Design Management and Advanced Technologies in the Development and Production of a Modern Recreational Craft

Vitor Carneiro, Francisco Cálão, Jorge Lino Alves, and Augusto Barata da Rocha

Abstract The Recreational Craft Production (RCP) sector has undergone important advances in the last decade, mainly due to the incorporation of design management and advanced technologies in product development, prototyping and production. The RCP sector, that represents in Europe more than €20 billion in annual revenue, is a highly competitive sector with important challenges related to design, productivity, competitiveness, safety and environmental requirements. This paper describes the complete stages of product development/production of a modern craft using design management concepts, CAD/CAM/CAE technologies, FEM simulations for structural stability and flow simulation of the friction interface hull/sea water. A modern multi-step hull is developed to reduce friction and the corresponding pressure distribution is analysed and compared to the corresponding traditional hull (without step). The coordinates of the centre of mass, centre of buoyancy and waterline are calculated. The longitudinal and transversal stability is analysed and the Gz curve presented, for both cases. The calculations show that the introduction of a stepped hull has a major influence on the pressure distribution under the hull and on the final coordinates of the centre of buoyancy. The mould design of both hull and deck is

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presented and a technique for interference and clearance evaluation for demoulding, before CNC machining of the moulds is applied. Additive manufacturing, used to produce scale models of the final craft, demonstrates major benefits to improve design and to discuss commercial and technical issues. Different alternatives of manufacturing processes (hull and deck) are analysed during the production phase. Finally, the application of design management, additive manufacturing and advanced technologies allows a reduction of time-to-market, the successful achievement of the final reviewed specifications of the craft and the increase in competitiveness and productivity of the final product.

Keywords Design management · Product development · Recreational craft · SME's

1 Introduction

One of the first records of the use of recreational crafts dates from the beginning of the seventeenth century in Holland, when crafts were created for sports and leisure purposes, for use by nobles and kings with the intention of celebrating the arrival of large merchandising ships (Kobbé 1914).

These recreational crafts were initially built in wood, with classical techniques of naval architecture. The first patent related to fiberglass was awarded to the Prussian inventor Hermann Hammesfahr (1845–1914) in the United States of America in 1880 (Hammesfahr 1880; Mitchell 1999). A suitable resin for combining the fiberglass with a plastic to produce a composite material was developed in 1936 by DuPont. The first produced composite craft is credited to Ray Greene of Owens Corning in 1937 (Marsh 2006).

The sales of recreational crafts began to have some commercial success only from the mid-nineteenth century, with the beginning of nautical races in Europe and the United States of America (Boats 2018). However, the Second World War stagnated de development and production of the fiberglass recreational crafts, despite their crucial role, when hundreds of crafts crossed the Channel to the French port of Dunkirk between 27 May and 4 June 1940. Fishing boats, pleasure yachts and lifeboats—known as the little ships—were all pressed into service to rescue hundreds of thousands of British, French and Belgian soldiers who had been forced back to the coast in the face of the German advance across Europe. This event was officially called "Operation Dynamo" and proved to be a pivotal moment of the Second World War (Press Association 2015).

The beginning of high competition nautical sports helped to popularize this composite, due to the advantages it presents, making the craft lighter and cheaper and consequently more competitive (Mitchell 1999).

Historically, Portugal has always been recognized worldwide as a country with very strong connections to nautical activities, from the time of the Discoveries (1415–1543), a period that allowed a revolution in the maritime industry, to the present day.

In 1964, Manuel Alves Barbosa, was invited by the King of Morocco to participate in a powerboat race. Fascinated by the fiberglass technology and potential of this new method of shipbuilding, highly resistant, maintenance-free and with an unparalleled versatility of innovation and series construction, Manuel Alves Barbosa started the negotiations that culminated in the creation of the Barbosa e Sciacca Lda. shipyard in Aveiro. This was the first Portuguese shipyard to produce fiberglass crafts and one of the first at European level, later called Riamar.

In the last decade the nautical market has seen a remarkable growth. As it is an extremely competitive market, in which new models are manufactured annually, equipped with innovative technologies and appealing design, companies in this sector are forced to periodically introduce new models on the market. It is in this context of growth of this industry that Nautav (owner of the Riamar), in partnership with the DesignStudio of the Faculty of Engineering of the University of Porto (FEUP), started a new approach of craft design and production combined with design management procedures, with the development of a new models, in order to expand its currently offer currently.

This paper is structured as follows. In the first section an integrated approach of design management is presented with the identification of the main topics and parameters for design management during the product development process in the context of Small and Medium-Sized Enterprises (SMEs). In the second section, the stages of the product development of a modern recreational craft are presented. A modern multi-step hull is developed to reduce friction, to increase performance and reduce consumption. In the third section stability calculations and FEM flow simulations of the pressure interface hull/sea water were performed and analysed. A comparison between the developed multi-step hull and a traditional hull (without step) is analysed. In the fourth section, the prototypes production is described. In the fifth section the mould fabrication and corresponding craft production is described. Finally the main conclusions are presented.

2 Design Management Integration

Design management in the context of SMEs is particularly important and challenging. These organizations face numerous financial and human resource constraints; and sometimes they lack the design skills and experience they need (Oakley 1982) which means they must find those competences and resources externally. In addition, and unlike large companies, many SMEs have no formal methodology to frame design development (Berends et al. 2011) and run on outdated management models (Alarcon et al. 2015) designed to be rigid and isolated which block their desired strategy from becoming reality.

Given the value that design can contribute to business performance for SMEs (Berends et al. 2011; Bruce et al. 1999; Chiva and Alegre 2009), optimizing the product development process and its management have become strategic imperatives. The design process, however, requires input from multiple disciplines, and may consist of several integrated methodological approaches. SMEs may not have the required expertise in house, and so the company and external project contributors may conduct the process jointly.

In a previous publication (Carneiro et al. 2021) the authors presented a survey and analysis of the literature identifying the key parameters, dependencies, and connections involved in SME design management (at the operational level) during the product development process. It was shown that parameters of design management involved in the SME product development process are complex, as are the connections between them. At the heart of the SME, product development process are a complex sets of design management parameters and dependencies that require careful consideration (Fig. 1). Each of the five aspects of design management comes with a set of relevant subtopics directly or indirectly related to each other. Their connections become even more intricate once the sub-connections that also occur between the subtopics of different aspects are considered—all of which are combined to create a complex web of interdependencies. For example, in the "Managing Design Projects" group, the "Project Design" subtopic is sub-connected to the "Design Coordination" and "Design Skills" subtopics of the "Design Management Capabilities" group (marked with a dotted yellow line). To exemplify this complexity, and render it visible, we have chosen to depict potential connections and sub-connections among subtopics using a single, continuous, graded line between groups. More sub-connections exist, attesting the complexity inherent in the relationships among all these aspects of design management.

The process of innovation in the manufacturing of new crafts at Nautav company was accompanied by a detailed analysis and internal discussion of each of the parameters, described in Fig. 1, to assess their potential and constraints. In a pilot study, each parameter was evaluated quantitatively and qualitatively, allowing a realistic

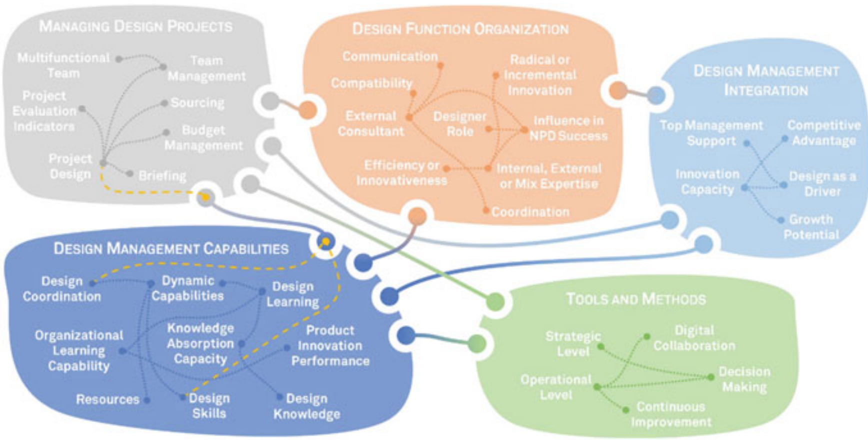

Fig. 1 Map of the main topics and parameters for design management during the product development process in the context of SMEs

image of the company's strengths and weaknesses in each of the multiple areas that constitute the design management. This methodology allowed the identification of critical sectors of this innovation process and taking measures to mitigate them. It was identified that the Design Function Organization was the most critical area that had to be reinforced with higher commitment at the top management level.

This pilot study also made possible to obtain a clearer and more structured image of the main topics and parameters for design management during the product development process in the context of SMEs, which will allow the development of a future structured methodology for the implementation of a design management policy in SMEs.

3 Recreational Craft Product Development

Recreational crafts are classified according to category, craft typology and propulsion system (DGRM 2018). The craft developed in this project is category C, considered suitable for winds of force equal to or less than 6 on the Beaufort scale and waves with an indicative height equal to or less than 2 m; the typology of the craft is constituted by deck and hull joined at the boat fender zone (Fig. 2), with structural pavement and equipped with an outboard engine.

The hull is the main structure of most marine crafts, allowing the boat to float and withstand the forces resulting from the weight of the rest of the structure and crew. The deck is the permanent cover over the hull, which, in addition to protecting against the outside elements, also provides structural reinforcement to the hull. On recreational boats, the deck is the social area where passengers spend most of their time. The hull and deck are joined in the area of the fender, a rubber, wood or stainless steel strip that has the function of absorbing shocks between crafts or between the craft and the pier(s).

Considering the target market, Nautav defined the specifications with all the project requirements, of which the following stand out:

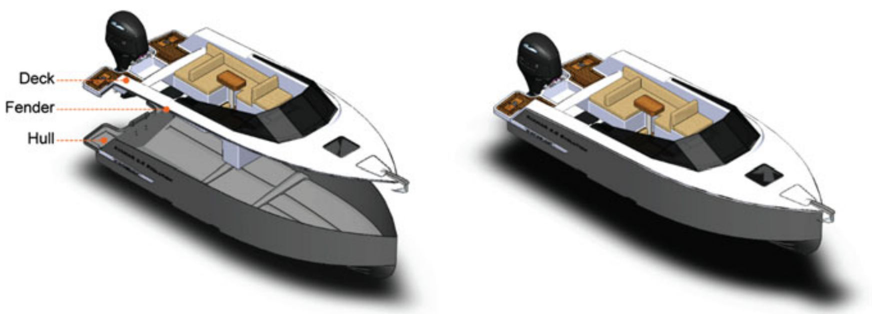

Fig. 2 Hull, deck and fender zone of a recreational craft

- Length of the craft (not including the engine) from bow to stern of 6.5 m and a maximum width of 2.5 m;
- Possibility of assembling several deck versions with the same hull, allowing the creation of a new line and expanding the offer;
- Craft equipped with an outboard engine from 130 to 250 hp;
- Deck coated with non-slip synthetic teak;
- Finishing of the boat with gelcoat to avoid painting;
- Production of the craft through manual moulding or, alternatively, by infusion, without ever losing the quality of construction and finishing that characterize Riamar crafts. Through this fully automated process, it is possible to minimize the joints between hull and deck and the finishing work. In addition, this process is fully automated, minimizing human error;
- Finally, a hull with a double step. The step (Fig. 3) is a transversal cavity that runs along the hull from side to side, and comes high enough on the side of the craft to reach above the waterline. As the craft moves forward, the side air inlets of the cavity allow to create a "cushion" of air bubbles into the cavity creating a low pressure zone and as result drag forces that the water causes on the hull decrease (Rudow 2012). The advantages of using this technology consist of a reduction in drag and friction forces, resulting in a greater ability of the craft to reach higher speeds compared to a craft without a step (traditional hull) and to obtain better efficiency in fuel consumption.

The modelling of the craft was performed using 3D CAD software, through surface and solid modelling. Initially, each component of the craft was individually modelled, followed by assembly and respective analysis of minimum and maximum clearances and interference between the various components (Fig. 4). Additionally, the moulds and inserts of the hull and deck were also modelled and the respective assembly was carried out. This analysis allowed simulating the demoulding process, verifying the existence of interferences and their causes, thus avoiding and anticipating errors in the production phase (Fig. 5). This phase is complex with multiple iterations of modelling, assembling, simulation and analysis, until the desired result is obtained.

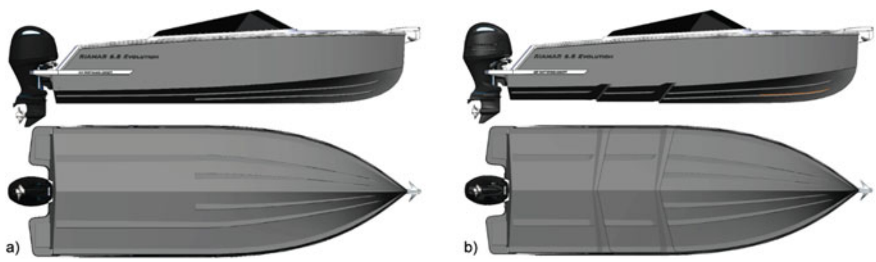

Fig. 3 Traditional hull (**a**) and multi-stepped hull (**b**)

Fig. 4 3D modelling process: **a** individual modelling of components; **b** components assembly; **c** analysis of interferences and clearances of the various components

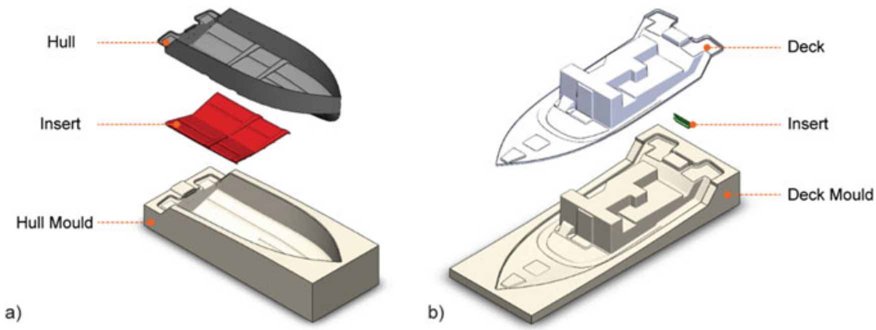

Fig. 5 3D model of the mould and insert of the hull (**a**) and deck (**b**) to simulate the demoulding process

4 Stability Calculations and Flow Simulation (FEM)

The static analysis of longitudinal and transversal stability makes it possible to understand the behaviour of the craft in the water, namely its centre of gravity (G), the waterline, centre of buoyancy (B) and the maximum heel supported by the craft. The dynamic analysis of the craft, using the finite element method (FEM), allowed the simulation of the boat wake, pressure distribution on the surface of the hull and the drag force caused by the water when in contact with the hull. To understand the analyses carried out, it is necessary to understand the different concepts related to the longitudinal and transverse stability of a craft.

4.1 Basic Principles

4.1.1 Archimedes' Principle, Displacement, Centre of Gravity and Centre of Buoyancy

Archimedes' principle states that the upward buoyancy force that is exerted on a body immersed in a fluid, whether fully or partially, is equal to the weight of the fluid that the body displaces. Archimedes' principle is a law of physics fundamental to fluid mechanics (Oliveira and Lopes 2013).

The weight of the fluid displaced by a craft is known as *Displacement*, and the displaced water creates an upward force, or buoyancy force, which is equal to the weight of the craft. The displaced water has a centre of mass, or *Centre of Buoyancy* (B), which varies according to the shape of a craft's hull and keel. The weight of a craft is distributed along its length, pushing the entire craft downwards. All the weight acts downwards through its *Centre of Gravity* (G).

4.1.2 Longitudinal Stability

In static equilibrium, the centre of gravity (G) and the centre of buoyancy (B) are aligned with z-axis (Fig. 6).

4.1.3 Transversal Stability, Angle of Heel, GZ Curve, Angle of Vanishing Stability (AVS)

To keep a craft stable in the water and prevent it from leaning over, the centre of gravity needs to be as low as possible. When the craft is in the upright position, the centre of gravity (G) is aligned vertically with the centre of buoyancy (B) and there's no righting lever (Gz). If the craft heels to the wind or waves, the centre of buoyancy (B) will move to laterally and a righting lever (Gz) is generated (Fig. 7).

Figure 8 shows a typical Gz curve (or Righting Moment Curve or Curve of Static Stability). When the craft heels, the righting lever (Gz) will increase to a maximum (60° of heel in Fig. 8). If the craft continues to heel the righting lever (Gz) starts to reduce until it reaches zero again (130° of heel in Fig. 8). This point is called the

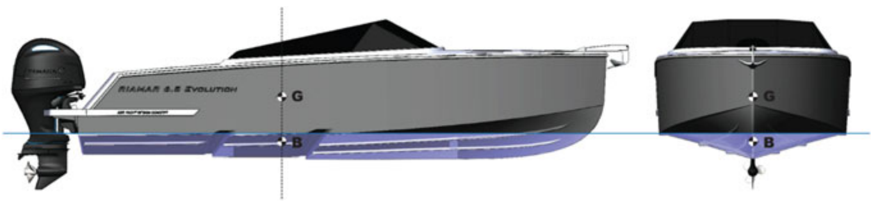

Fig. 6 Centre of gravity (G) and the centre of buoyancy (B) aligned with z-axis

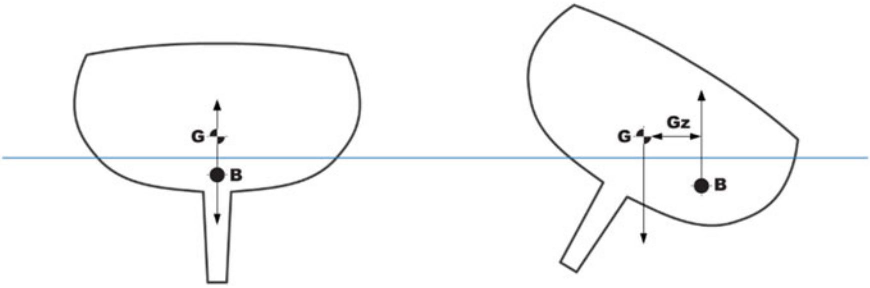

Fig. 7 Centre of gravity (G), Centre of Buoyancy (B) and Righting lever (Gz). Adapted from Simpson (2022)

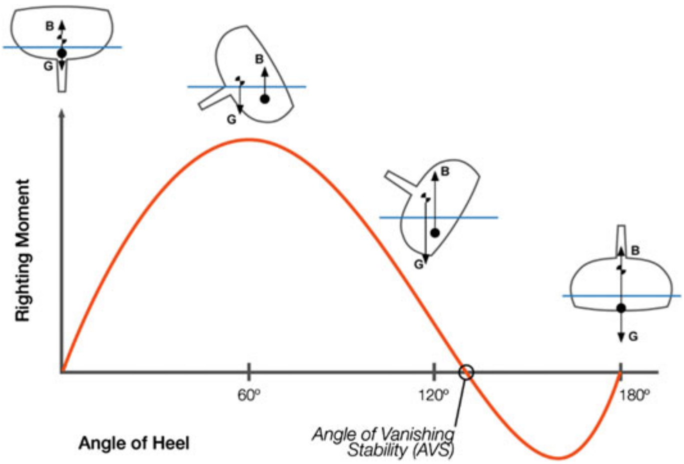

Fig. 8 Gz curve and he angle of vanishing stability (AVS). Adapted from Simpson (2022)

Angle of Vanishing Stability (AVS), also known as the Limit of Positive Stability (LPS). If the angle of heel exceeds the AVS the righting lever (Gz) will become negative and will act as a capsizing lever rather than righting lever.

Righting Moment Curves (Gz curves) are published by craft manufacturers to show the stability characteristics of their crafts designs. In Europe, the Recreational Craft Directive (RCD) states that recreational crafts between 2.5 and 24 m must carry builder's plates to categorize their boats in either Category A (Ocean), B (Offshore) or C (Inshore) and meet minimum standards of stability.

4.2 Longitudinal Stability Calculations

Using CAD software, the centre of gravity (G) was calculated using fiberglass density of 2440 kg/m^3 and the weight of a 200 hp engine was also considered. The total estimated weight of the boat was 1531 kg. Figure 9 shows the centre of gravity (G) along x and z axis and their coordinates (mm).

The craft's waterline was calculated by equalizing the buoyancy force and the craft's' total weight. The coordinates of the centre of buoyancy (B) are obtained from the centre of gravity of the displaced water (Fig. 10).

For longitudinal stability on a craft it is necessary that the centre of gravity and the centre of buoyancy are vertically aligned, while the keel is parallel to a horizontal plane. Comparing the previous two figures, it can be seen that the x-axis position of the centre of gravity must be pushed forward ~147 mm so that the craft is in a horizontal position and longitudinal stability is guaranteed. With the addition of other essential components of the craft such as the mooring system, cabin furniture and navigation systems it is possible to correct this difference.

The following graph (Fig. 11) shows the evolution of the buoyancy force and corresponding centre of buoyancy (B) with increasing water line levels. The blue horizontal

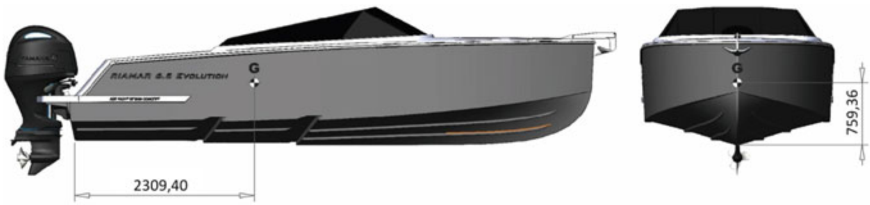

Fig. 9 Centre of gravity (G) of the designed craft (dimensions in mm)

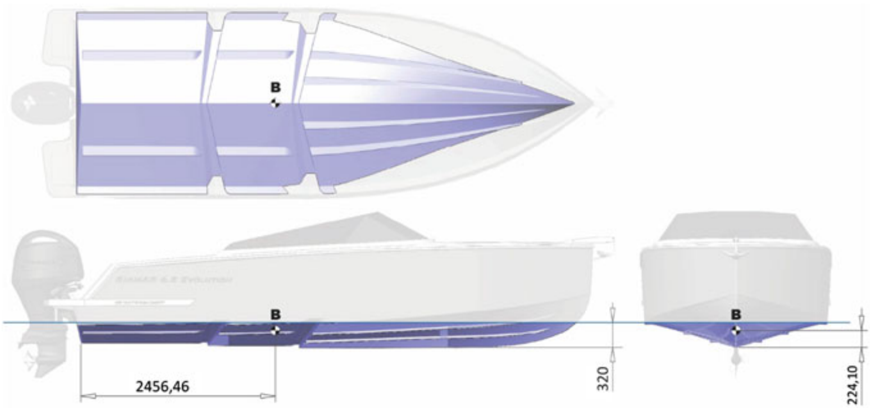

Fig. 10 Calculation of the waterline and the centre of buoyancy (B) (dimensions in mm)

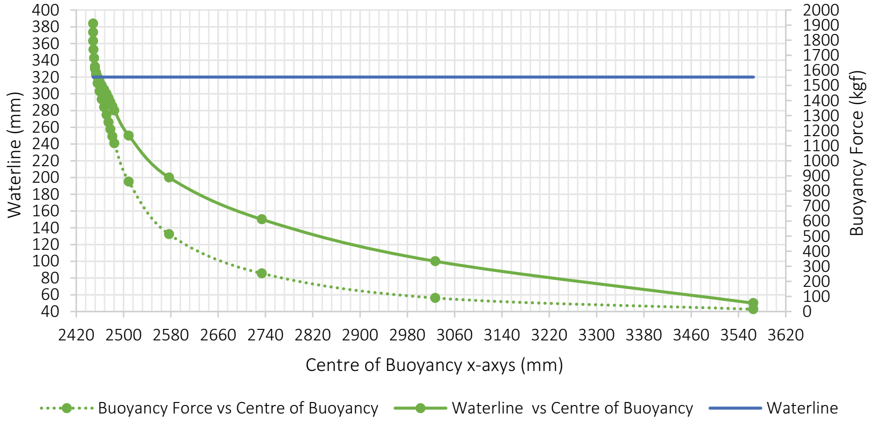

Fig. 11 Longitudinal stability of the designed craft

line corresponds to the craft's final waterline (320 mm of draft) and corresponding centre of buoyancy (B).

4.3 *Transversal Stability Calculations*

The calculation of the transversal stability allowed to obtain the Angle of Vanishing Stability (AVS). The Righting Lever (Gz) and the corresponding Righting Moment (RM) values were calculated for each angle of heel. The craft was rotated around its centre of gravity (G), through an axis parallel to the x-axis (longitudinal direction of the craft). For each heel angle the waterline was calculated by equalizing the buoyancy force with the weight of the craft. The following graph (Gz Curve) (Fig. 12) shows the Righting Moment (RM) for each angle of heel. As it can be seen in the graph, the AVS is 89°.

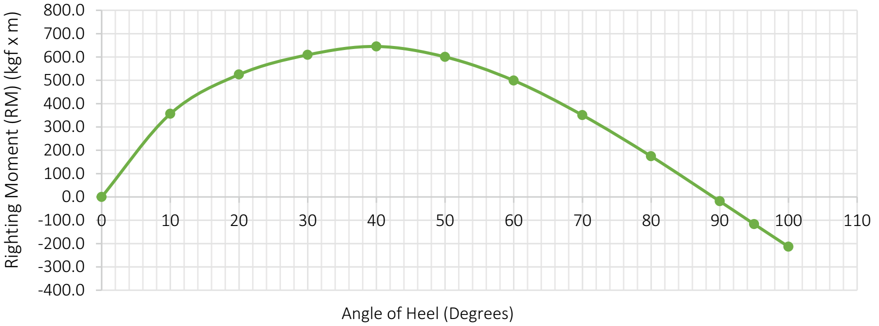

Fig. 12 Transversal stability (Gz curve) of the multi-step hull

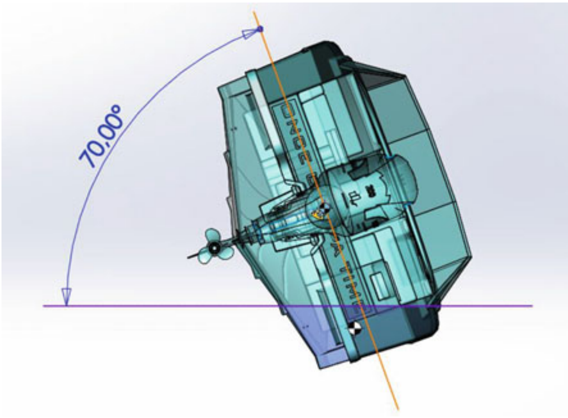

Fig. 13 Maximum angle of heel of the designed craft

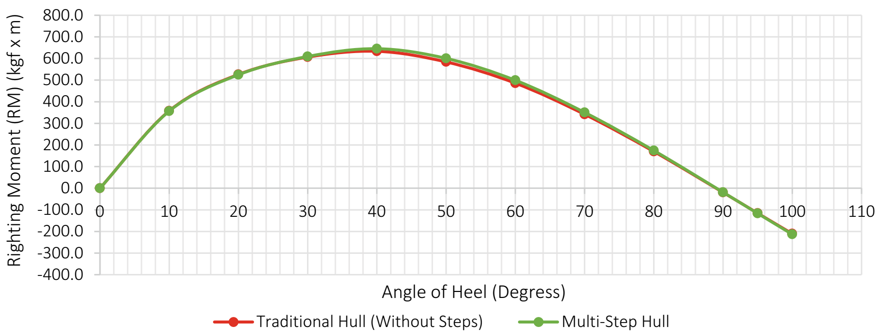

Fig. 14 Comparison of transversal stability (Gz curve) of the multi-step hull and the corresponding traditional hull

However, due to the craft pit edge, the maximum angle of heel is lower, it is limited to 70°, as shown in Fig. 13. If the crafts exceeds the heel angle of 70°, water will start overflowing the edge.

Figure 14 shows a comparison of the righting moment of the multi-step hull with the corresponding traditional hull (Gz Curve). As it can be seen, from a transversal stability point of view, the two hulls are very similar.

4.4 Dynamic Analysis

This chapter describes the dynamic analysis of the craft's performance in open water. For comparative and analysis purposes, both the hull with the double step and without the step, known as the traditional hull, were simulated. For the analysis, the add in

Flow Simulation, from the SolidWorks software, was used to obtain the CFD simulations, introducing parameters related to atmospheric conditions and the behaviour of the fluid.

4.4.1 Simulation Parameters

To carry out the simulations the following input parameters were defined (Table 1).

The creation of an automatic mesh with advanced refinement was also selected (thinner in the impact zones between the hull and the water) and the simulation volume comprises a length of 33 m, a width of 22 m and a height of 5 m. In order to simulate the trim effect caused by the engine propelling force, an inclination of 5° was assigned (Ghadimi et al. 2014). The total simulation time was respectively 1 h and 13 min for the traditional hull and 1 h and 15 min for the multi-step hull.

4.4.2 Results

Figure 15 presents the flow disturbance caused by the craft displacement at 16 knots. As it can be seen, the traditional hull creates higher disturbance than the multi-step hull. This means a lower drag of the multi-step hull leading to increased performance and fuel consumption reduction. In this analysis wave effect of water surface was not considered.

In Fig. 16 it is possible to observe the pressure distribution in the hull surface resulting from the 16 knot speed. The traditional hull presents a smother pressure distribution in middle region of the hull. However, the multi-step hull presents lower pressures (green regions) at the peripheral region of the hull which creates a desired air suction effect and resulting air bubble cushion that reduces drag and increases

Table 1 Parameters and values used in the simulations

Parameters	Type/value
Flow analysis	External
Total analysis time	10 s
Output time	1 s
Type of flow	Free surface
Fluids	Air and water
Regime	Laminar and turbulent
Thermal condition on the surface	Adiabatic walls
Pressure	101,325 Pa (1 atm)
Temperature	293.15 K (20 °C)
Speed	16 Kn (8.23 m/s)
Water line	0.290 m (traditional hull) 0.320 m (multi-step hull)

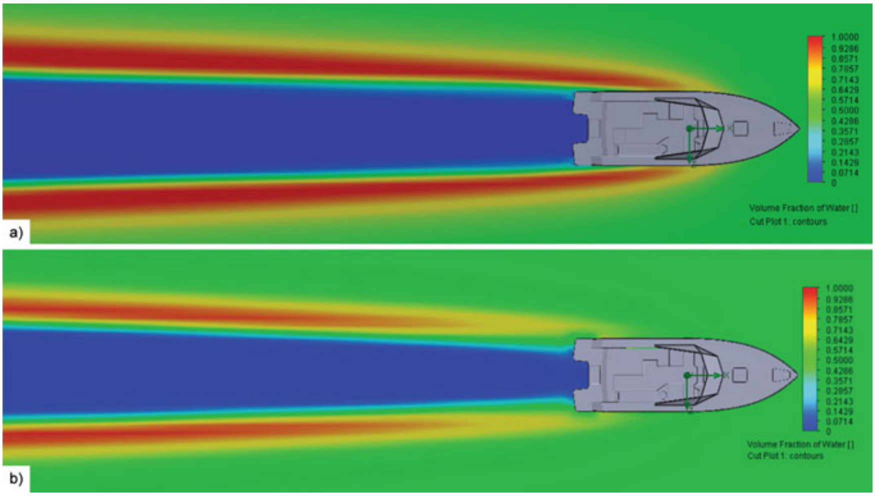

Fig. 15 Water flow disturbance at a speed of 16 knots: **a** traditional hull; **b** multi-step hull

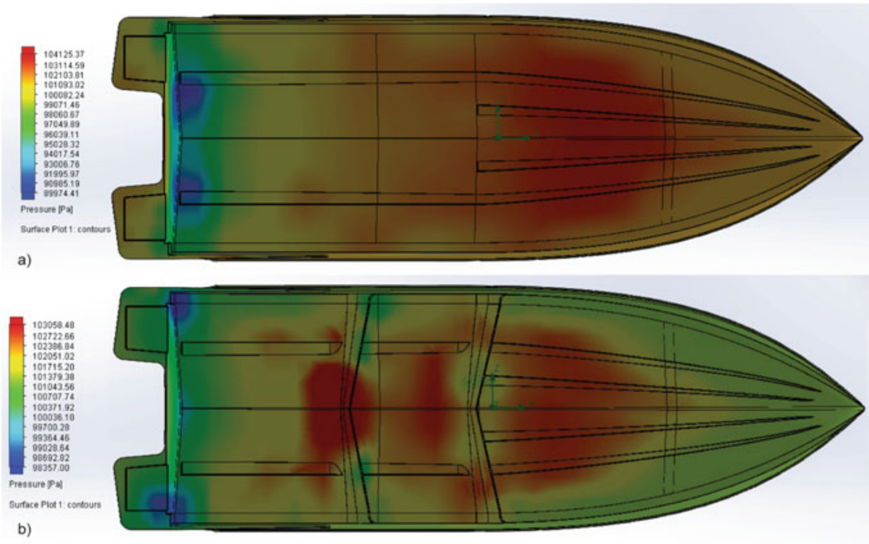

Fig. 16 Hull pressure distribution at a speed of 16 knot: **a** traditional hull; **b** multi-step hull

performance. It is also observed that the lowers pressures (blue regions) in the stern region are more peripheral in the multi-step hull and more central in the traditional hull leading to increased transversal stability for the multi-step hull.

5 Prototypes Manufacturing

To validate the design and global structure of the craft, prototypes were produced by 3D printing using the fused filament extrusion (FFF) manufacturing process, at a scale of 1:20. For the printing of the prototypes, a Prusa i3 MK3S printer was used with a 0.4 mm nozzle fed with PLA (*Polyactic Acid*) filament of 1.75 ± 0.05 mm in diameter, where a layer resolution of 0.15 mm was used. It is also important to highlight the fact that the craft is printed in two separate parts, due to its size being greater than the capacity of the printing table (Fig. 17a, b). In total, it took 267 h of printing and 1765 g of filament. FFF technology allows the production of parts with good quality and mechanical strength. In addition, and by the same process, moulds (positive and negative) of the hull and deck were also produced at a scale of 1:40 (Fig. 17c).

For the 3D printing of the engine, PolyJet technology was used, which allows the production of thin-walled parts, complex geometries and intricate details. Additionally, it enables to create parts with movements with a single print, which is the case of the engine (two degrees of freedom: steering and trim). The engine was printed on an EDEN 260 V equipment (Stratasys), with deposition of 16 μm light-curing acrylic resin layers. Vero Gray material was used, with a total printing time of 1.5 h, with a consumption of 76 g of construction material and 51 g of support material (Fig. 18).

The successive iterations of the hull and deck design supported by prototypes manufactured by 3D printing allowed to reach optimized final versions, both in terms of design and in terms of the production process (Fig. 19).

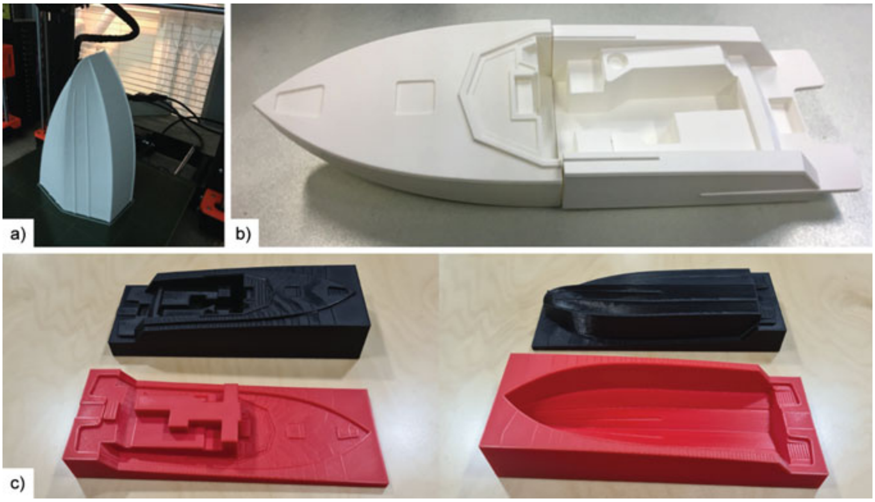

Fig. 17 3D printing by extrusion of fused filament of the designed craft at 1:20 scale (**a** and **b**) and the respective moulds at 1:40 scale (**c**)

Fig. 18 3D printing of the craft's engine using PolyJet technology

Fig. 19 Prototypes produced by additive manufacturing: *Walkaround* version, *Open* version and *Classic* version (from left to right)

The production of prototypes by 3D printing brought competitive advantages, in a faster and less expensive development process than traditional methods (CNC, injection moulding, among others). The prototypes created are faithful to the final craft, as the smallest details are replicated. The use of these technologies made it possible to analyse design errors in more detail, study and optimize the final manufacturing process and quickly collect relevant feedback from the different sectors of the company (design, commercial, and production), which would hardly be achieved only with the visualization of the 3D model on a screen.

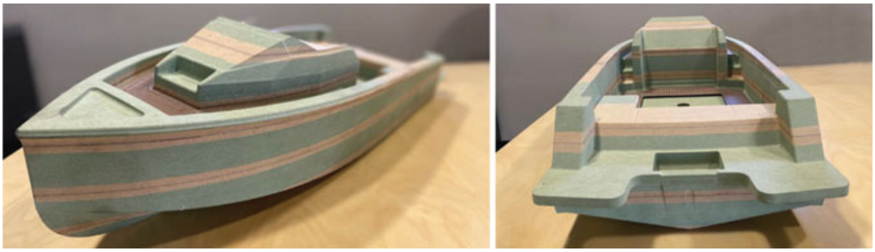

Fig. 20 Unfinished prototype manufactured in MDF by a CNC drilling machine

After the achievement of the final geometry and craft design supported by additive manufacturing, new prototypes at a larger scale (1:10) were manufactured in MDF by a 5 axis CNC drilling machine, for commercial and demonstration purposes in a nautical exhibition fair, thus collecting the reactions of the target audience to the new model (Fig. 20).

6 Production Process

The production process starts with the manufacture of male plugs for the hull and deck, from which female fiberglass moulds reinforced with a steel structure will later be produced. The male plugs will be manufactured in a 5 axis CNC drilling machine, from Optima with a working area of 10 m length, 3.5 m width and 2 m height. These male plugs geometries will be manufactured in polystyrene and polyurethane foam coated with appropriated resin paste from Sika and finally fine machining of the final surfaces to achieve a smooth and accurate surface.

Fiberglass moulds reinforced with a steel structure will be then manufactured from the previous described plugs. These moulds will allow manual fiberglass fabrication as well fiberglass infusion process. The mould is first sprayed with gelcoat, then fiberglass cloth is applied, and then resin is used to saturate or "wet out" the fiberglass. After curing, a hull or a boat part will be obtained (Fig. 21).

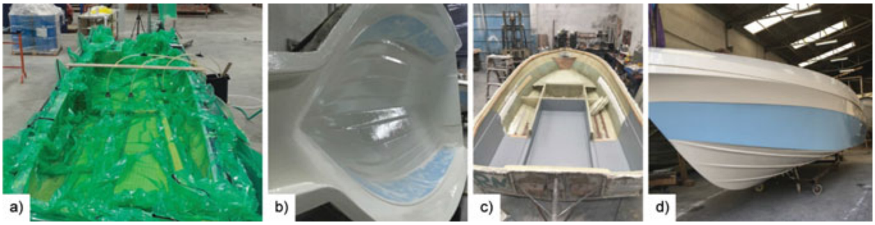

Fig. 21 Craft production process: **a** fiberglass infusion process of a hull; **b** gelcoat sprayed into the mould; **c** fiberglass cloth saturated in resin in the curing process; **d** craft hull after demoulding

7 Conclusions

This paper presents the innovation path for the design and development of a modern recreational craft using advanced technologies of computer-aided design and manufacturing (CAD/CAM), numerical simulation by finite elements (FEM) and additive manufacturing. Design management concepts were analysed from an integrated point of view to assess the internal management and technological capabilities. This analysis allowed to identify the key resources of the company that had to be reinforced as well as the external partnerships needed to accomplish the innovation procedure.

Three-dimensional digital models were created, analysis of static stability of the craft was carried out, FEM simulations were performed to validate the advantages of the two-step hull, and prototypes of different scales were fabricated, allowing the development of a continuous, iterative and flexible creative process, leading to the optimized final solution with the support of the company's internal competences and complementary academic skills.

Through the partnership with University of Porto it was possible to transfer academic/scientific knowledge to the company, leading to a significant technological upgrade. Through this partnership it was possible to shorten the development time of the new model, reduce manufacturing and assembly time, simultaneously designing new production strategies.

This project also made it possible to obtain a clearer and more structured image of the main topics and parameters for design management during the product development process in the context of SMEs, which will allow the development of a future structured methodology, for the implementation of a design management integrated policy in SME's.

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