Innovative solutions enabling modular product architecture in boatbuilding

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ABSTRACT: Boatbuilding industry is always in search for innovative technologies. This is especially true for pleasure vessel production, for which the high request from customers and the significant economic value of products call for more rapid construction methodologies able not to affect the elevate quality standard of manufactures. In this framework, boat-outfitting procedures can be shortened and simplified by exploiting modular design concepts. With reference to a 65-foot sailing yacht, the authors focused on proposing a modular product architecture approach for outfitting based on a frame in which both systems and flooring are integrated with each other. The use of advanced 3D modelling tools allowed obtaining a precise representation of the system/structure interfaces and the correct mounting sequence for each defined modulus. The proposed methodology was validated by comparing production times between the traditional approach and the modular one, with the latter turning out to be significantly lowered.

1 INTRODUCTION

The boatbuilding market recovery, and the subsequent increased demand of pleasure vessels, forced boatbuilders to search for continuous advancements able to allow reducing delivery times and costs, while maintaining high quality standards. In particular, the management of construction processes and the improvement of production performances, merged with the necessity of fulfilling customers' requests, represent fundamental ways to acquire advantageous positions in a business full of competitors.

In this framework, modular product architecture concepts may find fruitful application to enhance vessel production (Bertram 2005). Modularisation is already a consolidated practice with respect to several types of large-size ships, which include cruise and navy units (Braidotti et al. 2020, Cuzner et al. 2017). However, modular product architecture may be integrated with small-crafts production technologies by tailoring a specific strategy (Beuß et al. 2016, Henriksen & Røstad 2014). In such a way, vessel production may be enhanced by implementing a sequential and more complex process based on the superimposition of hull construction and outfitting phases. Furthermore, Regulatory Bodies targets involving polluting emissions may be reached (Degan et al. 2021, Lagemann et al. 2021).

Herein, with reference to a 65-foot sailing yacht adopted as case study, the authors started from the state-of-the-art of boatbuilding production technologies to implement an innovative process based on modular product architecture approach. Specifically, a procedure based on both prefabrication and modularisation aimed at simplifying outfitting operations was developed. The main innovation consists in introducing a frame in which both systems and flooring are integrated with each other and to which all the prefabricated modules can be linked through defined interfaces. As designers nowadays can count on the use of advanced IT tools since early design stages (Lindner & Bronsart 2017, la Monaca et al. 2020), these may represent crucial instruments in modularity approaches (Fernández & Cosma 2019): here, the authors used a 3D modelling tool to verify the shape of the proposed frame and its interactions with hull, structures, systems, and modules.

2 MODULARITY IN PRODUCTION

2.1 *Boat production approaches*

In boatbuilding industry, the production strategy is affected by several aspects that include time and costs management, customers' requests, and high quality standards. Furthermore, it also differs depending on the purpose of the boat design: mass production or one-off construction.

In a mass production process, manufacturing phases are a succession of activities linked together and carried out by different operators in different workstations. Procedures are standardised and the process outputs must have the same features; it is clear that production operations are sequenced describing a certain production cycle of known and predetermined duration. Mass-produced vessels allow the owner minimal customisations; often, to satisfy all the customer's requests, boatbuilders must rely on one-off production.

In such a case, owner's requests define design constraints. Moreover, requests for modification may occur even in advanced stages of production. As a result, the boatyard must be able to organize and plan all the activities related to the design and construction by synchronizing the entire process. The different phases of setting up the project must follow one another at a fast pace, sometimes overlapping each other.

As regards customised pleasure vessels production, the most time- and cost-consuming activity is outfitting. Indeed, this phase can begin after the construction of the hull and structures is completed (Figure 1). Moreover, it is one of the most complex and delicate activities due to the relevant number of components involved. In such a phase, production and quality management is fundamental due to the strict mounting sequences: in fact, a delay in supply, a failure or a mounting mistake may significantly compromise the whole stage.

These criticalities require a better planning of the entire construction process, and modular product architecture may represent a potential solution able to ensure elevated customisation of the product (Pandremenos and Chryssolouris 2014).

2.2 *Modular product architecture*

"Modular design refers to designing products by organizing sub-assemblies and components as distinct building blocks (i.e., modules) that can be integrated through configuration to fulfil various customer and engineering requirement" (Tseng et al. 2018).

When describing modularity concepts, product architecture cannot be left out since they are strictly related. (Ulrich 1995) defines product architecture as the scheme by which the function of a product is allocated to physical components and, more precisely, as follows:

- the arrangement of functional elements;
- the mapping from functional elements to physical components;
- the specification of the interfaces among interacting physical components.

Modular architecture is a specific product architecture type, opposed to integral architecture. Modular architecture consists of one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components. The basic elements in modular architecture are the modulus, which are part of a complex system aimed at facilitating assembly by means of defined and specific interfaces (i.e., they can be simply called *building blocks*). As (Pahl & Beitz 1996) explains, four types of modulus exist on the basis of their functionality:

- Basic modulus – it implements fundamental basic functions for a system or a product which, theoretically, is not variable;
- Auxiliary modulus – it implements auxiliary functions to those of basic modules;
- Adaptive modulus – it is able to manage unpredictable constraints, by performing adaptive functions on parts of a system or product;
- Non-modulus – it implements customer-specific functions and must be individually designed.

All the modules in which the whole architecture is split must interact with each other. (Ulrich 1995) defines four different types of interaction, described below and represented in Figure 2:

- Slot modularity: each of the interfaces between components is of a different type from the others, so that the various components in the product cannot be interchanged;
- Bus modularity: there is a common bus to which the other physical components connect via the same type of interface;
- Sectional modularity: all interfaces are of the same type and there is no single element to which all the other components attach. The assembly is built up by connecting the components to each other via identical interfaces.

In general, the main characteristics of modular product architecture can be summarised as follows: i) product standardisation; ii) product subdivision in less complex and independent systems; and iii) product variety and high production rates. Being directly linked to production phases, it is common practice to limit modularisation approaches to them; however, if employed already during early design stages, they could enhance the product quality by supporting a better planning and management of the design itself. This is extremely important in ship design and construction, as it will be deepened in the next section.

2.3 *Modular product architecture in shipbuilding*

In shipbuilding, modular product architecture finds application in two different forms: the first implies the use of modularity to reduce construction and delivery times while maintaining elevate quality standards, while the second aims at build flexible units able to grant different operational profiles, as especially required for navy, working and research vessels (Khan 2016).

In ship design, two types of standard modules are defined: ship modules and task-related modules (Ove Erikstad & Levander 2012).

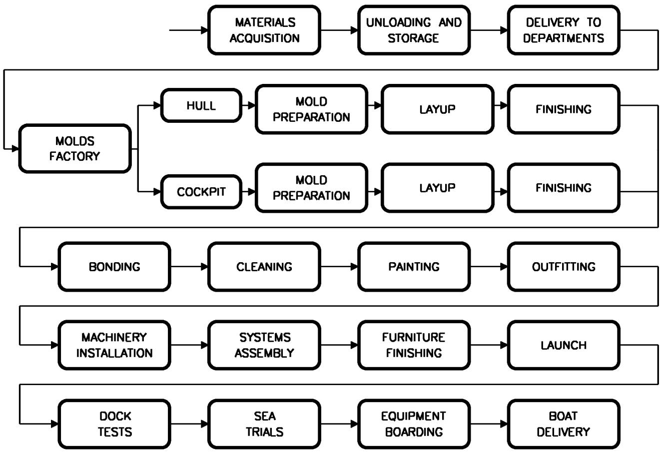

Figure 1. Common production strategy for pleasure vessels.

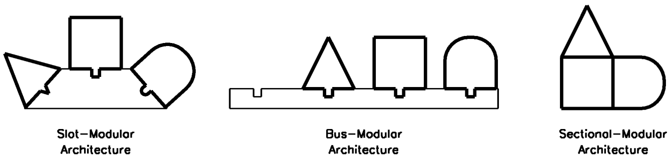

Figure 2. Possible interactions between moduli (Ulrich, 1995).

Ship modules include those parts that serve basic functions for ship operations, transition, storage, and accommodation such as main hull, deckhouse, bridge, tanks and voids, etc. Task-related modules are strictly related to the operational profile and the activities of the ship; some examples are weapons and sensor systems for navy ships, as well as topside modules such as cranes for offshore supply vessels.

A common approach to exploit modularity is based on *configure-to-order* (CTO) strategy (Choi et al. 2018). Design team creates prototype designs by configuring pre-developed standard modules and ship design projects can be defined by module configuration, evaluation, and selection to best meet individual customers' needs.

Modularity concepts are already consolidated as regards the design and construction of large-size ships, such as cruise passenger ones. In fact, during construction, these are subdivided into blocks which are in turn subdivided into smaller modules. Modularisation and prefabrication are so applied, obtaining benefits such as reducing inefficient hours spent on-board vessels during construction by moving a major part of the work from the ship into workshops (Essén 2019). Exploitation of modular product architecture offers significant advantages when approaching big constructions, but its use can be fruitfully widened to other sectors such as boatbuilding, in which times and costs are fundamental factors to ensure profits and market competitiveness. In the following, the implementation of modular product architecture developed for a case-study pleasure vessels is thoroughly presented. The authors propose an approach for outfitting based on both modularisation and the implementation of a frame in which both systems and flooring are integrated.

3 CASE STUDY

A 65-foot sailing yacht was considered as case study vessel (Figure 3). In the initial design phases, two specific constraints were identified: the hull geometry and the preliminary layout of the internal spaces. All the subsequent considerations regarding outfitting modularisation were drawn by not affecting these two aspects.

3.1 *Outfitting strategy*

The developed strategy for outfitting, consisting of the subdivision of complex systems in smaller and simpler modules, progresses through the following three phases:

- Pre-outfitting of the modules;
- Construction and outfitting of the system/flooring platform;
- On-board systems outfitting.

In the pre-outfitting phase, the vessel is subdivided into several furniture blocks. The aim is to work simultaneously on several systems, in order to outfit furniture blocks with all the required components. In such a way, pre-outfitting is performed on the ground and therefore significantly simplified: technical personnel is able to work on blocks in comfortable and ergonomic positions, contrary to what happens inside the hull where spaces are limited. The dimension of the blocks in which the furniture is subdivided depends on handling facilities and systems spatial distribution within the hull. On the basis of such considerations, the modules subdivision for the case-study vessel was elaborated and is shown in Figure 4.

The most challenging modules are those involving restroom and dinette spaces. Indeed, these include systems such as secondary sewage discharges and pipes for potable water. For each system, a precise interface with the hull must be studied and fitted so that accessibility is ensured, during both mounting and maintenance phases. In the other modules, furniture is prevalent and the pre-outfitting involves electrical and lighting systems.

Even though the pre-outfitting of the modules presents the advantage of simplifying operations, it does not reduce production times significantly. Indeed, the amount of system components to be mounted on-board once the hull and the structures is still relevant. These include the following elements: i) principal pipes for hot and cold water distribution; ii) principal pipes for sewage discharge; iii) principal pipes for HVAC system; iv) bunkering and transferring of fuel and freshwater; v) freshwater system; vi) engine room systems; and vii) bilge system.

Figure 3. 65-foot sailing yacht adopted as case study.

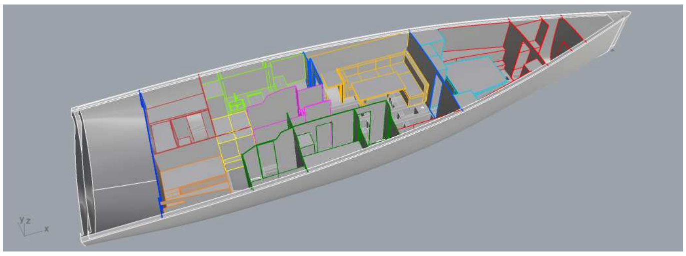

Figure 4. Modules subdivision.

In order to solve the problem, pre-outfitting could be improved by adopting a *full modular* approach in which each modulus powers the adjacent one. However, this solution shows criticalities such as excessive fractioning of systems, increased number of connections and redistribution of spaces and systems.

As a result, in order to anticipate systems installation and connections among modules, the authors focused on developing a frame able to serve as both platform on which the systems are mounted and support for the flooring, as presented in the following section.

3.2 *Frame*

The developed frame is made of aluminium section bars and extends from amidship to the fore of the hull, where almost all the systems are located. The frame geometry was studied in accordance with the following factors:

- Position of the flooring and of the structural grate;
- Position of bulkheads;
- Preliminary position of systems.

The frame design was reproduced through a 3D model (Figure 5), in order to verify its sizes and volume and its integration with the hull structural members. In particular, the frame longitudinal elements are to be fixed on girders, while its transversal elements are to be fixed on floors. The frame turns to be asymmetric due to the presence of a bulkhead that required translating a frame longitudinal element on the right side.

All the systems were analysed in order to identify the components that could be installed on the frame before on-board outfitting and to set up additional structural members for their support. As a result, the following systems may be pre-outfitted on the frame:

- Main pipe for potable water distribution;
- Main pipe for AC distribution;
- Main pipe for bunkering and transferring of fuel;
- Main pipe for bunkering and transferring of water;
- Vents for fuel tanks;
- Vents for water tanks;
- Filters and pumps for fuel transferring;
- Pumps for potable water distribution;
- Freshwater system components.

To increment pre-outfitting operations, a structure able to support the engine block was added to the frame with the aim of modularising also the engine room. On the basis of the preliminary position of such space, the sizes and volumes of the system components were evaluated in order to define the geometry of the supporting structure. In this manner, besides the advantages mentioned in the previous section, connections between system branches to be performed on-board are minimised.

In conclusion, just few systems and machinery (e.g., boiler, desalter, and sewage discharge) still are to be installed on-board. These will be interfaced with the systems pre-outfitted both within the modules and on the frame: as a result, such a configuration allows progressing with two different and independent production lines, one for hull and structures construction and one for outfitting operations.

Figure 6 presents the 3D model of the frame pre-outfitted with the above-mentioned systems, while Figure 7 shows the pre-outfitted frame coupled with the on-board systems within the hull.

3.3 *Developed production strategy*

Figure 8 shows the whole production strategy developed by the authors in the present research.

As it joints both prefabrication and pre-outfitting through modular approach, it allows simultaneous processing by anticipating as much as possible the critical phases of the process.

As the construction of hull and structures proceeds, the pre-outfitting of systems on modules and on the tailored frame is performed too. In this manner, once the construction phase is completed, frame and modules can be embarked in the expected order and correct position and systems can be set up and connected with each other properly.

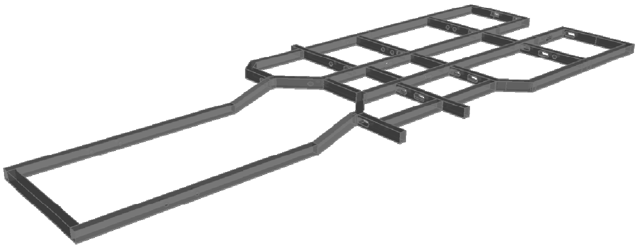

Figure 5. Implemented frame.

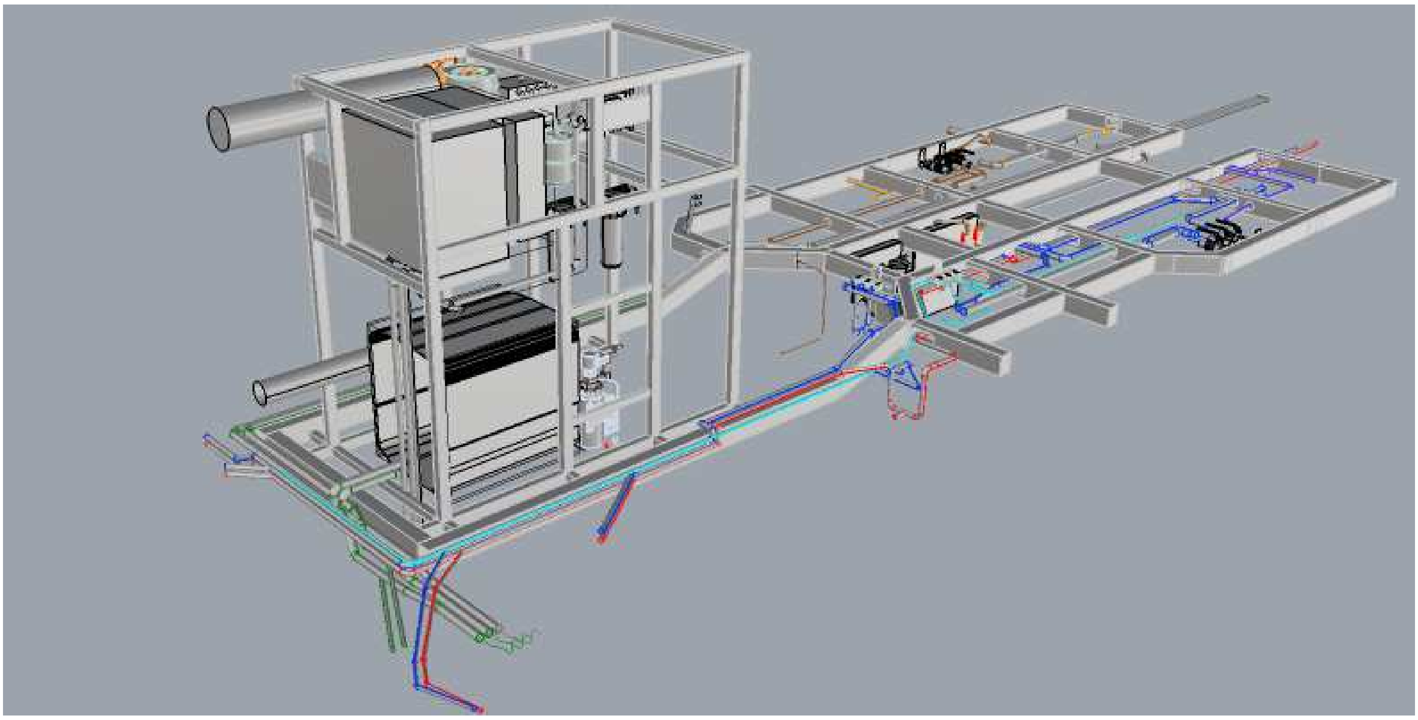

Figure 6. 3D model of the pre-outfitted frame.

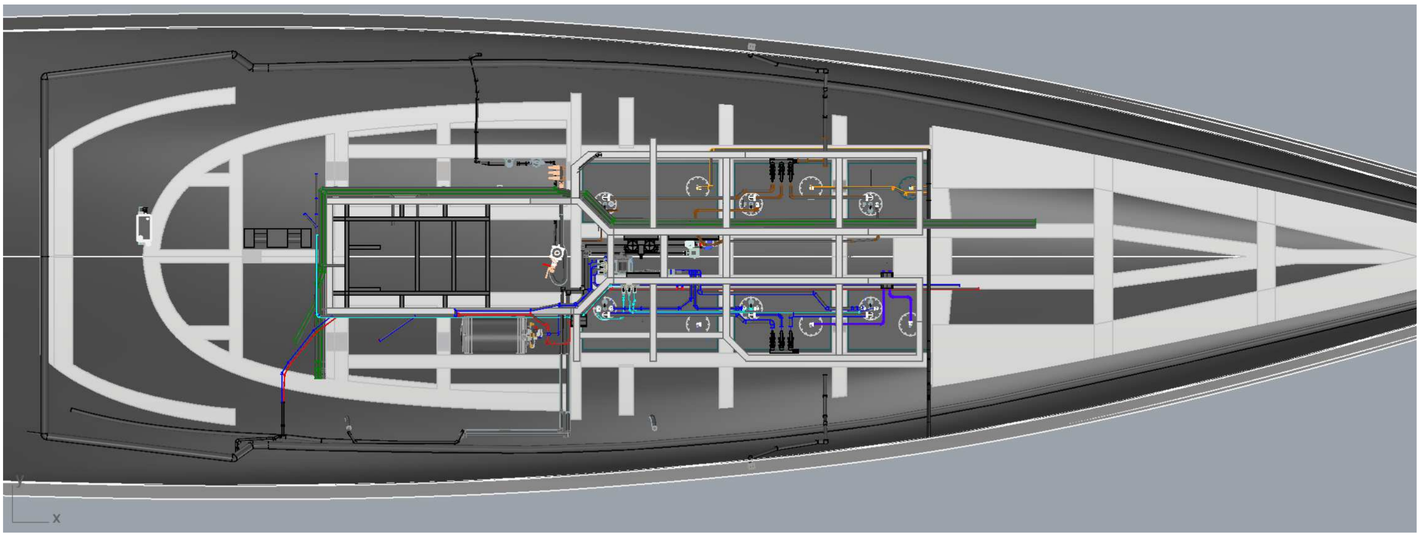

Figure 7. Pre-outfitted frame coupled with the on-board systems.

4 CONCLUSIONS

The present research aimed at developing a production strategy for pleasure vessels able to allow increasing the efficiency of processes and reducing costs and delivery times.

From the analysis of the production sequence commonly adopted in boatbuilding, outfitting turned to be one of the most critical phase since it has to wait for the completion of the hull construction and structural lamination phases. Therefore, in order to parallelise the activities and reduce processing times, the authors proposed an innovative production strategy based on modular product architecture and consisting of two phases: the subdivision of the vessel into pre-outfitted modules and the implantation of a tailored frame able to provide support for both systems and flooring.

The proposed strategy proved to offer significant benefits: prefabrication allows parallelising several activities with great advantages in terms of efficiency of the process and simplifies operations remarkably. In fact, technical personnel can work in bigger and more comfortable spaces without interferences. Not only does the processing become more efficient, but it also increases the quality of the installation.

As regards the time reduction, the authors estimated that, for the case-study vessel, the proposed approach allows saving 6 weeks to complete the boat construction. This drastic saving, which turns to be a significant percentage of the entire production period, could be exploited to offer clients greater possibility of customisation, thus acquiring advantages over competitors.

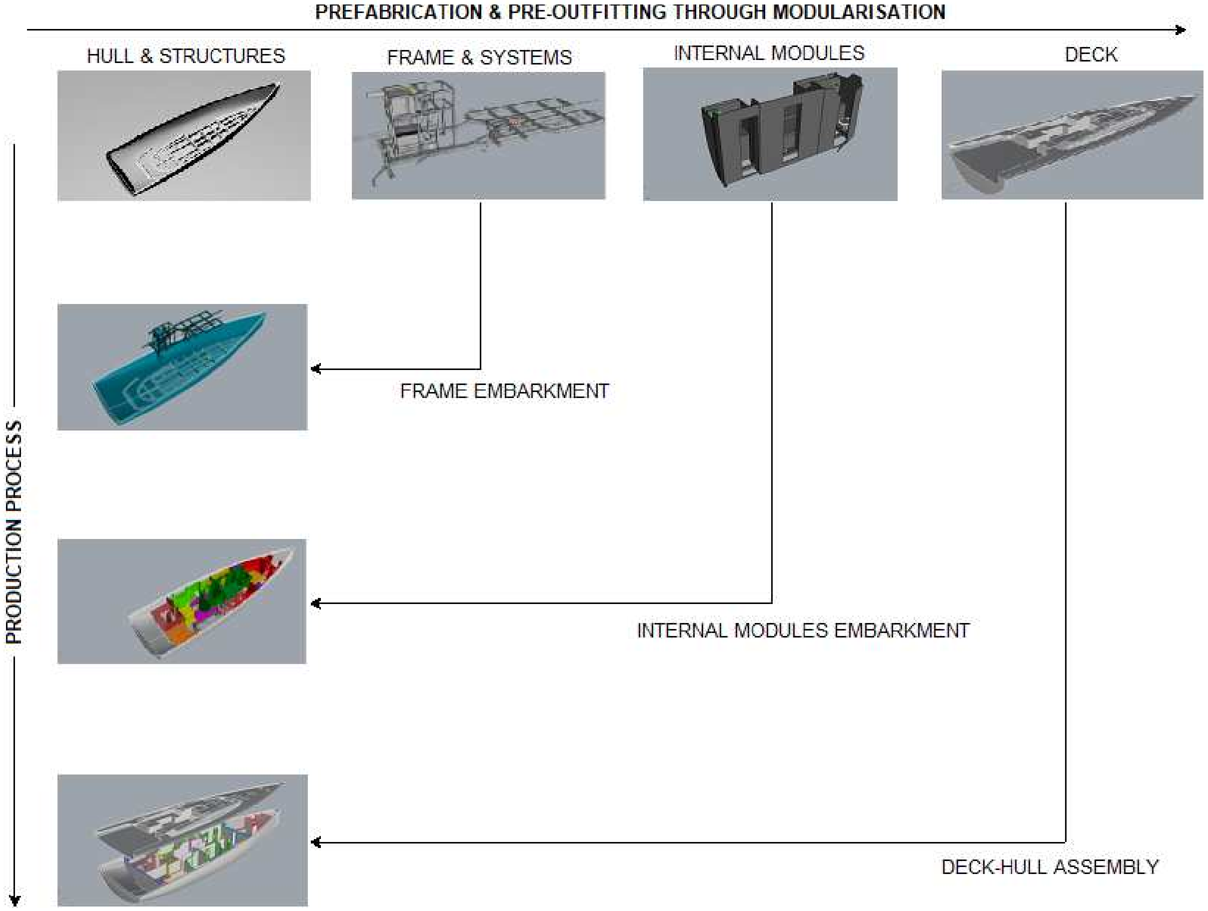

Figure 8. Implemented prefabrication and pre-outfitting strategy.

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