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# A novel approach for planning of shipbuilding processes

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## Summary

Shipbuilding is acknowledged as an uncertain, complex, and unique industrial effort that yields massive products consisting of numerous parts and is vulnerable to unexpected events. The industry is also dominated by customer requirements through designs tailor-made for a specific ship. Planning in shipbuilding is therefore considered a formidable process. Consequently, many studies have been conducted to develop a planning framework for the industry to efficiently handle planning process. Yet none of these studies are deemed substantial enough to be regarded as holistic, straightforward, well-accepted, and compatible with the nature of shipbuilding. This study is therefore an important contribution by presenting a novel, hybrid, and integrated general-purpose planning framework applicable to all shipbuilding processes. The novel method exploits historical ship construction scheduling data, synthesizing hierarchical planning, dynamic scheduling, and discrete-event simulation, which is validated through an empirical study in this paper.

*Key words:* *shipbuilding; planning; scheduling; multi-agent systems; discrete-event simulation*

## 1. Introduction

### 1.1. Purpose of the Study

Shipbuilding is an Engineering-to-Order industry where product characteristics are determined for a specific order, strictly adhering to specifications prescribed by the ship owner. Correspondingly, the main characteristics of shipbuilding projects are indicated as uncertainty, complexity, and uniqueness. Uncertainty is claimed to occur due to unexpected occurrences, also known as real-time events including disruptions in material supply, workforce, storage availability, and malfunction in production equipment [1], [2]. Complexity is asserted to emerge from the correlation of activities with each other, forming a network with many stakeholders involved. Uniqueness is alleged to arise from the fact that ships are hefty structures comprising many parts, components, and equipment, and also incorporating many engineering disciplines. This makes them unsuitable for prototype testing, demanding excessive man-hours before being delivered [3].

Despite the its significance, high relevance to cost and time management, and the scarcity of resources, there are obvious inadequacies in the existing planning methods used in most of today's shipyards. First of all, production planning is mostly performed manually and in a decentralized manner, leading to an inefficient planning process. The lack of flexibility of planning processes against unexpected occurrences is another insufficiency preventing efficient responses to real-time events [4]. The absence of a well-accepted methodology or a general-purpose (i.e., a simple, not specialized to a ship, easily configurable and widely applicable to many ship types) framework is also a drawback, leading planning activities to rely solely on the knowledge of experienced personnel. Therefore, a such planning methodology would surely be advantageous in the industry as a solution for the aforementioned inadequacies. However, the planning methodologies proposed for the industry are far from being well-accepted and holistic, hence most shipyards prefer to develop their own planning methods [5]. This phenomenon diminishes the precision and standardization of planning activities. Likewise, available methodologies fail to represent all shipbuilding processes (i.e., design, procurement, construction, outfitting, paint-insulation, assembly, test and trials), but merely concentrate on block construction. Practitioners of planning in shipbuilding undoubtedly encounter issues regarding the application of methodologies that are not convenient for representing the nature of shipbuilding processes.

In this paper, a general-purpose, holistic, straightforward, and standardized planning framework that is compatible with the nature of shipbuilding is proposed. This method hybridizes the most applicable techniques, including dynamic scheduling, hierarchical planning, and discrete-event simulation. The purpose of the study, shipbuilding practice, and planning and scheduling in the industry are briefly explained in Section 1. The state of the art in development of a planning framework in the industry is presented in Section 2. The novel framework is elaborated in Section 3. An empirical study for validation is established in Section 4. Implications and conclusions are presented in Section 5, and future work is discussed in Section 6.

### 1.2. Shipbuilding Practice

Ships are constructed using various materials and techniques, with steel being the primary material used in the majority of cases. For the purpose of this paper, only ships made of steel, specifically in the form of interim products called blocks, will be considered. These blocks consist of parts and pieces that are welded together to create more complex structures. Subsequently, these outfitted modular structures are then equipped with pipes, ducts, cable trays, cables, and some equipment, based on the shipyard's capabilities and production methods, to a certain extent. The hull and superstructure of the ship are formed by erecting these structures on a slipway or in a dock [6].

The design of ships follows an iterative process known as the design spiral. In each cycle, specific design specifications are elaborated, and the design is finalized in the last iteration. During the detailed design stage, production documentation is generated [7]. Procurement involves the definition, classification, delivery, and storage of materials and equipment to be used during ship production. Piping, cabling, and ventilation items are installed on-unit, on-block, or on-board during the outfitting phase. Assembly refers to the placement of equipment and systems in their proper positions. Tests and trials are conducted to verify that the materials, equipment, systems, and the ship itself are in satisfactory condition for operation [6].

### 1.3. Planning and Scheduling in Shipbuilding

Long-term strategic decisions are made considering manpower, industrial capabilities, and financial investments for a shipbuilding project [8]. Planning and scheduling are the most significant tools for making such decisions, yet they are frequently used interchangeably, leading to common ambiguity. Planning involves the designation of suitable policies regarding scope, time, cost, quality, human resources, coordination, risk, and procurement in order to achieve specific goals. Scheduling, on the other hand, is less comprehensive and refers to the practical application of the policies defined during planning [9].

Ship production planning is mostly performed in compliance with the principles of Product Work Breakdown Structures, abbreviated as PWBS. PWBS is primarily used for block assembly processes and spatial scheduling of hull construction blocks [10]. PWBS assumes hierarchical organization of shipbuilding activities based on hull construction blocks, which allows for overlapping of shipbuilding processes enabling efficiently planning and execution of shipbuilding processes and activities.

Scheduling in shipbuilding is typically carried out using a couple of methods. The most frequently used methods include the Project Evaluation and Review Technique (PERT), Critical Path Method (CPM), and Critical Chain/Buffer Management Method (CC/BM) [11]. PERT is used in shipbuilding projects or processes where time management takes precedence over cost management. It is primarily employed for large, sophisticated, and extraordinary projects. The method is beneficial for managing events where information about the details and durations of activities is not precisely known. Therefore, the method is quite useful under uncertain and rough planning conditions. It utilizes a network structure of arrows and nodes, established based on the relationships of tasks. The scheduling technique estimates the completion time of each task and the minimum time required to execute the overall project.

The Critical Path Method is utilized when durations and details of activities are already known, making the method applicable for relatively certain projects or processes. The activities are connected to each other based on relationships, represented in the form of a Gantt chart. As the name suggests, the method focuses on the critical path, which is the longest sequence of activities prescribing the minimum completion time of the project. Activities are classified as critical and non-critical based on their position on the critical path. Any change in the duration of a critical activity is expected to affect the overall completion time of the project [12].

Critical Chain/Buffer Management is proposed based on the Theory of Constraints, aiming to increase the throughput of a project. In this method, factors, i.e., constraints, are defined on a critical path, limiting rate of production or workflow. Subsequently, measures are taken to fully exploit the constraints. Non-constraint activities are then subordinated to constraint activities. After that, the capacity of constraints is elevated. Finally, constraints are checked to determine if they are still bottlenecks, and new ones are defined if necessary, leading to the cycle being rerun [13].

Shipbuilding master schedules are created in accordance with project milestones. These milestones represent the completion of significant processes or events on the timeline [14]. They are imposed by the contract or defined through the planning process, including the date of the contract, project start, first steel cut, keel laying, block assembly and erection, tank tests, integration of the main propulsion system, auxiliary systems, heating, ventilation and air conditioning system, electrical systems, accommodation spaces equipment, deck and cargo spaces equipment, launching, acceptance tests, and delivery [6].

Hull production schedules are generated in conformity with the shipbuilding master schedules. Design, outfitting, painting, hull erection, and budget control schedules originate from the hull production schedules. Shipyard facilities primarily develop their own work schedules in accordance with the hull erection schedule and production schedules. Material and equipment lead times are determined during the scheduling of construction activities [6].

## 2. State of the Art in Development of Shipbuilding Planning Frameworks

Planning and scheduling in shipbuilding, despite their significance, are often performed relying solely on the experience of workers and personnel in charge of planning. Development of a systematic, and general-purpose planning framework, in conjunction with the digital twin concept of Industry 4.0, is therefore considerably studied by scholars. The most prominent techniques are identified as dynamic scheduling, hierarchical planning, and discrete-event simulation.

Dynamic scheduling and hierarchical planning are commonly used together in the development of planning frameworks. Dynamic scheduling involves incorporating the effects of unexpected events, such as real-time occurrences, into pre-established schedules. It is achieved through various techniques such as heuristics, meta-heuristics, knowledge-based systems, fuzzy logic, artificial intelligence, machine learning, neural networks, and multi-agent systems [15]. The term "agent" generally refers to entities capable of performing tasks on behalf of their operators. Agents have the ability to autonomously make decisions, possess at least limited control over their environment, respond to real-time events, predict outcomes, cooperate with other agents, and integrate into a system. Agents can be classified as human, robotic, or software agents [16]. Hierarchical planning involves organizing activities into layers to create a sequenced, planned, and easily manageable modular structure. Each planner in a layer must adhere to the restrictions set by the planners in the upper layers when making decisions and planning. Hierarchical planning architectures are commonly used for complex projects to manage uncertainties [17].

One of the most prominent and recent studies includes the automatic development of realistic production plans, through which daily working schedules as Gantt charts can be generated. In this study, the complex shipbuilding production process at the shop level is hierarchically modeled, shipbuilding activities are correlated and simulated through discrete-event simulation, and eventually detailed schedules are generated, considering the workload of employees. The framework is applied to a virtual shipyard for the construction process of a single shipbuilding hull block [4].

In another study, a general-purpose planning framework is proposed for Engineering-to-Order industries, based on a hierarchical planning approach. This framework is developed to be applied to not only production but also design, engineering, sell, and validation. In this study, capacity planning is performed upon acceptance of a new project at tactical level, and then detailed plans and schedules are generated at operational level [18].

The Fourth Industrial Revolution, namely Industry 4.0, has not only brought a new perspective to production but also to planning and scheduling processes. The term ‘digital twin’ is examined within this context which could be defined as the virtual modeling of a physical system, enabling more dynamic and constant monitoring of performance, condition, and maintenance data. Planning frameworks for shipbuilding developed as part of digital twin structures are available. In one such study, a digital twin system is constructed, in which shipyard resources and worker availability are correlated with virtual production activities, enabling dynamic response to unexpected occurrences first through the digital twin and then reflecting on the physical production process [19]. A similar study suggests the application of the digital twin concept primarily for proactive dynamic production planning, using real-time production feedback data [20].

One practical application of hierarchical planning is milestone planning, which focuses on achieving significant dates or project milestones rather than detailed tasks. This approach is often considered a top-down or forward-looking planning perspective, decomposing top-level requirements into intermediate and lower levels [21]. It is considered robust, comprehensive, understandable, traceable, and flexible in terms of agility and practicability [22], [23]. Milestone planning is typically realized through the relationship between soft milestones that is defined by contracts with strict penalties and hard milestones adherence to which is desired but not strictly enforced [24].

Planning frameworks that rely on dynamic scheduling techniques are primarily introduced to define the work sequence of block assembly, block erection, and efficient utilization of block storage spaces [25], [26], [27]. One study focused on obtaining the best activity sequence during CNC (Computer Numerical Control) based on historical ship construction scheduling data [28]. Another framework was proposed for defining activity precedence diagrams [29].

There are numerous examples of the hybrid application of dynamic scheduling and hierarchical planning. One of the most frequently cited example in recent studies is the Daewoo Advanced Scheduling (DAS) Project which combines hierarchical planning and dynamic scheduling using multi-agent systems. The DAS architecture consists of four modules that manage block erection, construction of flat and curved blocks, resource utilization, and long-term construction schedules [30].

In another study, ship construction was divided into layers. The uppermost layer, known as the strategic or tactical phase, involves portfolio and capacity management executed under the supervision of a project portfolio management team. Design, procurement, production, and installation schedules are generated from capacity plans, with each schedule having a responsible scheduler. A hierarchical framework for shipbuilding processes was proposed, where the planner of each layer sets limitations to be followed by lower layers. Simulation was used to validate block assembly and outfitting plans [31].

An Advanced Planning System (APS) was developed for shipbuilding processes, which includes long-term planning for purchase, design, procurement, and construction activities. Both long and short-term planning phases are executed to develop master schedules throughout the project [32].

Complex engineering problems involve stochastic parameters that hinder precise estimations. Simulation is often used to validate schedules that are based on vague assumptions and probabilities. It involves modeling and analyzing production flow and capacity. Events in the simulation are classified as continuous or discrete [33]. Discrete-events refer to entities or variables that change their status only at certain points in time. These events are interconnected and their status changes only at specific time points. The production flow is assumed to be constant between consecutive discrete-events [34]. Such systems are modeled and numerical methods are used to run simulations based on certain assumptions, data, and computational skills, allowing assumptions to be made about the system’s behavior [33].

In addition to the practical benefits for production, scholars also use discrete-event simulation for more sophisticated objectives, including the development of new planning frameworks and process analysis and improvement. This includes workflow scheduling analysis, evaluating the impact of new projects, analyzing conflicting jobs and bottlenecks, and presenting different scenarios [2]. In one study, a framework was proposed in which schedules generated by software agents for the shop floor were validated using discrete-event simulation to respond to unexpected incidents during production [35]. Another relevant paper suggests verifying novel paradigms like automated workshops using simulation software [36].

A hierarchical block production planning method is introduced, based on milestones such as the date of keel laying, launching, and delivery. The method employs a backward planning approach starting from the erection of the last block, utilizing discrete-event simulation [37]. A collaborative study between Navantia Shipyard and Coruna University used discrete-event simulation to validate schedules not only during the initial planning stages of production but also for each component of a ship construction block [38]. A combination of multi-agent based systems, discrete-event simulation, and system dynamics is proposed, with discrete-event simulation at the core, implemented through AnyLogic [39]. The construction manager is responsible for integration, retrieving information from the multi-agent based tendering process, and integrating real-time events through programming. The validated schedules from the simulation are presented using Oracle Primavera P6 [40], Microsoft Project [41], and Microsoft Excel [42], as stated in the study [43].

The state of art review reveals significant findings. Firstly, the examined studies obviously aimed to develop a general-purpose planning framework for shipbuilding, focusing on block construction, block erection sequence, and spatial scheduling. Consequently, the need for a holistic planning framework that encompasses all shipbuilding processes, not just construction, is obvious. Secondly, there is an incontrovertible tendency to combine dynamic scheduling, hierarchical planning, and discrete-event simulation techniques to address the uncertainty, complexity, and uniqueness of shipbuilding, in order to develop a more sophisticated approach.

## 3. Proposed SHIP/S Framework

Considering the findings of Section 2, it could be reasoned that the lack of a well-accepted and holistic framework in shipbuilding planning and scheduling might be due to its NP-Hard (i.e., non-deterministic polynomial time hard) nature. This means that there are no exact efficient solutions or algorithms that can be obtained deterministically without utilizing heuristic approaches. This arises from the uncertain, complex, and unique nature of shipbuilding [44]. A holistic approach is obviously required to incorporate the entire shipbuilding processes during planning in order to deal with such a dead end. Thus, the authors of this paper opted to synthesize hierarchical planning, dynamic scheduling, and discrete-event simulation to form an integrated novel framework that benefits from historical ship construction scheduling data. This approach aims to achieve a well-accepted, holistic, and general-purpose method for a more efficient planning in the industry. The proposed method is also expected to react to real-time events received from physical production, hence providing a basis for another approach for a contemporary digital twin concept for the industry.

The framework developed is named ‘Simulated Hierarchical-Dynamic, and Integrated Planning and Scheduling Method’ or simply abbreviated as ‘SHIP/S’. The SHIP/S framework comprises the following components: ‘Statistical Data Analysis and Capacity Allocation Module (SDA-CAM)’, ‘Master Scheduling Module’, ‘Detail Scheduling Module’, ‘Planning and Simulation Layer’, ‘First and Second Scheduling Layers’, ‘Updating Mechanism’, and ‘Feeding Mechanism’. SDA-CAM, Updating Mechanism, and Feeding Mechanisms are integrated through an interface. The framework involves the analysis of historical ship construction scheduling data to yield an initial version of predefined critical project milestones and the allocation of shipyard capacity to ships in the SDA-CAM Module, relying on systematic analysis of expert knowledge. Selection method of critical project milestones are indicated in [6] and elaborated in Section 1.3. The framework prescribes the undertaking of simulation by considering the allocated capacity and initial critical project milestones. The initial critical project milestones are validated and amended as per the simulation results, which are reviewed and modified if necessary in the Master Scheduling Module. Detailed schedules are created through the First and Second Scheduling Layers using a general-purpose shipbuilding scheduling file that adheres to the modified critical milestones. The results are fed into SDA-CAM to continually develop the database.

Human agents play a crucial role in the SHIP/S framework, namely autonomous and mediating agents. Autonomous agents (i.e., process agents) are responsible for planning and scheduling shipbuilding processes and act autonomously as long as they abide by upper-level agents. Mediating agents (i.e., project, critical resources, monitoring, and project coordination agents) are responsible for coordinating and managing autonomous agents. The project agent is responsible for the management of the entire project. The critical resources agent tracks conflicts of resource assignments and overloads. The monitoring agent is responsible for reporting the project progress. The project coordination agent is the most prominent agent in the hierarchy and is liable for the management of the entire project portfolio. The components of the framework are further elaborated in Sections 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, and illustrated in Figure 1.

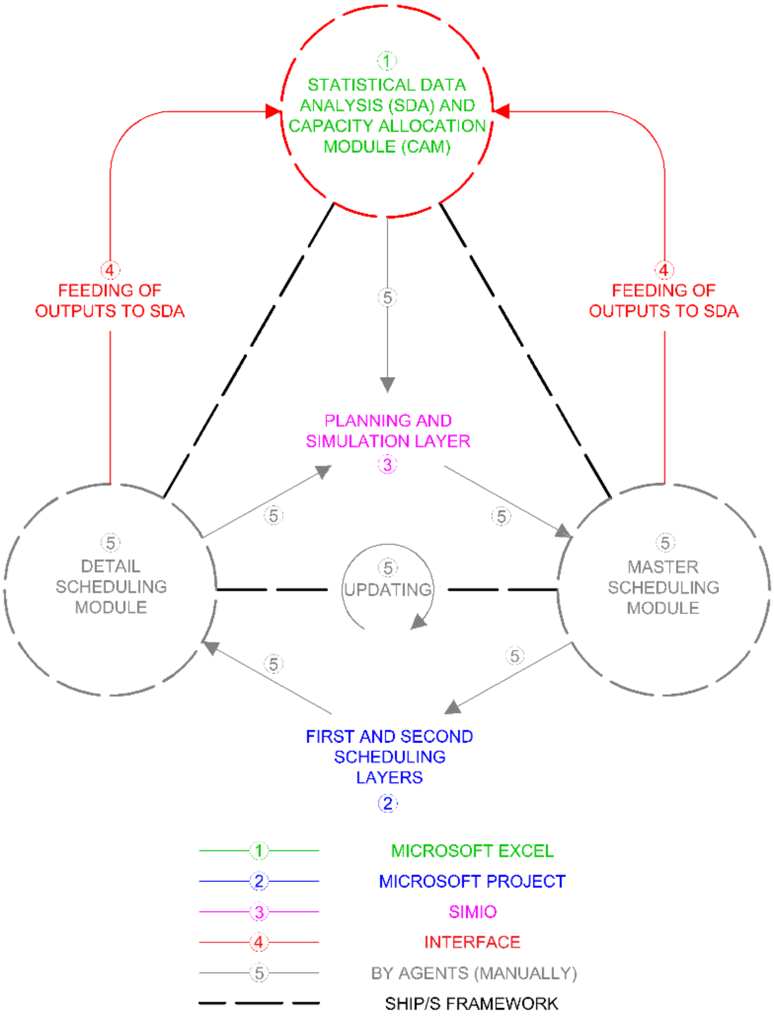


**Fig. 1** SHIP/S framework

## 3.1. Statistical Data Analysis and Capacity Allocation Module (SDA-CAM)

### 3.1.1. The Module

The Statistical Data Analysis and Capacity Allocation Module is designed for two purposes. The first is to provide a set of initial critical project milestones for a specific shipbuilding project. This is achieved through the analysis of specially collected historical ship construction scheduling data. The aim is to initiate milestone planning practices as indicated in Section 2. The second is to allocate capacity to shipbuilding projects.

The former is realized by defining the most important planning milestones for a specific project, as indicated in Section 1.3, and gathering historical ship construction scheduling data related to ships of the required ship type. Since these ships may vary in terms of their features and specifications, the selection of ships to be analyzed must consider their resemblance to the shipbuilding project being planned. Subsequently, regression analysis is performed as elaborated in Section 3.1.2. The latter objective is accomplished as clarified in Section 3.1.3.

#### 3.1.2. Regression Analysis of Historical Ship Construction Scheduling Data

Regression analysis is a fundamental technique used to uncover correlations between a dependent variable and independent variable(s) by plotting a best-fitting line based on observations. This analysis is carried out in the SDA-CAM Module which provides formulas to define the relationship between milestones. These milestones are interconnected parametrically through the subtraction of each milestone from the entry into force date of the contract for construction. This subtraction is referred to as the ‘parametric gap’ in this study.

#### 3.1.3. Capacity Allocation

The allocation of capacity in shipbuilding projects is a critical aspect of planning and resource management. The allocation process involves determining how manpower, equipment, and budget resources should be distributed among various projects, processes, or activities. The goal is to ensure efficient utilization of resources while meeting project deadlines and objectives [45].

Capacity planning in shipbuilding typically relies on a combination of factors, including expert knowledge, historical data from previous ship construction schedules, and labor standards. Experts play a crucial role in estimating and monitoring the required man-hours for each project within the portfolio. They use their expertise, along with an understanding of task and project characteristics, past experiences, and prevailing conditions, to make predictions and estimations [3].

The capacity allocation process within the shipyard is guided by a shipbuilding master schedule plan and a utilization factor of resources. A multi-criteria decision-making method is often employed to allocate capacity to projects therefore such a method as defined by [46] is selected within the context of the SHIP/S Framework. This method considers multiple criteria and provides significance coefficients for each criterion. These coefficients, derived from expert knowledge, help determine the relative importance of each project and guide the allocation of capacity resources. The chosen multi-criteria decision-making method is preferred due to its simplicity and straightforwardness, aligning with the expert knowledge available. By assigning significance coefficients to criteria, the method facilitates the allocation of capacity resources based on the relative importance of different projects. This approach ensures that capacity is allocated efficiently and effectively, considering the specific needs and priorities of each project within the shipbuilding portfolio [47]

##### 3.1.3.1. Development of Hierarchy.

The criteria for capacity allocation are hierarchically organized in accordance with [48] and provided in Table 1. The hierarchy represents the consecutive adherence of the layers in numerical order, specifically the 1st, 2nd, and 3rd layers.

##### 3.1.3.2. Capacity Allocation Procedure.

The shipyard’s total capacity and values for each ship corresponding to criteria stated in Table 1, are entered into the SDA-CAM Module in collaboration with the project agent. The criteria and hierarchy outlined in Table 1 are established using the authors’ industrial experience and knowledge. Agents respond to pairwise questions using the SDA-CAM, and their judgments are analyzed according to Section 3.1.3 to determine the most significant criterion for capacity allocation. The shipyard capacity is ultimately allocated in direct proportion to the corresponding values of the most important criterion through the interface.

**Table 1** Hierarchy for capacity allocation procedure

| Strategy Management<br>*(1st Layer)* | Utilization Management<br>*(2nd Layer)* | | Load Management<br>*(3rd Layer)* |
|---|---|---|---|
| • Order Book (Turnover)<br>• Profitability<br>• Milestone Adherence per Ship<br>• Difficulty per Ship<br>• Novelty per Ship<br>• Value Added per Ship | **Design** | • Engineering Utilization<br>• Software Utilization<br>• Hardware Utilization | • Man-Hour per Ship<br>• Load per Ship<br>• Man-Hour per Activity/Sub-Process/Process<br>• Load per Activity/Sub-Process/Process<br>• Work-in-Process (WIP) |
| | **Procurement** | • Warehouse Utilization<br>• Spatial Utilization<br>• Budgetary Utilization | |
| | **Construction** | • Spatial Utilization<br>• Material Utilization<br>• Quay Utilization<br>• Slipway Utilization<br>• Shop Utilization | |
| | **Outfitting** | • Shop Utilization<br>• Material Utilization<br>• Equipment Utilization<br>• Spatial Utilization | |
| | **Paint-Insulati** | • Shop Utilization<br>• Material Utilization<br>• Spatial Utilization | |
| | **Assembly** | • Spatial Utilization<br>• Shop Utilization<br>• Equipment Utilization | |
| | **Test-Trials** | • Dock Utilization<br>• Harbor Utilization<br>• Safety Utilization | |

### 3.2. Planning and Simulation Layer

Discrete-event simulation is performed through the Planning and Simulation Layer using Simio [49]. This process is based on initial critical project milestones and allocated capacity obtained as per Section 3.1. The objective of this layer is to validate the initial critical project milestones and generate a set of more precise milestones for the subsequent phases of the framework.

In the context of this study, a general-purpose shipyard layout is created, which can be configured for a specific shipbuilding project. The layout is so configured as to achieve optimal material flow, reduced work-in-process and inventory, a uniform flow by reducing buffer accumulation, and a mitigated number of lifts and distance traveled for the transportation of interim products within the shipyard layout [6]. The layout includes basic components of a representative shipyard layout, as illustrated in Figure 2. The components of the layout are labeled from ‘a’ to ‘m’ to reflect the flow of material, equipment, and interim products. The simulation is configured based on this general-purpose layout and its components, production machinery, and equipment listed in Figure 2. However, it is expected that the layout will be modified according to the specific project and shipyard requirements. The production capacity of machinery, transportation abilities of vehicles and cranes, cutting and assembly potential of stations are entered into the simulation. All interim products (i.e., sub-assemblies, blocks, outfitted blocks) are modeled as separate entities. The release of materials and equipment from warehouses and stockyards is defined and modeled, with the user expected to input the corresponding rates. The simulation is then run for a given project, and if the initial run does not validate the hard milestones [24], the simulation is re-run with new iterations of critical milestones until the hard milestones are validated. It is important to note that the ship model itself is not included in the simulation model for ease of application, and parameters related to the ship model (e.g., hull weight, number of pipes in the ship, number of machinery items, systems) are reflected externally.

## 3.3. Master Scheduling Module

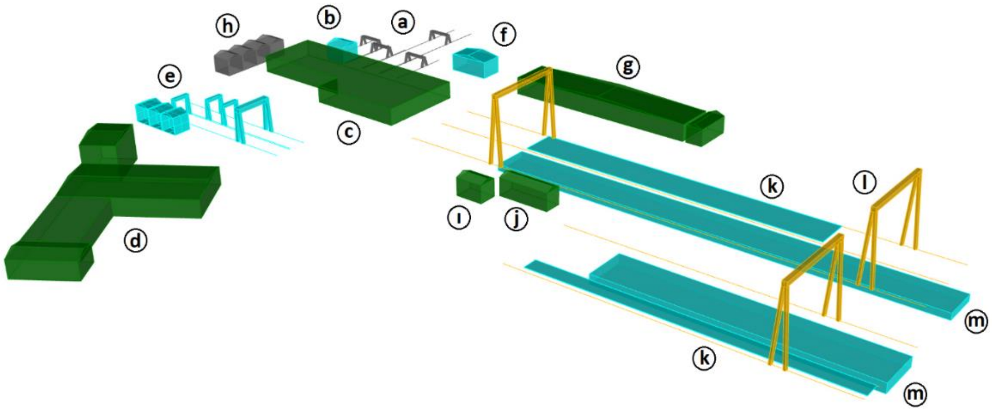
### 3.3.1. The Module

Initial critical project milestones obtained as prescribed in Section 3.1 and validated through Section 3.2 are then forwarded to the Master Scheduling Module for review by autonomous process agents, who will assess their appropriateness and provide feedback. The convenience of the agents' entries is evaluated by the critical resources agent, project agent and project coordination agent in accordance with Section 3.3.2.

### 3.3.2. Hierarchies and Interaction between Agents

The framework relies on the efficient cooperation of agents and is established based on two hierarchies. The first hierarchy implies that the project agent, critical resources agent, monitoring agent, and coordination agents are authorized to supervise the autonomous process agents. This indicates that the process agents are free to make decisions regarding the schedules of their processes as long as they abide by the upper limits defined by the mediating agents.

The second hierarchy involves the subordination of the non-critical activities to critical ones, similar to principles of the Theory of Constraints [50]. The SHIP/S framework considers construction, outfitting, painting-insulation, and assembly processes as the critical processes.



| | | | | | |
|---|---|---|---|---|---|
| a. | Steel Stockyard | f. | Pipe Assembly Shop | j. | Painting Shop |
| b. | Pre-treatment Shop | g. | Outfitting Shop | k. | Pre-Erection Area |
| c. | Cutting Shop | h. | Warehouse | l. | Gantry Crane |
| d. | Panel Line | ı. | Blasting Shop | m. | Slipway |
| e. | Assembly Area | | | | |

**Fig. 2** Basic shipyard layout

The critical path is expected to be formed through the activities belonging to these processes. The activities that make up the critical path are determined based on precedence, activity durations, milestones, and constraints.

On the other hand, the framework assumes that design, procurement, and test and trial processes are non-critical processes. Consequently, the activities constituting these processes are expected to be subordinated to the affiliated critical processes.

### 3.4. First and Second Scheduling Layers

Initial critical project milestones reviewed and finalized through Section 3.3 are then proceeded to the First Scheduling Layer to form the shipbuilding master schedule. Detailed process schedules are eventually retrieved via the Second Scheduling Layer. For this purpose, a general-purpose shipbuilding scheduling file comprising elementary shipbuilding processes, subprocesses and activities is developed within the context of the study, following the ‘Non-Linear Approach, NLA’. NLA proposes a planning database of general-purpose plans created beforehand, from which the most appropriate plan is selected to generate schedules [51]. This is achieved through the iterative application of different schedules and the determination of the best schedule based on certain criteria such as cost, and time [52]. A few general-purpose shipbuilding schedule files are created on Microsoft Project [41], taking into consideration shipbuilding activities, their relationships, and constraints. The most appropriate one is selected to be used. The shipbuilding master schedule is then implemented based on the critical project milestones, using the general-purpose shipbuilding scheduling file, and the scheduling of shipbuilding processes is performed. Finally, detailed process schedules are generated, providing the dates of activities within subprocesses.

### 3.5. Detail Scheduling Module

The detailed process schedules created through Section 3.4 are tracked for monitoring purposes on the Detail Scheduling Module. The schedulers are not allowed to surpass the limits set by upper planners and are expected to abide by the limits imposed by mediating agents. In case of any conflicts or inconsistencies, these should be subject to the approval of the project coordination agent. This module is designed to provide a basis for monitoring the progress of design, procurement, construction, outfitting, painting and insulation, assembly, test and trials detail schedules. The interaction between agents achieved as defined in Section 3.3.2.

### 3.6. Updating Mechanism

The Statistical Data Analysis and Capacity Allocation Module (SDA-CAM), Updating Mechanism, and Feeding Mechanisms are accessible through the interface. Real-time events are to be notified using various instruments including mobile devices [53], barcodes [54], RFID [55], wearable sensors [56], [57], or mobile sensors [58]. As a result, each agent is expected to report real-time events through the aforementioned devices. If adherence to limits set by master shipbuilding schedule is not possible due to disturbances in detailed process schedules, the sequence defined in Sections 3.2, 3.3, 3.4, and 3.5 is repeated until the real-time event is appropriately incorporated into the simulation, aligning with the hard milestones.

### 3.7. Feeding Mechanism

The feeding mechanism is designed for perpetually updating the historical ship construction scheduling database so that the database is always kept up-to-date and continuously enriched by new data. This is achieved by entering the outputs of the Master Scheduling Module and Detail Scheduling Module into the historical ship construction scheduling database.

## 4. Empirical Study

The purpose of the empirical study is to validate the SHIP/S framework elaborated in Section 3. A representative ship and a shipyard are therefore preemptively configured, referred to hereinafter as ‘the Ship’ and ‘the Shipyard’, respectively. Subsequently, critical project milestones of a number of already built ships are clustered for data analysis. These ships are constructed in various shipyards with comparable production capacities in terms of kind, tonnage, number, and dimensions of ships. They are selected to be of the same type, having similar dimensions with each other and with the Ship. Additionally, an actual ship that is comparable to the Ship and the ships included in the database is chosen. The SHIP/S framework is then employed on the Ship, and the construction is simulated at the Shipyard.

In this Section, statistical data analysis is provided in Section 4.1. The application of the remaining steps of the framework is presented in Section 4.2, including a comparison of the results obtained for the Ship through SHIP/S and the milestones of the actual ship for validation.

### 4.1. Data Analysis

Regression analysis as explained in the Section 3.1.2, is applied to the parametric gaps presented in Table 2. The parametric gaps are calculated for the ships gathered in the database by subtraction of relevant critical project milestone from entry into force date of the contract of the specific ship. The correlation between the parametric gaps is visualized through Figures 3-17. It is remarked that the axes of Figures 3-17 represent the parametric gaps calculated for ships in the dataset. The values on the *X*-axis indicate the first parametric gap, and the values on the *Y*-axis depict the second parametric gap, both measured in ‘days’ (e.g., Values on the *X*-axis belong to $T_{BL,A}$, and values on the *Y*-axis belong to $T_{FST}$ in Figure 3).

**Table 2** Parametric gap for critical project milestones

| Parametric Gap | Symbol |
|---|---|
| Entry into Force Date of the Contract | $T$ |
| T-First Steel Cut | $T_{FST}$ |
| T-Commencing for Block Assembly | $T_{BL,A}$ |
| T-Commencing for Block Erection | $T_{BL,E}$ |
| T-Commencing for Tank Tests | $T_{TNK}$ |
| T-Commencing for Superstructure Assembly | $T_{STR}$ |
| T-Commencing for Integration of Main Propulsion System | $T_{MPR}$ |
| T-Commencing for Integration of Auxiliary Systems | $T_{AUX}$ |
| T-Commencing for Integration of Heating, Ventilation and Air Conditioning System (HVAC) | $T_{HVC}$ |
| T-Commencing for Integration of Electrical Systems | $T_{ELC}$ |
| T-Commencing for Integration of Accommodation Spaces Equipment | $T_{ACC}$ |
| T-Commencing for Integration of Deck and Cargo Spaces Equipment | $T_{D,CA}$ |
| T-Commencing for Integration of Communication Systems | $T_{COMM}$ |
| T-Launching | $T_{LAU}$ |
| T-Commencing for Harbor Acceptance Tests | $T_{HAT}$ |
| T-Commencing for Sea Acceptance Tests | $T_{SAT}$ |
| T-Delivery | $T_{DEL}$ |

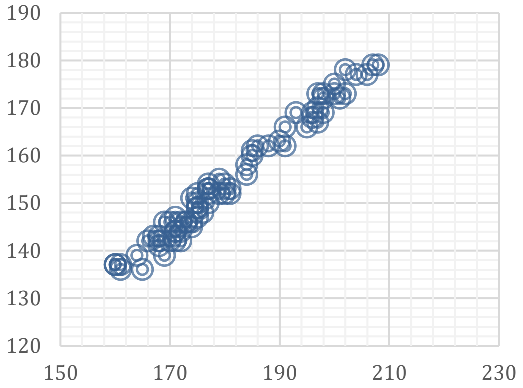


**Fig. 3** Correlation between $T_{BL,A}$ - $T_{FST}$

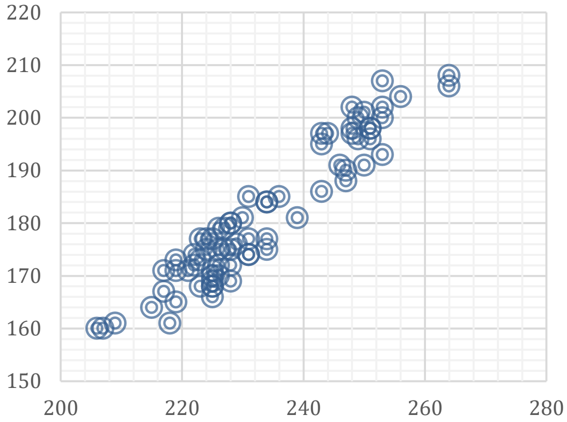


**Fig. 4** Correlation between $T_{BL,E}$ - $T_{BL,A}$

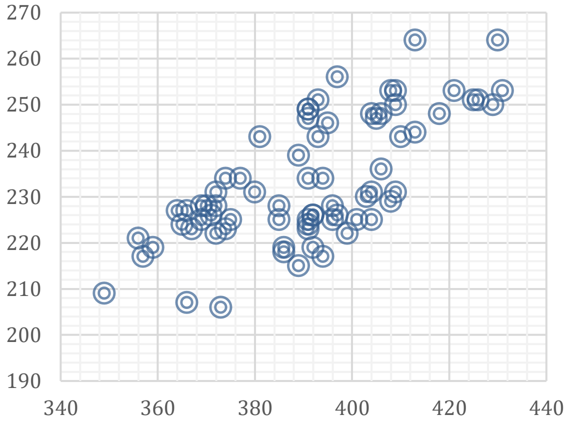


**Fig. 5** Correlation between $T_{TNK}$ - $T_{BL,E}$

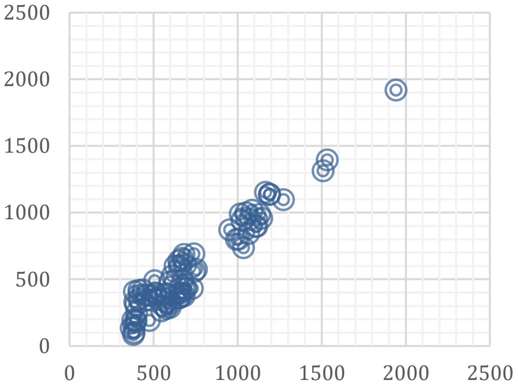


**Fig. 6** Correlation between $T_{MPR}$ - $T_{STR}$

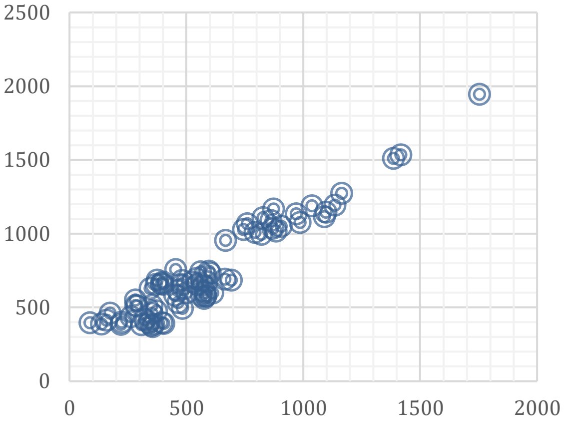


**Fig. 7** Correlation between $T_{AUX}$ - $T_{MPR}$

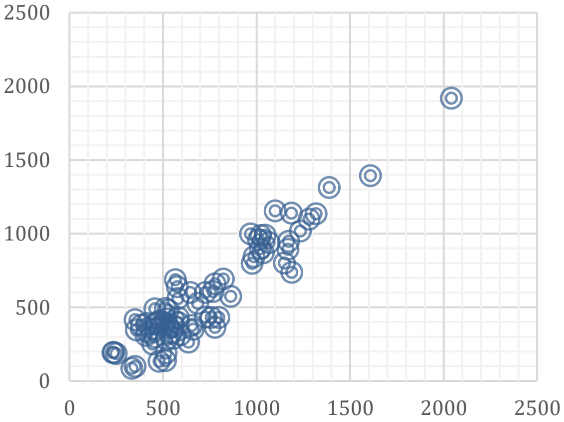


**Fig. 8** Correlation between $T_{HVC}$ - $T_{STR}$

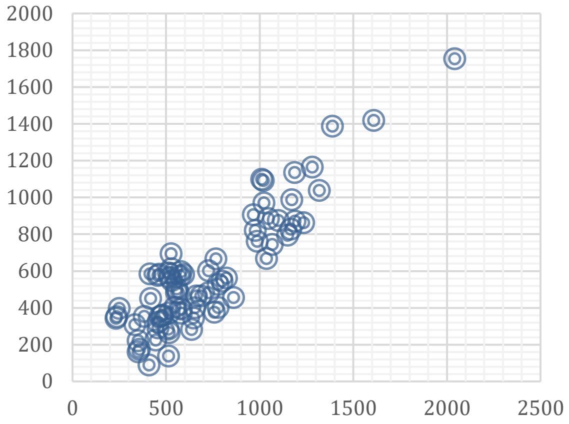


**Fig. 9** Correlation between $T_{HVC}$ - $T_{AUX}$

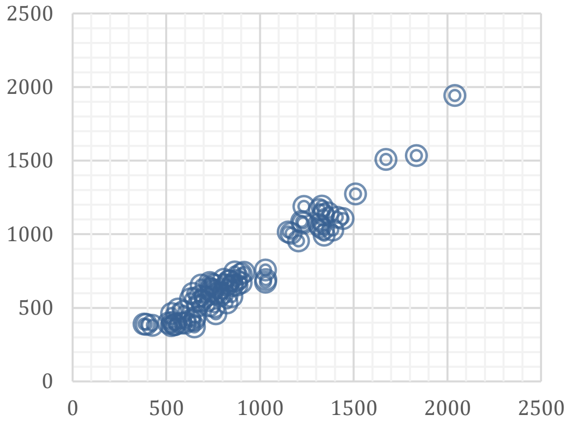


**Fig. 12** Correlation between $T_{D,CA}$ - $T_{MPR}$

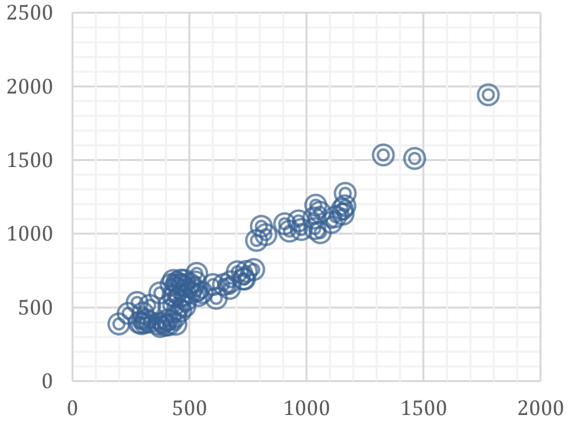


**Fig. 10** Correlation between $T_{ELC}$ - $T_{MPR}$

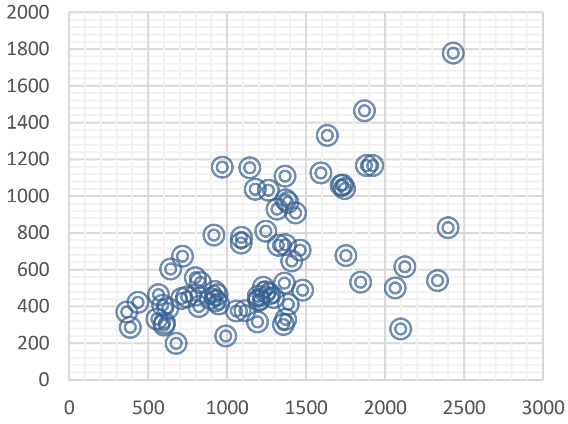


**Fig. 13** Correlation between $T_{COMM}$ - $T_{ELC}$

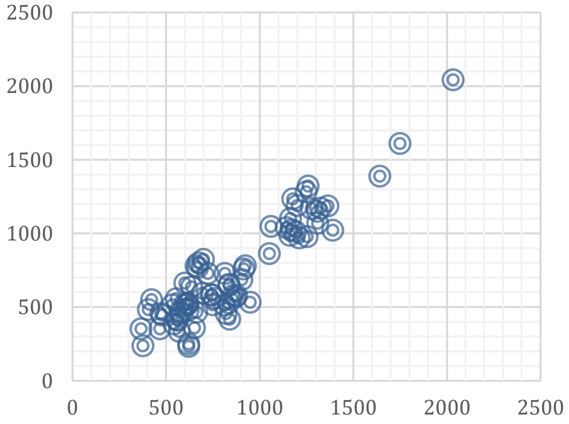


**Fig. 11** Correlation between $T_{ACC}$ - $T_{HVC}$

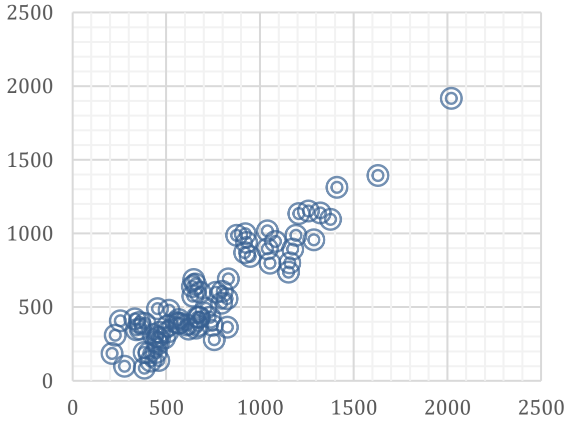


**Fig. 14** Correlation between $T_{LAU}$ - $T_{STR}$

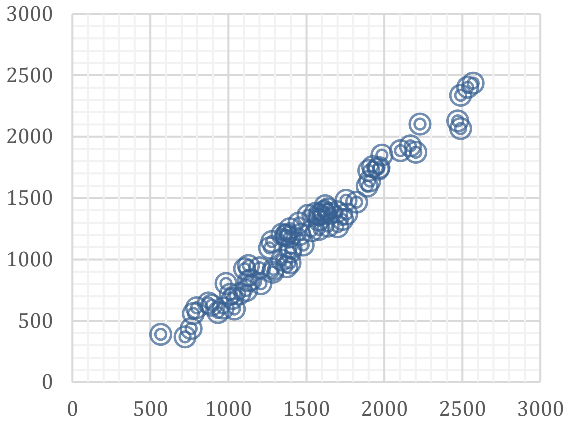


**Fig. 15** Correlation between $T_{HAT} - T_{COMM}$

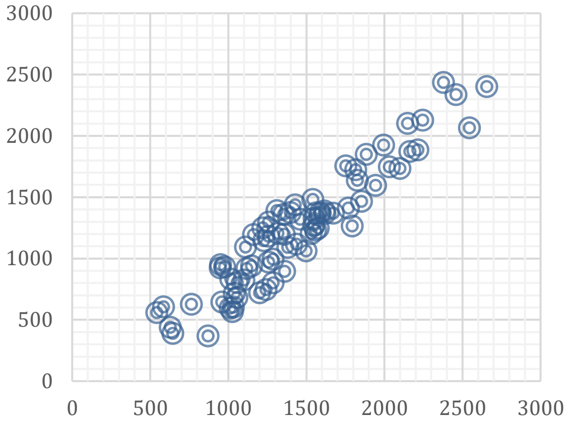


**Fig. 16** Correlation between $T_{SAT} - T_{COMM}$

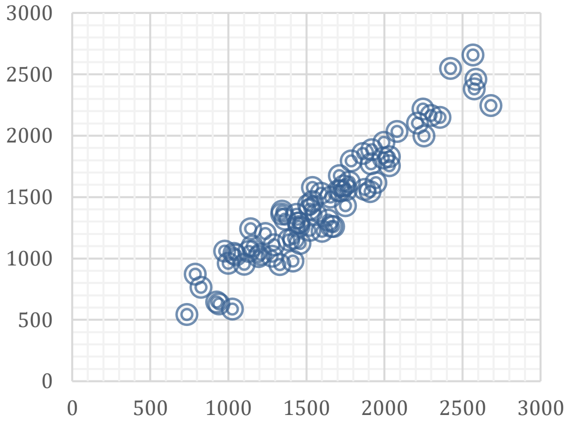


**Fig. 17** Correlation between $T_{DEL}$ - $T_{SAT}$

In order to obtain initial critical project milestones to be processed during further steps of the SHIP/S framework, correlations between parametric gaps are to be calculated. Equations 1-15 are yielded based on regression analysis performed for this empirical study using the data set specifically collected for the purpose of the study. They are calculated in units of ‘days’ using Equations 1-15.

It should be noted that correlations calculated through the formulae given as Equations 1-15 are not universal equations that could be applied on every shipbuilding projects. It should further be remarked that every new project of same or different ship type with divergent shipbuilding specifications or even identical ship being built in a shipyard with different production capacity requires selection of relevant ship data in data set and application of a new a regression analysis.

$$T_{BL,A} = 1.024T_{FST} + 22.602 \tag{1}$$

$$T_{BL,E} = 0.984T_{BL,A} + 55.054 \tag{2}$$

$$T_{TNK} = 0.984T_{BL,E} + 161.492 \tag{3}$$

$$T_{STR} = \textit{No Parametric Relationship} \tag{4}$$

$$T_{MPR} = 0.884T_{STR} + 225.731 \tag{5}$$

$$T_{AUX} = 0.948T_{MPR} - 105.36 \tag{6}$$

$$T_{HVC} = 0.694T_{STR} + 0.282T_{AUX} + 164.623 \tag{7}$$

$$T_{ELC} = 0.976T_{MPR} - 67.655 \tag{8}$$

$$T_{ACC} = 0.906T_{HVC} + 203.573 \tag{9}$$

$$T_{D,CA} = 1.057T_{MPR} + 137.402 \tag{10}$$

$$T_{COMM} = 0.785T_{ELC} + 720.911 \tag{11}$$

$$T_{LAU} = 0.937T_{STR} + 195.802 \tag{12}$$

$$T_{HAT} = 0.936T_{C,WE} + 350.297 \tag{13}$$

$$T_{SAT} = 1.055T_{C,WE} + 326.405 \tag{14}$$

$$T_{DEL} = 0.931T_{SAT} + 258.287 \tag{15}$$

## 4.2. Application

### 4.2.1. General

In this Section, the SHIP/S Framework is applied to the Ship in order to provide practical knowledge and validate the framework using numeric values and a comparison of the results with the actual ship. To accomplish this, the initial critical project milestones are obtained in Section 4.2.2. The cumulative capacity of the Shipyard is then allocated to the Ship in Section 4.2.3. The initial critical milestones are modified in Section 4.2.4 based on simulation and subsequent agent reviews. Finally, schedules are generated in Section 4.2.5.

### 4.2.2. Initial Critical Project Milestones

Initial critical project milestones are acquired through solving Equations 1-15 by setting *T* as January 1st, 2020. This entry into force date is chosen to ensure similarity between project milestones of the Ship and the actual ship, starting from the first step of the shipbuilding construction project. The initial critical project milestones are listed in Table 3.

**Table 3** Initial critical project milestones

| Critical Project Milestone | Date |
|---|---|
| Entry into Force Date of the Contract (*T*) | 01.01.2020 |
| First Steel Cut | 26.05.2020 |
| Commencing for Block Assembly | 22.06.2020 |
| Commencing for Block Erection | 14.08.2020 |
| Commencing for Tank Tests | 19.01.2021 |
| Commencing for Superstructure Assembly | 26.03.2021 |
| Commencing for Integration of Main Propulsion System | 16.09.2021 |
| Commencing for Integration of Auxiliary Systems | 02.05.2021 |
| Commencing for Integration of HVAC | 06.01.2022 |
| Commencing for Integration of Electrical Systems | 26.06.2021 |
| Commencing for Integration of Accommodation Spaces Equipment | 21.05.2022 |
| Commencing for Integration of Deck and Cargo Spaces Equipment | 08.03.2022 |
| Commencing for Integration of Communication Systems | 21.02.2023 |
| Launching | 10.09.2021 |
| Commencing for Harbor Acceptance Tests | 25.11.2023 |
| Commencing for Sea Acceptance Tests | 17.03.2024 |
| Delivery | 16.08.2024 |

### 4.2.3. Capacity Allocation

The Shipyard is fictionalized to have five ship construction projects. The capacity allocation procedure, as described in Section 3.1.3, is executed through the knowledge of agents, then global significance scores of the criteria are obtained as depicted in Table 4.

’Profitability’ is eventually found to be the most important criterion for the allocation of shipyard capabilities. Shipyard capabilities are allocated between the Ship and other projects in direct proportion to the profitability of the projects.

**Table 4** Ordering of criteria for allocation of shipyard capabilities

| Criteria | Level | Global Score |
|---|---|---|
| Profitability | Strategy Management | 0.240 |
| Milestone Adherence per Ship | Strategy Management | 0.197 |
| Value Added per Ship | Strategy Management | 0.150 |
| Reducing Idleness | Strategy Management | 0.070 |
| … | … | … |

### 4.2.4. Modified Critical Project Milestones

The simulation is executed as prescribed in Section 3.2, incorporating the initial critical project milestones as described in Section 4.2.2 and the allocated capacity of the Shipyard as given in Section 4.2.3. The initial milestones are modified according to the results of the simulation in order to comply with the hard milestones. The modified milestones are then passed on to the Master Scheduling Module, as indicated in Section 3.3, and reviewed by agents to ensure the Shipyard’s functionality and address any discrepancies.

The finalized modified critical project milestones are then compared parametrically with the actual ship, and the results are illustrated in Table 5.

**Table 5** Modified critical project milestones

| Critical Project Milestone | SHIP/S (*T*+*X*) (Months) | Actual Project (*T*+*X*) (Months) | Deviation (Months) |
|---|---|---|---|
| Entry into Force Date of the Contract (*T*) | 0 | 0 | 0 |
| First Steel Cut | 5 | 5 | 0 |
| Commencing for Block Assembly | 6 | 9 | 3 |
| Commencing for Block Erection | 7 | 14 | 7 |
| Commencing for Tank Tests | 10 | 16 | 6 |
| Commencing for Superstructure Assembly | 18 | 21 | 3 |
| Commencing for Integration of Main Propulsion System | 20 | 29 | 9 |
| Commencing for Integration of Auxiliary Systems | 20 | 26 | 6 |
| Commencing for Integration of HVAC | 16 | 23 | 7 |
| Commencing for Integration of Electrical Systems | 20 | 26 | 6 |
| Commencing for Integration of Accommodation Spaces Equipment | 31 | 33 | 2 |
| Commencing for Integration of Deck and Cargo Spaces Equipment | 16 | 23 | 7 |
| Commencing for Integration of Communication Systems | 27 | 35 | 8 |
| Launching | 21 | 28 | 7 |
| Commencing for Harbor Acceptance Tests | 48 | 44 | -4 |
| Commencing for Sea Acceptance Tests | 52 | 49 | -3 |
| Delivery | 57 | 53 | -4 |

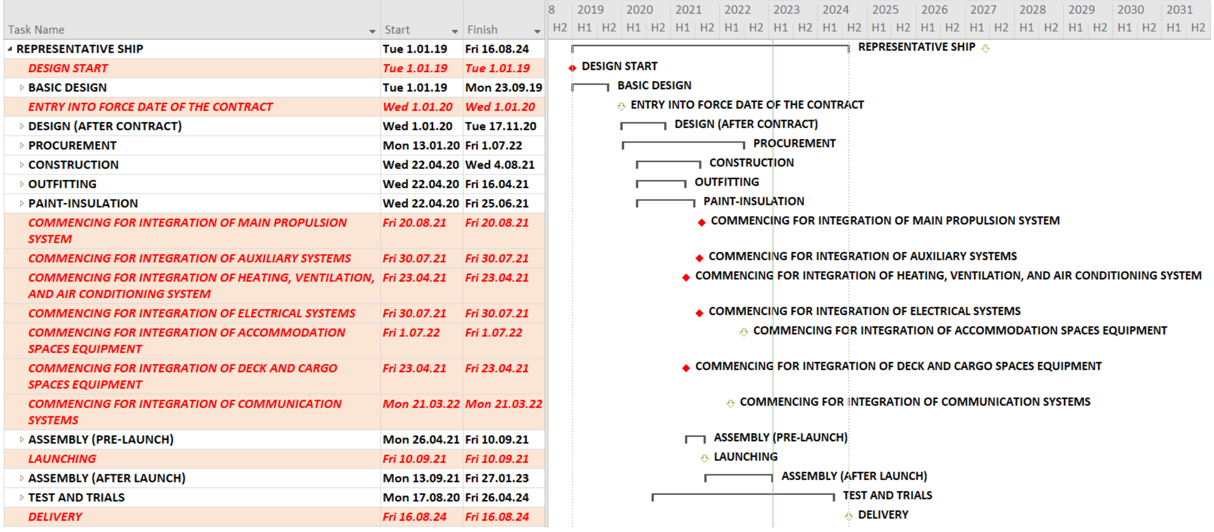
### 4.2.5. Generation of Schedules

A shipbuilding master schedule, as shown in Figure 18, is created based on the configuration of a general-purpose shipbuilding schedule file, following modified critical project milestones. Detailed schedules for each process are created using the Second Scheduling Layer, which utilizes autonomous process agents. While schedules for all shipbuilding processes (such as design, procurement, construction, outfitting, paint-insulation, assembly, and test and trials) are generated through the Second Scheduling Layer, only the construction process schedule is presented in Figure 19 for simplicity. The schedules for other processes are created using the hierarchies defined in Section 3.3.2. The application of the Detail Scheduling Module, Updating Mechanism, and Feeding Mechanism defined in Sections 3.5, 3.6, and 3.7, respectively, is not considered essential for the empirical study and has been omitted.

## 5. Implications and Conclusions

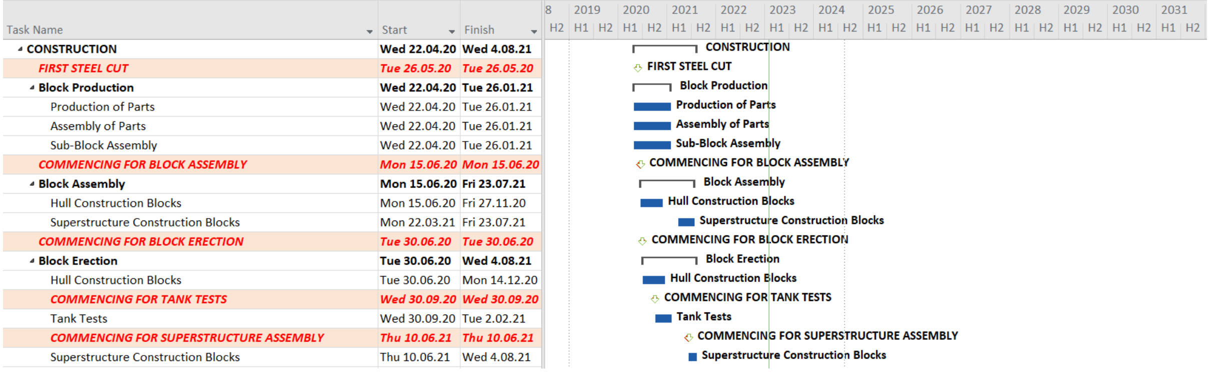
Planning and scheduling in shipbuilding are often executed based on practices of shipyards instead of a global, well-accepted, general-purpose planning framework. It could reasonably be presumed that in case of availability of such a method these efforts could be less burdensome, more efficient, and less prone to errors or misinterpretations stemming from subjective estimation of the process itself. Considering the uncertainty, complexity, and uniqueness of the industry, this deficiency has attracted attention from scholars and led to significant contributions offering methodologies proposing planning frameworks. Yet, none is found to be holistic as to include all shipbuilding processes including design, procurement, construction, outfitting, paint-insulation, assembly, test and trials and deemed to be a sufficient solution to address the nature of shipbuilding. Thus, in this paper a novel framework, namely

SHIP/S, is successfully developed based on a hybrid application of regression analysis of historical ship construction scheduling data, dynamic scheduling, hierarchical planning, and discrete-event simulation to reasonably refer to the nature of the industry and configured to enclose shipbuilding processes as a more holistic, straightforward and feasible approach. Applicability is proven by an empirical study, and the results are also compared with an actual ship. The comparison between the results obtained via SHIP/S and the actual ship reveals similar results proving the applicability of the framework.



| Task Name | Start | Finish |
|---|---|---|
| REPRESENTATIVE SHIP | Tue 1.01.19 | Fri 16.08.24 |
| *DESIGN START* | *Tue 1.01.19* | *Tue 1.01.19* |
| BASIC DESIGN | Tue 1.01.19 | Mon 23.09.19 |
| *ENTRY INTO FORCE DATE OF THE CONTRACT* | *Wed 1.01.20* | *Wed 1.01.20* |
| DESIGN (AFTER CONTRACT) | Wed 1.01.20 | Tue 17.11.20 |
| PROCUREMENT | Mon 13.01.20 | Fri 1.07.22 |
| CONSTRUCTION | Wed 22.04.20 | Wed 4.08.21 |
| OUTFITTING | Wed 22.04.20 | Fri 16.04.21 |
| PAINT-INSULATION | Wed 22.04.20 | Fri 25.06.21 |
| *COMMENCING FOR INTEGRATION OF MAIN PROPULSION SYSTEM* | *Fri 20.08.21* | *Fri 20.08.21* |
| *COMMENCING FOR INTEGRATION OF AUXILIARY SYSTEMS* | *Fri 30.07.21* | *Fri 30.07.21* |
| *COMMENCING FOR INTEGRATION OF HEATING, VENTILATION, AND AIR CONDITIONING SYSTEM* | *Fri 23.04.21* | *Fri 23.04.21* |
| *COMMENCING FOR INTEGRATION OF ELECTRICAL SYSTEMS* | *Fri 30.07.21* | *Fri 30.07.21* |
| *COMMENCING FOR INTEGRATION OF ACCOMMODATION SPACES EQUIPMENT* | *Fri 1.07.22* | *Fri 1.07.22* |
| *COMMENCING FOR INTEGRATION OF DECK AND CARGO SPACES EQUIPMENT* | *Fri 23.04.21* | *Fri 23.04.21* |
| *COMMENCING FOR INTEGRATION OF COMMUNICATION SYSTEMS* | *Mon 21.03.22* | *Mon 21.03.22* |
| ASSEMBLY (PRE-LAUNCH) | Mon 26.04.21 | Fri 10.09.21 |
| *LAUNCHING* | *Fri 10.09.21* | *Fri 10.09.21* |
| ASSEMBLY (AFTER LAUNCH) | Mon 13.09.21 | Fri 27.01.23 |
| TEST AND TRIALS | Mon 17.08.20 | Fri 26.04.24 |
| *DELIVERY* | *Fri 16.08.24* | *Fri 16.08.24* |

**Fig. 18** Shipbuilding master schedule



| Task Name | Start | Finish |
|---|---|---|
| CONSTRUCTION | Wed 22.04.20 | Wed 4.08.21 |
| *FIRST STEEL CUT* | *Tue 26.05.20* | *Tue 26.05.20* |
| Block Production | Wed 22.04.20 | Tue 26.01.21 |
| Production of Parts | Wed 22.04.20 | Tue 26.01.21 |
| Assembly of Parts | Wed 22.04.20 | Tue 26.01.21 |
| Sub-Block Assembly | Wed 22.04.20 | Tue 26.01.21 |
| *COMMENCING FOR BLOCK ASSEMBLY* | *Mon 15.06.20* | *Mon 15.06.20* |
| Block Assembly | Mon 15.06.20 | Fri 23.07.21 |
| Hull Construction Blocks | Mon 15.06.20 | Fri 27.11.20 |
| Superstructure Construction Blocks | Mon 22.03.21 | Fri 23.07.21 |
| *COMMENCING FOR BLOCK ERECTION* | *Tue 30.06.20* | *Tue 30.06.20* |
| Block Erection | Tue 30.06.20 | Wed 4.08.21 |
| Hull Construction Blocks | Tue 30.06.20 | Mon 14.12.20 |
| *COMMENCING FOR TANK TESTS* | *Wed 30.09.20* | *Wed 30.09.20* |
| Tank Tests | Wed 30.09.20 | Tue 2.02.21 |
| *COMMENCING FOR SUPERSTRUCTURE ASSEMBLY* | *Thu 10.06.21* | *Thu 10.06.21* |
| Superstructure Construction Blocks | Thu 10.06.21 | Wed 4.08.21 |

**Fig. 19** Construction process schedule adhering to shipbuilding master schedule

On the other hand, the comparison also revealed some minor deviations from milestones of the actual ship, including commencing for block erection, tank tests, integration of the main propulsion system, integration of auxiliary systems, integration of HVAC, electrical systems, deck and cargo spaces equipment, communication systems, and launching. Two reasons are thereof raised. First, the execution of the actual ship is severely affected by the global pandemic, which is beyond expectations and not encapsulated in the framework implemented in this study using the dataset. Second, the data collection may not have been performed as precisely as expected. However, both reasons should not be judged as sufficient evidence for hampering the applicability of the framework, considering the rather high precision achieved through comparison.

The precious contribution provided by this study is indisputable. It not only delivers a general view of planning and scheduling in shipbuilding but also grants a more holistic approach to planning entire shipbuilding processes. A better, more integrated method is proposed, benefiting from the analysis of historical ship construction scheduling data, capacity allocation techniques, hierarchical planning, dynamic scheduling, and discrete-event simulation. The authors of this paper are confident that the application of this framework could convert conventional planning and scheduling activities into a more efficient, holistic, and less laborious practice.

## 6. Future Work

It is recommended for enthusiastic researchers and software developers to evolve a more sophisticated interface for the framework, enabling all modules, layers, and mechanisms to be incorporated into a single formation. Practitioners in this field are urged to automate the framework and minimize manual interventions as much as possible. It is also advisable to enhance the capabilities of the framework, elaborate on and improve the general-purpose shipbuilding simulation file to incorporate the ship model itself, and enhance the general-purpose shipbuilding scheduling file. Similarly, it is proposed to establish a more precise basis for the comparison of shipyards during the retrieval of historical ship construction scheduling data so that data can be selected and utilized more efficiently.

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