies from 1:3:5:7 [23] (the cost of the specific outfitting activity performance for the on-block outfitting is three times higher than the cost of the same outfitting activity performed in the workshop or at the pre-assembly line, five times higher in outfitting on the berth, i.e., slipway (on-board outfitting), and seven times higher in outfitting on board after launching) up to 1:3:7:11 [25].

Due to the increase in closed outfitting spaces, the access to the assembly position is harder, more overhead work is required, more additional and repair work occurs, and overlapping of the special outfitting professions and their systems' routes (piping—cable trays—ventilation channels—exhausts, and the like) increases causing additional correction activities and new repairs; consequently, an increased number of working hours results in an increase in energy consumption for the work equipment and machinery.

Furthermore, the more closed spaces there are, and the simultaneous performance of different outfitting activities there are within the same, result in a much higher necessity for temporary illumination and ventilation, which are significant electric energy consumers. Therefore, shipyards continuously strive to decrease the number of outfitting activities after launching, in favour of increasing the number of outfitting activities at the earliest possible stage of the shipbuilding process [25]. Even though outfitting in the early phases of the ship's construction requires a higher level of planning, and workshop and technological documentation preparation, resulting in a longer design period and therefore a later start of steel cutting, it is expected for a shorter ship construction period to be achieved, thereby keeping the same or even shortening the ship's delivery term, all accomplished with a lower number of outfitting working hours [23–25].

However, some international shipyards recognise the benefits of advanced outfitting, mostly when building cargo vessels, with a ratio of realised savings of 1:3:8 (three times more cost for the same on-block outfitting activity than for the workshop or pre-assembly workshop outfitting, and eight times more for on-board outfitting); in the construction of cruise vessels, due to the large interior surfaces (passenger cabins, public spaces, ship crew area), and due to the strong involvement of the subcontractors (usually a „turnkey" contract deal), some shipyards prefer to keep the brunt of the outfitting on board, mostly because of a less complicated transfer of responsibility between the shipyard and subcontractors following the work completion phase progress [24]. The last especially refers to assembly-type shipyards. Furthermore, some naval shipyard producers redirect even more of the focus of the outfitting activities into the construction phase while the ship is on the berth, or even to a larger extent to the phase after launching. The reason for that, according to their assertions, is the complexity of the naval vessel systems (much higher quantity of pipes, ten times longer electric cables and complex arming systems) and the necessity for a longer stay on the outfitting quay due to the complex inspections and testing of the outfit and ship systems in the sea [24].

Advanced outfitting generally refers to installing the elements of a certain vessel's system into the outfit assembly or the complete outfit block assembly (including flooring, ladders, railings and more—mostly applicable to engine room components), which is, later on during the shipbuilding process, installed into a 2D section, a larger erected section or into a ship (on the berth or after launching); the sanitary (wet) module and passenger cabin module or the crew cabin module are also considered as part of the outfit block assembly. Furthermore, advanced outfitting refers to installing the outfit assemblies and outfit block assemblies, machines, piping, electrical components and other ship equipment into 2D sections and larger erected sections, all before being lifted onto the slipway. The last refers to installing the outfit assemblies and outfit block assemblies, machines, piping, electrical components and other ship outfits into the ship while on the slipway or after launching [24]. Advanced outfitting in relation to the shipbuilding stages is presented in Figure 5.

Figure 5. Advanced outfitting in relation to the shipbuilding stages.

Along with the previously mentioned advantages of advanced outfitting, further advantages are the reduced need for temporary ventilation and illumination, scaffolding and vertical transport. Advanced outfitting also engages more low-skilled workers, enabling the better redistribution of high-profile skilled workers within the production process. Advanced outfitting reduces the danger of work injuries, upgrades the working culture and raises adherence to working instructions and procedures, resulting in a higher-quality product.

4. Using Digital Twin in the Shipbuilding Process

The observed shipyard has recognised the benefits of advanced outfitting even in building passenger and cruise ships, and since entering this shipbuilding niche, has continuously worked on upgrading the ship outfitting level before launching, with a tendency to maximise the outfitting degree in the phase prior to the blocks assembly into the hull (on-block outfitting phase). The subject phase is recognised as an optimal one to prevent congestion on pre-assembly production lines (panels, sections) through intensive outfitting activities, as well as by preventing obstruction of the dynamic of blocks assembly on the slipway (thereby minimizing on-board outfitting activities on the berth only to outfit missing areas in block junctions).

4.1. Digital Twin Development Phases

The modern software programs for 3D modelling enable the defining of ship outfitting technology that could, with (i) highly developed planning documentation, (ii) an accurate overview of technological assembly requirements to outfit (position, function, dimensions) and (iii) timely procurement of the same, theoretically result in the almost complete outfitting of the ship in the construction phase before blocks assembly, i.e., joining at the slipway (advanced outfitting).

Following the initial requirements of the client in terms of the development of the vessel, in the initial design phase, the observed shipyard models the ship [15], using program tools such as Rhino, version 5, and NAPA 2022.1, which, by their software content, enable, among other things [27], the parallel implementation of hull shape optimisation by CFD analysis and ship stability calculation, in iterations until the criteria for the ship's input parameters are met; hull optimisation is approached after the ship's speed prediction data confirm the adequacy of the modelled form. Further on, in the initial design stage, a preliminary designed key outfit (engines, generators, air conditioning units and all other big outfitting items in terms of volume and weight) is positioned into the ship model, which creates the "Digital Twin ship of early stage" [1].

After signing the shipbuilding contract, 3D ship modelling continues [15] by implementing CAD software application such as AVEVA Marine, version 12.1, which enables designers (modellers) and technologists to choose the best technical–technological solutions in the virtual surrounding of the ship space [6] aiming to define the highest possible outfitting level in the blocks erection phase, i.e., before lifting them on the slipway ("On-time Outfitting"). Virtual ship modelling in this design phase creates a "Digital Twin ship prototype" [1]—a 3D ship model supported by the material components, technological data sheets and other documents required to extract workshop documentation (from the 3D model), meaning the start of production (steel cutting). The interaction of the shipyard's, client's, classification society's and the key suppliers' teams through work on the ship's digital prototype enables the advanced optimisation of design solutions to meet customer requirements with reduced costs in the ship's construction and operation, and thus greater cost-effectiveness of the project [18]. A segment of the 3D ship model developed by the AVEVA program tool is shown in Figure 6.

From blocks erection until the ship's delivery, the virtual model becomes an "Experimental Digital Twin ship" [1]. With constant interaction between the designers, technologists and outfitting workshops [15], the preparatory (initial) designed state and the performed one are compared and analysed, i.e., outfitting situations between the virtual and physical spaces are harmonised; this prevents errors in outfitting and allows for timely changes in the design (i.e., if the client requests the same or different outfit is chosen), while avoiding or minimising the need to engage (additional) production hours in outfitting. The mentioned interaction can be upgraded to a far higher level with the help of Augmented Reality (AR) tools [14,18] and result in even better, i.e., more timely, harmonisation of the virtual and physical environments, and thus reducing the "Design department–Production" communication hours about the subject. Furthermore, involving the owner's representative in Augmented Reality using appropriate devices (tablets, Smart glasses) [18] can, for instance, speed up the adjustments, i.e., decision making about the implementation of possible requests for modifications.

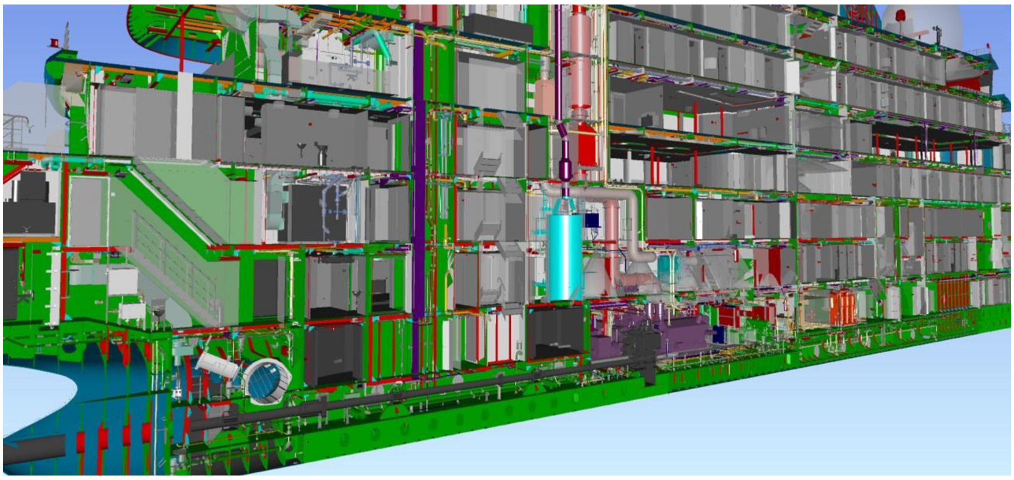

Figure 6. Digital Twin ship prototype.

Ultimately, depending on the software tools available to the client, as well as outfitting the ship with appropriate sensors and actuators [1,10], the Experimental Digital Twin ship, after the ship's delivery to the owner, can become a Digital Twin ship in the full sense [9]. Figure 7 shows the Digital Twin development phases.

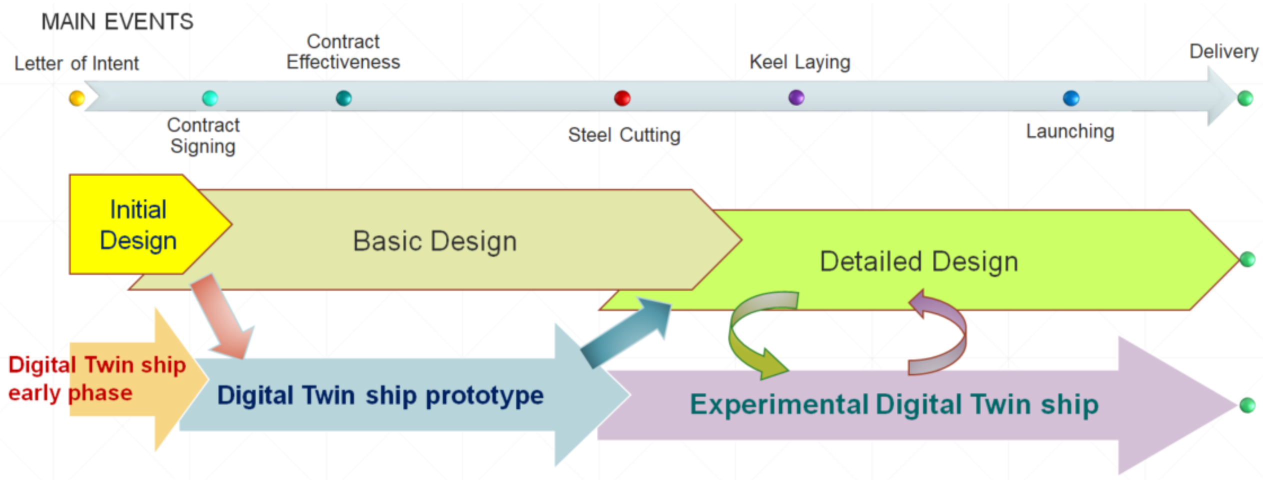

Figure 7. Digital Twin development phases.

4.2. Digital Twin Application

To analyse the results of the Digital Twin implementation in the shipbuilding process, this research, through the data collection method, compares the data of two new build projects [28], selected from the production program of the observed shipyard—a passenger and a cruise ship. The basic ships' parameters are shown in Table 1.

The new builds are intended to transport passengers with cabin accommodation and are very similar in terms of outfitting complexity. They were realised under the same production and spatial conditions and with the same infrastructural possibilities (horizontal and vertical transport). Therefore, they have the approximately same dimensions and maximum possible weights of assembled sections, i.e., blocks. Furthermore, it is assumed that there were no differences in workers' skills in the realisation of the subject projects, with an emphasis on the level of expertise when implementing assembly activities. The basic difference in the realisation of the two projects mentioned above is that for the design and construction of the cruise ship, a 3D model was used, but using the Digital Twin form and content, respectively. Figure 8 shows the duration of the passenger vessel, i.e., cruise vessel shipbuilding phases in relation to the main events, while Table 2 shows the duration of the outfitting stages with an expressed ratio.

Table 1. Principal dimensions.

Items	Passenger Vessel	Cruise Vessel
Length overall, Loa (m)	168	128
Breadth, B (m)	30	21.5
Draught, T (m)	6.7	5
Gross Tonnage, GT	41,700	13,760
Compensated Gross Tonnage, CGT	38,135	29,050
Deadweight, dwt (t)	11,300	1644

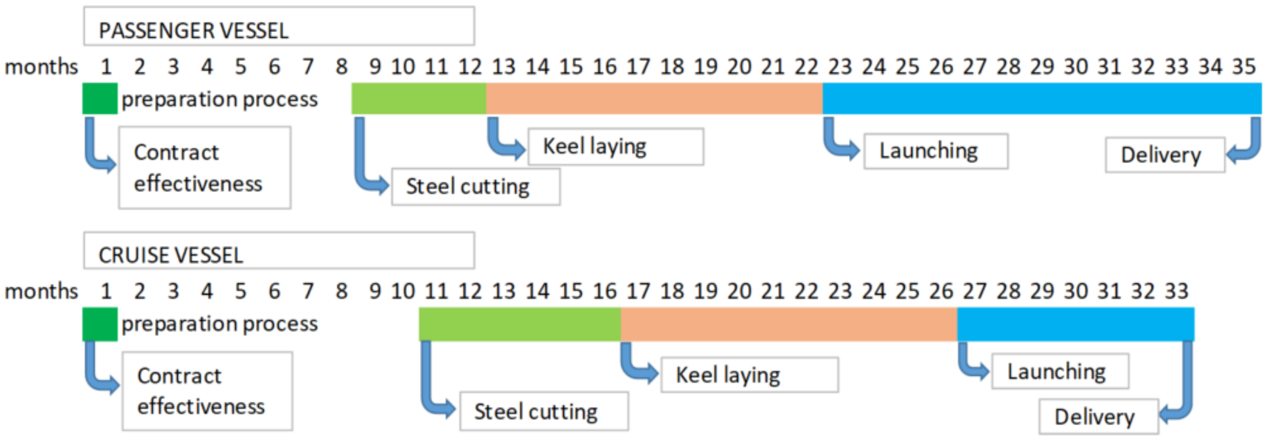

Figure 8. Shipbuilding duration in relation to the main events.

Table 2. Outfitting stages—duration and ratio.

	Passenger Vessel		Cruise Vessel		
	Duration, Working Hours	Duration Ratio (PVDR [1]), %	Duration, Working Hours	Duration Ratio (CVDR [2]), %	Duration on PVDR Ratio, Working Hours
On-block outfitting	2352	0.52	2688	0.7	2003.56
On-board outfitting (after launching)	2184	0.48	1176	0.3	1860.44

[1] Passenger vessel duration ratio. [2] Cruise vessel duration ratio.

Table 3 shows the number of working hours spent for outfitting professions, the total number of working hours spent on welding, as well as the number of production working hours spent in total during the shipbuilding production process.

During the realisation of both observed projects, work equipment and machinery of the same models and characteristics were used (specifically—welding machines) as well as the same type of temporary energy equipment (ventilation and lighting in the ship's spaces). The Metal Inert Gas (MIG) procedure was used for the large majority of welding activities in the projects; therefore, to simplify the analysis of results, we assume that all spent welding hours (Table 3) relate to this procedure. Likewise, and based on empirical and statistical data of the shipyard observed, and for this research, it is adopted that the effective daily work of welding electric arc, i.e., the welding machine, is 2 h. The average electric power of the standard welding machine operating by the MIG procedure is 15 kW.

Table 3. Working hours—welding (total) and outfitting.

	Passenger Vessel [1]			Cruise Vessel [1]			Difference (%)	
	Man-Hours	**Man-Hours/CGT**	**Repairs Ratio (%)**	**Man-Hours**	**Man-Hours/CGT**	**Repairs Ratio (%)**	**Man-Hours/CGT**	**Repairs Ratio**
Welding in total	536,918	14.08	na	353,586	12.17	Na	−13.55	na
Assembly—machinery	147,935	3.88	10.8	78,159	2.69	2.2	−30.64	−79.63
Assembly—piping	238,498	6.25	27.1	213,714	7.36	8.3	17.63	−69.37
Assembly—locksmith	159,498	4.18	22.6	109,850	3.78	1.7	−9.59	−92.48
Assembly—electro	268,979	7.05	11	153,131	5.27	5.7	−25.27	−48.18
Assembly in total	814,910	21.37	na	554,854	19.1	Na	−10.62	na
Shipbuilding process in total	2,027,647	53.17	na	1,230,683	42.36	Na	−20.32	na

[1] Data collected pursuant to [28].

Furthermore, according to the data collected by the observed shipyard, under the assumption that four outfitting workers work (welding activities included) in the space of nearly 120 m^3, it is necessary to have one exhaust fan operating to ventilate that ship's space while the outfitting works are performed in the assembled block before lifting it onto the slipway. In contrast, while the outfit assembly works are carried out on board after launching, one exhaust and one supply fan are needed to ventilate the same outfitting space. The average electric power of the supply fan models used is 11 kW and 7.5 kW for exhaust fans. The required air exchange per worker in a flow of 3400 m^3/h is prescribed. Furthermore, each worker needs one mobile lighting fixture to illuminate the observed unit volume of the block space during the on-block outfitting before lifting it onto the slipway, while an average of four light bulbs of general lighting are used when outfitting the ship after launching to illuminate that same area. Mobile lighting fixtures have an average power of 60 W, while light bulbs of general lighting have an average power of 150 W. The use of incandescent light sources is implied.

Finally, during the implementation of both projects, there was no significant difference in the current legislation regarding occupational safety measures, the same internal procedures and work instructions were applied, and the same personal protective equipment was used; Table 4 shows the number of injuries at work during the period of hull construction and ship outfitting.

Table 4. Injuries at work.

Items	Passenger Vessel	Cruise Vessel	Equation
Man-hours in the build process, total, *MH* (h)	2,027,647	1,230,683	
Number of injuries at work, total, *NI*	64	23	
Lost injury time, *LTI* (h)	31,960	4208	
Injury frequency rate, FR	33.06	18.69	FR = $(NI \times 106)/MH$
Injury severity rate, SR	16.51	3.42	SR = $(LTI \times 1000)/MH$

5. Results and Discussion

As the result of the outfitting activities being performed in earlier stages of the cruise vessel's construction, particularly during the blocks erection (on-block outfitting phase), the analysis of the collected data (Table 3) shows a significant reduction in the number of working hours for outfitting, up to 30%, depending on the profession. There are about 10% savings in the total number of ship outfitting working hours on average. It can be noticed that the research results show no improvement in reducing the number of working hours for piping assembly; on the contrary, an increase of almost 18% occurred. The reason is that pipe assembly works were a focus of advanced outfitting from the very beginning of the development and the application of the subject technological approach in question to the shipbuilding process, regardless of the production program of the shipyard [24]. Hence, the scope of advanced outfitting with the piping components has increased throughout history and is perfected in performance. However, the application of a virtual ship model, today in Digital Twin form, achieves a significant reduction in the consumption of working hours to eliminate errors in assembly, both in pipe assembly activities and all other outfitting professions, with an emphasis on locksmith work—or a 90% improvement—all as a result of redirecting the activities of advanced outfitting towards the blocks erection phase. Empirical and statistical data of the observed shipyard indicate that, today, it completes approximately 70% of the total ship outfitting in the phase of construction before lifting blocks onto the slipway, with a tendency for further growth, compared to the indicators before applying the 3D ship model in the form of a digital prototype—approximately 31% in the construction of a cargo vessel [23], or an average of 40% (Europe) up to 50% (Japan) in the construction of a cruise vessel [24].

Separating welding devices for the MIG procedure, along with the ventilation and lighting equipment required for outfitting space working conditions, as the significant consumers of electrical energy (statistic indicators of the shipyard), the consumption of electrical energy during the outfitting process and shipbuilding process (EEC_{DT}) can be defined by the following equation and based on the selected indicators:

$$EEC_{DT} = WH \times K_{arc} \times P_{WA} + ((P_{LBL} + P_{FBL}) \times V \times D_{BL}) \times K_{NBBL} + (P_{LBO} + P_{FBO}) \times V \times D_{BO} \times K_{IBO} \times K_{CBO} \quad (1)$$

where V stands for the ship space total volume, WH the total welding hours, K_{arc} the coefficient of effective welding work of the electric arc, P_{WA} the welding machine electric power, P_{LBL} the electric power of illumination required to illuminate 1 m^3 of outfitting space within the block erection stage, P_{FBL} the power of ventilation devices required for the defined air exchange within 1 m^3 in the outfitting space in the block erection phase, D_{BL} the duration of the on-block outfitting process, K_{NBBL} the coefficient of parallel block outfitting in their erection phase, P_{LBO} the illumination electric power required to illuminate 1 m^3 of outfitting ship space after launching, P_{FBO} the electric power of ventilation devices required for the defined air exchange in 1 m^3 of ship space after launching, and D_{BO} the duration of on-board outfitting after launching. Two coefficients are defined related to engaging devices providing temporary energy during the performance of outfitting activities on board after launching: K_{IBO}, the empirically assessed coefficient of outfitting intensity according to the scope of activities of related technological outfitting phases and K_{CBO}, an empirically assessed coefficient of the ship spaces according to the complexity of the outfitting works.

According to (1), during the cruise ship outfitting and building, and concerning the consumers surveyed by this research, electrical energy was consumed according to the following:

$$EEC_{DT} = WH \times 0.25 \times P_{WA} + ((P_{LBL} + P_{FBL}) \times V \times D_{BL}) \times 0.0625 + (P_{LBO} + P_{FBO}) \times V \times D_{BO} \times 0.6 \times 0.5 \quad (2)$$

According to (2), electrical energy consumption during the outfitting process and shipbuilding process (EEC_{DT}) equalled 4,469,804.08 kWh.

If the cruise vessel project had been realised without the use of a digital ship prototype, the electrical energy consumption (EEC), analysed by the same consumers as in (1), would be calculated according to the following:

$$EEC = R_{PV} \times CGT_{CV} \times K_{arc} \times P_{WA} + ((P_{LBL} + P_{FBL}) \times V \times D_{BLPV}) \times K_{NBBL} + (P_{LBO} + P_{FBO}) \times V \times D_{BOPV} \times K_{IBO} \times K_{CBO} \quad (3)$$

where R_{PV} is the coefficient of welding hours spent according to the CGT of the passenger vessel, CGT_{CV} the compensated gross tonnage of the cruise vessel, D_{BLPV} the on-block outfitting duration according to its share in the overall outfitting and construction duration of the passenger vessel, and D_{BOPV} the duration of on-board outfitting according to its share in the total duration of the process of outfitting and building a passenger vessel.

According to (3), EEC would be:

$$EEC = 14.08 \times CGT_{CV} \times 0.25 \times P_{WA} + ((P_{LBL} + P_{FBL}) \times V \times D_{BLPV}) \times 0.0625 + (P_{LBO} + P_{FBO}) \times V \times D_{BOPV} \times 0.6 \times 0.5 \quad (4)$$

According to (4), if the cruise vessel project had been realized without the implementation of a 3D model in the form of Digital Twin, electrical energy consumption would have equalled 6,082,058.23 kWh

The difference in electrical energy consumption (ΔEEC) resulting in the parallel "construction" of a digital ship prototype is as follows:

$$\Delta EEC = EEC - EEC_{DT} \quad (5)$$

which makes a difference in consumption of 1,612,254.15 kWh, representing 20% electrical energy savings only in relation to the analysis of part of the direct energy consumption through the building of the observed ship [29].

Although research on the human role in the Smart Factory environment is in its infancy [30] and, in fact, analyses of the impact of Industry 4.0 technologies on occupational safety and health are yet to come [31], designing and building a ship prototype in a virtual surrounding enables the defining of technology for outfitting by performing the same work to a high degree of completion within more favourable working conditions, e.g., open outfitting spaces with a much higher share of continuous natural ventilation and natural light and thus a low level of temporary energy "obstacles" (cables, ventilation ducts), and avoiding overhead work, which ultimately results in an approximately 43% reduction in the incidence of injuries at work, with almost five times fewer severe injuries at work (Table 4).

6. Conclusions

Current trends in the maritime market define sustainability as a major factor in competitiveness, with demands on energy-efficient and environmentally friendly vessels manufactured in the same environment. Today's shipbuilding industry is focused on the growing presence of research, development and innovation activities in its business for the purposes of technical and technological improvements in the production process, aiming to achieve cost reductions and energy savings, and having available the digital technologies of Industry 4.0 as appropriate tools above all.

This research presents the importance of 3D modelling in a virtual environment by comparing the process of building and outfitting a passenger vessel and a cruise vessel in the observed shipyard. The research analysis is focused on a change in the number of working hours engaged for the outfitting activities and a change in the electric energy consumption during the shipbuilding process. Designing and building a ship in parallel through its 3D model in the Digital Twin form allowed ship outfitting in the earlier stages of construction up to a level of approximately 70%, which improved the productivity in the project realisation process by approximately 20%. Furthermore, 20% savings in electrical energy consumption were achieved only in relation to the scope of this research, thus reducing CO_2 emissions by 1140 t over two years. Additionally to that, as the result of advanced outfitting improvement, the injury frequency rate decreased by about 43% and the injury severity rate reduced by five times.

Even though quantitative analysis of the savings considering the vessel's insurance, fire and safety protection as well as financing costs were not included in this research, their significance are presumed; therefore, further study of this subject is recommended.

Although the proportion of errors in assembly activities was significantly reduced, from 50% to as much as 90%, depending on the outfitting profession, further improvements are possible by applying Augmented Reality (AR), in which direction further research is proposed to be performed. Furthermore, based on the realised savings in the number of outfitting working hours, it is assumed that the duration of the project realisation process is shortened; following that, this research should be expanded in order to define the method of process duration determination while considering the expected extension of the preparatory (design) phase. Additionally, this paper does not consider the impact of the need for earlier outfit procurement regarding the usual construction intervals between the main events (milestones) and the associated contractual payment schedule; therefore, the authors propose further analysis to adjust cash flow to meet outfitting dynamics.

This study targets in particular shipbuilding systems with cruise vessel, naval and/or mega-yacht new build programs because in the majority of shipyards within the subject market niche, outfitting activities are performed in the later stages of the building process, mainly on board on the berth/slipway or even after launching. One of the reasons for the division of such outfitting activities is either because of the complexity of piping and electrical systems, as well as the commissioning program at the quay (navy vessels), the large number of modifications in outfitting (mega-yachts) or the high ratio of subcontracted works on a turnkey basis (cruise vessels). Moreover, due to the afore mentioned payment schedule that is contractually commonly applied, i.e., 5 times 20%, whereby the instalment distribution is in relation to the main events, shipyards are aiming to reach the steel cutting milestone, as well as the keel laying and launching events, as early as possible, with an increase in savings (man-hours, energy, etc.) that could be achieved by implementing advanced outfitting in the earlier stages of ship construction, particularly during the sections and blocks erection. Therefore, this paper addresses and intends to contribute to the shipbuilding industry in general, irrespective of the chosen market niche(s).

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