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Toward More Sustainable River Transportation in Remote Regions of the Amazon, Brazil

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Abstract: This paper explores means of achieving more efficient and sustainable river transport in remote regions by making relatively simple, practical modifications to boats or implementing new technologies for propulsion and energy generation. The research focuses on the case of the simple boats used to transport children to school in riverine communities of the Brazilian Amazon. A range of options to improve the efficiency of existing boats is described. Under normal operational conditions, small improvements to these boats may have long-term environmental and socioeconomic benefits. Implementing changes such as those suggested, it may also be possible to boost sources of employment in these regions and elsewhere, where industrial and technological limitations are significant.

Keywords: efficient transport; riverine communities; sustainable cities; renewable energy; environment

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1. Introduction

Navigation using small boats is one of the main means of transport for remote riverine communities in many developing countries [1]. Often, such boats are the only way to access islands and other remote localities [2], and they become multi-purpose boats, used for passengers and cargo, as well as offering a wide range of services to the community, such as transportation of students to schools [3,4]. In the United Nations Goals for Sustainable Development [5–7], the fourth and tenth objectives are to provide quality education and to reduce inequalities between all peoples. In many parts of the world, to travel to their school, students have no alternative but to use small boats, sometimes on quite long journeys. In the Brazilian Amazon, it is estimated that in around 350 riverine communities, this type of river transport is the only means their children have to travel to school [8]. In remote regions, efficient, sustainable river transport for daily activities is required [9–11]. In several Amazonian regions, most riverboats are designed and constructed locally, using traditional shipbuilding techniques inherited over generations [12], rather than modern technological methods [12–14]. Despite the vital importance of these boats, they are often inadequate vessels, which may be slow and vulnerable to rain, winds, and currents, exposing the users to risk and discomfort [15,16].

Navigation in the Amazon waterways is mainly regulated by the Brazilian Navy, which establishes the minimum requirements for vessels [17]. However, in remote regions, it is often difficult to implement statutory shipbuilding and operational procedures when regulation is scarce [16,18,19]. This may have effects on the stability of the vessels used, human safety, and fuel consumption. Making the small boats used in remote regions safer, more efficient, and sustainable could help to minimize accidents and to preserve protected areas [20,21].

To improve the efficiency of boats used for river transport, factors related to the reduction of hydrodynamic resistance and improving the propulsion system must be addressed [22]. To find the optimal configuration of a specific boat for different operational conditions, detailed analyses of the interaction of the hull, engine, shaft, and propeller are required, as described by [23,24]. This generally requires advanced study, not often found in the small shipyards of remote river communities [25], where the components of a propulsion system are often selected based on previous empirical experience [12], with outboard engines being the most common choice for small riverboats. One means of improving the performance of boats is to implement permanent modifications to the hull, perhaps by optimization methods. This could possibly lessen the hydrodynamic resistance [22,26–31] and fuel consumption for specific operational conditions. Small modifications to the shape of the hull of an existing boat could easily be carried out in any small shipyard, even in a remote river community, and bring a permanent improvement to increase the performance of the boat [32]. Another area that can be looked into is the incorporation of hybrid technologies, that is, combining clean, renewable energy with traditional fossil fuels [22,33–36].

Research on improving hull shape is not new [28,29]. In fact, several works have investigated the optimization of ship hulls and the effects this has on performance [26,37–41]. Such optimization is commonly carried out using Computational Fluid Dynamics (CFD) methods, which are often applied in algorithms that allow numerical tests to be performed to reduce the hydrodynamic resistance of a vessel in various operational conditions, as reported by [37,38,40]. Similar work has examined the optimization of the hulls of ocean renewable energy devices [42–44], large commercial ships [45,46], and high-speed vessels [47,48]. Aside from hull optimization methods, other means could increase the performance and sustainability of small transport vessels. In this study, we aim to fill this gap. An integrated study is proposed to explore different ways of improving the efficiency and sustainability of existing boats that perform river transport activities in remote regions of developing countries. In many such cases, attaining sustainability is crucial in the face of environmental and socioeconomic restrictions. This paper examines the case of transporting school students by small boats in riverine communities in the Amazon region.

The study is divided as follows: Section 2 describes the main considerations to improve the efficiency of the boats. Then, Section 3 presents some challenges of scholar transport in the Amazon region, including a brief discussion of possible environmental and socioeconomic impacts. Finally, Section 4 presents different means of improving the sustainability of the boats, and Section 5 summarizes the main conclusions.

2. Main Considerations to Improve the Efficiency of Boats

There is no direct method to improve the efficiency of the small boats used for riverine transportation in remote regions. In fact, reducing the fuel consumption and increasing the performance of the boat requires several optimization projects since there are different fuel-optimal working conditions for each boat draft and speed [22].

Hochkirch and Bertram [22] explained that there are several ways of decreasing the consumption of fuel by a vessel: reducing the required power for operation and propulsion; using fuel energy for propulsion and on-board equipment more efficiently; and using hybrid technologies for operation, combining fossil fuels with renewables, such as solar energy. According to [22], there are several factors to be considered to reduce the power required for propulsion, thus improving the performance of a ship. These can be classified into improving the propulsion system and reducing the boat's hydrodynamic resistance, as shown in Figure 1. To improve ship propulsion (Figure 1a), the propeller must operate optimally. Propulsion losses due to rotation of the shaft and propeller must be reduced, as must friction loads between the water and the propulsor, as well as those caused by the generation of tip and hub vortices. The propeller must operate in optimal wake conditions. In addition, the efficiency of the interactions between the components of the engine-shaft-propeller system must be maximized to increase the transmission of power delivered from the engine to the propeller.

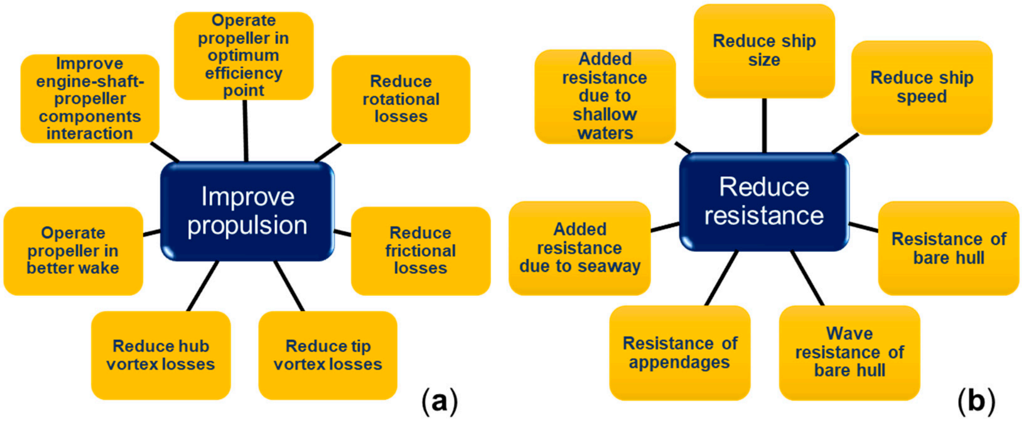

Figure 1. Factors that will reduce the power required for propulsion (**a**) by improving propulsion and (**b**) by reducing resistance. Adapted from [22].

On the other hand, to reduce resistance (Figure 1b), reducing the size of the vessel and its speed may help; however, this practice does not seem to be economically viable for most applications. Other factors that may reduce a vessel's total resistance are: the resistance of the bare hull; the resistance of the waves generated when the bare hull is in motion; the resistance caused by appendages of the hull; the resistance caused by the seaway; the resistance caused by wind; and unexpected environmental conditions. In a practical way, it is possible to define the total resistance of a ship as the sum of frictional resistance (due to the friction of the fluid and the hull surface) and residuary resistance (due to the combination of viscous pressure and the wave-making resistance) [24,49].

Molland et al. [24] describe how current attempts to decrease the hull resistance of vessels are related to speed, trim, added resistance in waves, bow shape, bulbous bows, stern shape, hull shape using CFD investigations, and air-bubble lubrication methods.

As shown in Figure 1, increasing a vessel's sustainability by improving its performance involves several factors. Hollenbach and Friesch [32] explained that a reduction in fuel oil consumption of a vessel depends mainly on its type, speed, and working conditions. Therefore, in systematic studies, some parameters must be kept fixed for experimental and numerical investigations [50–52].

A permanent long-term means of improving the performance of a vessel is to modify the shape of its hull to reduce resistance [26,37–41], as this could yield a constant benefit. Therefore, following Hollenbach and Friesch [32], various means of modifying the forebody, midship, and aft body of the hull shapes of vessels can be considered, as shown in Figure 2. The possible gains that each of these modifications produces in reducing ship resistance can also be analyzed. Although these values are theoretical, they provide a preliminary idea about how permanent hull modifications can be useful. For instance, according to these data, gains of ~2–5% can be produced by optimization strategies applied to the forebody hull form.

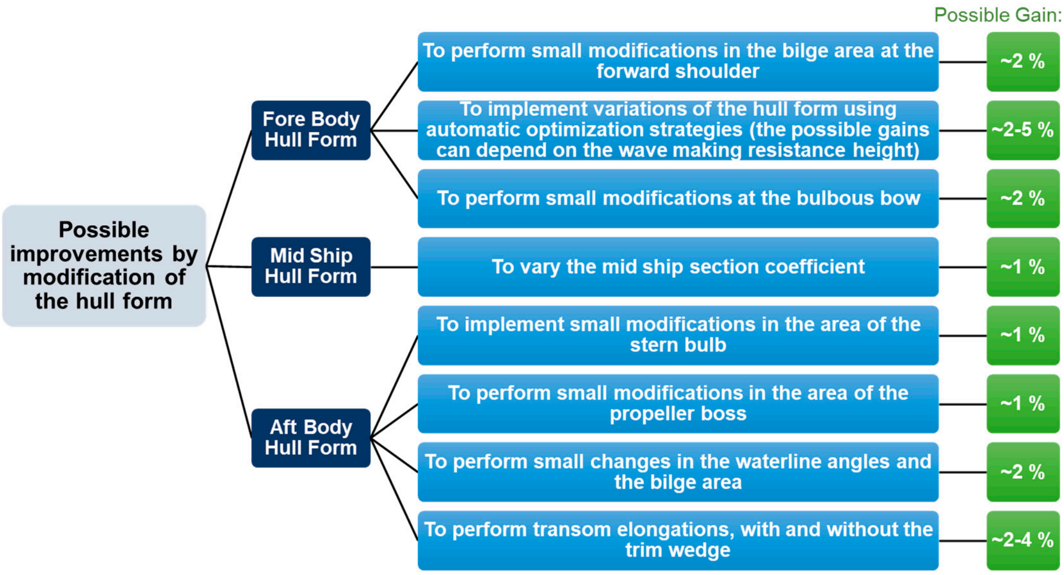

Figure 2. Possible gains in resistance reduction through permanent modifications of the hull, considering that the main dimensions of the vessel and the propeller diameter are unchanged. Modified from [32].

3. Challenges in the Amazon Region: The Case of School Transport

To explore alternatives that improve river transport using small boats in remote regions, the boats used for school transport in small riverine communities of the Brazilian Amazon were considered in this work. In these regions, river vessels are the main means of transport for passengers and cargo. However, the complexity of these waterways, due to their extension and interaction with preserved areas, makes transportation here a daily challenge. Many routes are unmarked. Figure 3 shows some of the river systems in the state of Amazonas, where many students who live in outlying areas use boats to travel to schools in the bigger communities, such as Manaus and Manaquiri.

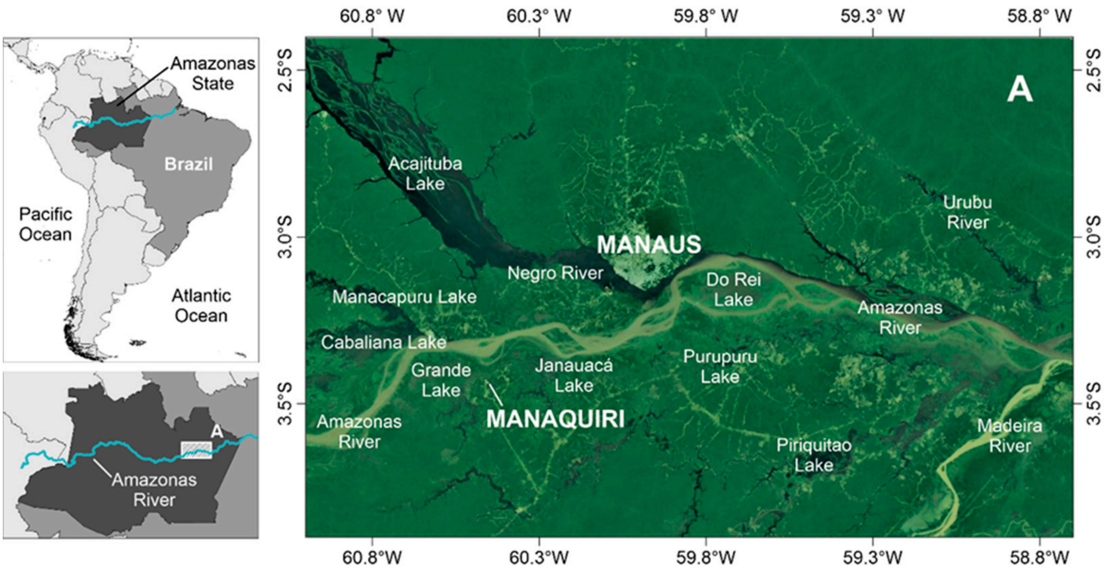

Figure 3. Example of the complexity of the fluvial system around the municipalities of Manaus and Manaquiri, Amazonas State, Brazil. Adapted from Google Maps.

Overall, it is estimated that in the north of Brazil, around 300,000 students use river transport to travel to school [53]. The Secretary of Education for the city of Manaus (Semed) has identified several rural schools that use river transport [54]: 20 on the river Amazon and 29 on the river Negro. Students may pass up to 3 h, twice a day, to travel to and from their school by boat [55], as in the remote communities of the municipality of Manaquiri, on the Amazon, for example, as shown in (Figure 4) [53].

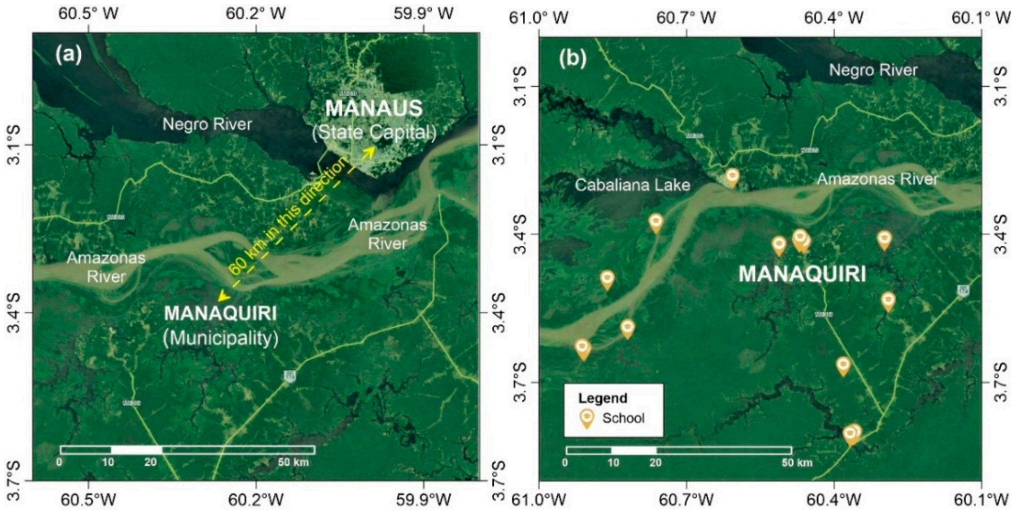

Figure 4. An example of a municipality in Amazonas State where river transport is necessary for education. (**a**) Location of Manaquiri municipality with respect to Manaus, the capital of Amazonas State. (**b**) Location of the main schools around Manaquiri. Adapted from Google Maps.

To overcome the challenges of school transportation, the National Fund for the Development of Education (FNDE) has provided resources for the development of school boats via the Caminhos da Escola (School Paths) program [56]. This initiative aims to offer faster, safer transportation for those using river transport to reach their classrooms. Figure 5 illustrates activities on the rivers related to school transport in the Amazon, Brazil. Figure 5a shows a type of boat widely used for school transport several years ago that is still used for school transport in some regions. Figure 5b,c show the school boats promoted by the local government, and in Figure 5d, these boats are seen at a station in the port of Manaus. Figure 5d shows a school boat performing daily activities in riverine communities. In Figure 5f, a school in Tapauá is presented, and finally, Figure 5g shows a different type of boat used for transporting people in remote regions of the state.

Figure 5. School transport in the state of Amazonas, Brazil. (**a**) An old boat used to transport children to school about ten years ago (Kleyphide Pereira da Silva 2020). (**b**) Front view of an Amazon school boat promoted by the government in

Manaus, Amazonas (Luiz Henrique Moreira Sousa 2020). (**c**) Profile view of the Amazon school boat in Itacoatiara, Amazonas (Fernando V. Dias Balieiro 2013). (**d**) School boat station in the port of Manaus, Amazonas (Harlysson Maia and Francisco Xavier de Carvalho Neto 2020). (**e**) A school boat performing its daily activities in a remote community on the Amazon (modified from [57]). (**f**) A typical school in the municipality of Tapauá, Amazonas (Fernando V. Dias Balieiro 2013). (**g**) A typical boat used for transporting people between remote communities in the state (Fernando V. Dias Balieiro 2013).

3.1. Possible Economic and Environmental Impacts

3.1.1. Economic Impact

As shown in Section 2, improving the sustainability and efficiency of the school boats depends on several factors. While a fuel reduction analysis is beyond the scope of this work, reducing the hull resistance of ships, also applicable to riverboats, may minimize the effort required by the engine and thus reduce the amount of fuel needed [22]. Small changes to the hull shape can reduce hydrodynamic resistance. Based on Figure 2, after hull optimization, it can be assumed that in specific working conditions, the fuel consumption of a typical Amazon school boat is reduced by ~5%. In the long-term, this could produce substantial economic benefits, as the boats travel long distances in areas where access to fuel may be limited. If a typical motorboat consumes an average of ~95 L per hour at cruising speed [58], and the current price of fuel in Brazil is 0.76 $USD/liter (6-26-2020, [59]), with constant activity 8 h per day, the estimated 5% reduction in fuel consumption would provide savings of ~38 L (~29 $USD) per day or ~13870 L (~10,541 $USD) per year for one boat. In a fleet of 10 boats, several thousand liters could be saved per year. This direct economic benefit also has an effect on daily activities in the Amazon region that use similar small boats, such as school transport, food commerce, fishing, health campaigns, and scientific activities.

3.1.2. Environmental Impact

By optimizing the hulls of these boats, the height of the waves they produce may be lessened. As these boats often travel close to the riverbanks, waves can cause erosion through applied shear effects [60]. Lower waves will produce less applied shear, and the riverbanks will be preserved, which, in turn, avoids riverbank instability that can affect trees, shrubs, and plants growing nearby, as well as aquatic species [61].

The reduction in gas emissions due to the use of less fuel is an obvious positive effect of optimizing the riverboats. Some of the greenhouse gases produced by the combustion of fossil fuels in inland navigation [62] are shown in Table 1 [63]. The Intergovernmental Panel on Climate Change [63] proposes emission factors for various types of engines (diesel, gasoline) for marine and inland vessels. A full overview of these for lake, river, coastal, and ocean vessels is found in [62]. Table 1 shows the approximate gas emission factors for European ships and boats on inland waters [63], estimated for four-stroke gasoline engines. In this table, the possible reduction in gas emissions by the optimized school boat is shown per day and per year, assuming the 5% reduction in fuel consumption described in the previous subsection. The reduction in gas emission per day (in grams) was obtained by multiplying the mass of the saved 38 L of fuel (Section 3.1.1), assuming that a liter of fuel weighs 0.750 kg, by the corresponding emission factor (in g/kg fuel). The reduction per day was then multiplied by 365 to obtain the reduction of gas emissions per year (Table 1). The reduction of greenhouse gases by a single optimized boat is seen to be significant, particularly for carbon dioxide (CO_2), which could be reduced by ~33 tons per year. The reduction in gas emissions may also have long-term benefits to the environment. However, it is important to consider other possible external factors related to the adequate functioning of the propulsion system and the operational conditions of the boats, which can sometimes be subject to stochastic environmental interactions.

Table 1. Possible reduction in gas emissions by the optimized school boat.

Gas	Emission Factor * (in g/kg fuel)	Reduction of Emissions per Day ** (in g)	Reduction of Emissions per Year ** (in g)
Carbon Dioxide (CO_2)	3.2×10^3	91.20×10^3	33.28×10^6
Methane (CH_4)	1.70	48.50	17.68×10^3
Nitrous Oxide (N_2O)	0.08	2.28	0.83×10^3
Carbon Monoxide (CO)	1×10^3	28.50×10^3	10.40×10^6
Nitrogen Oxides (NO, NO_2)	9.7	0.28×10^3	10.09×10^4
Non-Methane Volatile Organic Compounds (NMVOCs)	34	0.97×10^3	35.37×10^4

* IPCC default emission factors for European ships and boats on inland waterways for gasoline 4-stroke engines [62,63]. ** Considering fuel density as 750 g/liter.

4. Alternatives to Improve the Performance of Small River Boats in the Amazon Region

Hull optimization is only one means of improving the performance of existing small boats that operate on rivers in remote regions. Other alternatives are shown in Figure 6. Practical engineering guidelines are needed to facilitate hull optimization improvements in the shipyards of the area. These guidelines should include typical specifications of any project, including the requirements of the boat owner, preliminary design, project contract, project planning and detailing, and construction details [64,65]. Considering that shipbuilding and repair is an important economic activity in Amazonas State, with over 10,000 people employed in shipyards [14], it must be possible to facilitate practical hull modifications here.

The various transport activities that take place on the rivers in the remote regions of the Amazon employ different types of small boats that use various means of propulsion [25]. Often, these methods are selected with no regard for the hydrodynamic relation between the propellers and the shape and size of the hull of the boat [66]. Although the adequate selection of the propulsor depends on the hull form and operation conditions [24], the diffusion of guidelines for a proper selection and operation of commercial propulsors in communities can bring positive impacts. Research and development (R&D) initiatives are required to improve existing propulsion technologies for these boats or to encourage a search for new ones [66,67]. The use of hydrogen-based technologies for propulsion could be an alternative in the future [68–71]. Adequate operation of the propulsor is required to reduce possible propeller vibrations since low-frequency noise due to cavitation and a non-uniform wake can have environmental impacts. The frequency band of the sound generated may affect many organisms [24].

Hydrofoil technologies would reduce the hydrodynamic resistance of the vessels. Although hydrofoils are nothing new in marine transport [72,73], their development in remote river regions, such as in the Amazon, would require R&D activities. Modern and efficient concepts could also be considered, such as those recently shown in [74,75].

Current advances in renewable energy technologies mean that boats could be engineered to operate using technologies that combine fossil fuels and renewable energies [76]. Hybrid technologies would make their functioning more sustainable, and various energy resources are available in the Amazon region. In the early stages of innovation, existing commercial technologies could be installed to harness renewable energies at a small scale in the boats, for example, to activate navigation controls or to maintain a backup battery. This battery could then provide illumination for activities performed at night, as needed in remote areas without energy.

Since the solar energy potential in the Amazon can be estimated in tens to hundreds of MWp (Mega Watt peak) [77,78], the potential for photovoltaic (PV) devices is huge. Solar panels could easily be installed on the roof of a boat. There are already some solar-powered vessels in the Amazon region, used for tourism [79] and transport [80]. It is also worth mentioning that solar challenges have been introduced in Brazil, which has encouraged universities and research centers to develop solar-powered devices in national and international competitions [81–83]. The use of solar energy to power marine vessels is currently increasing. For instance, solar energy is being considered by automobile companies for electric yachts [84].

Wind energy could be harnessed using small commercial wind turbines placed on the roof of a boat for small-scale power generation, such as those shown by [85]. Although wind currents are not constant in the Amazon region, these small devices could take advantage of the currents when they occur, thus contributing to battery charging.

With respect to hydrokinetic energy, water currents offer constant availability in the numerous rivers of the region. The flow velocity close to the water surface is small in some rivers (~0.4-0.6 m/s) but can reach ~2 m/s in other places (for details, see [86]). An array of small turbines could be deployed beneath the water surface to take advantage of river currents (see a simplified concept in Figure 6). While the boat moves forward, this may not be convenient due to the possible increase in hydrodynamic resistance. However, when the boat is at rest, these currents could be made use of. Some commercial devices that work at low current velocities (e.g., ~0.9 m/s [87]) could be adapted for this application. Some of these are practical and sufficiently portable to charge small electronic devices by harnessing wind or water currents [88]. Arrangements of these devices could be used to generate energy for electronic devices on the boat, particularly when it is at rest.

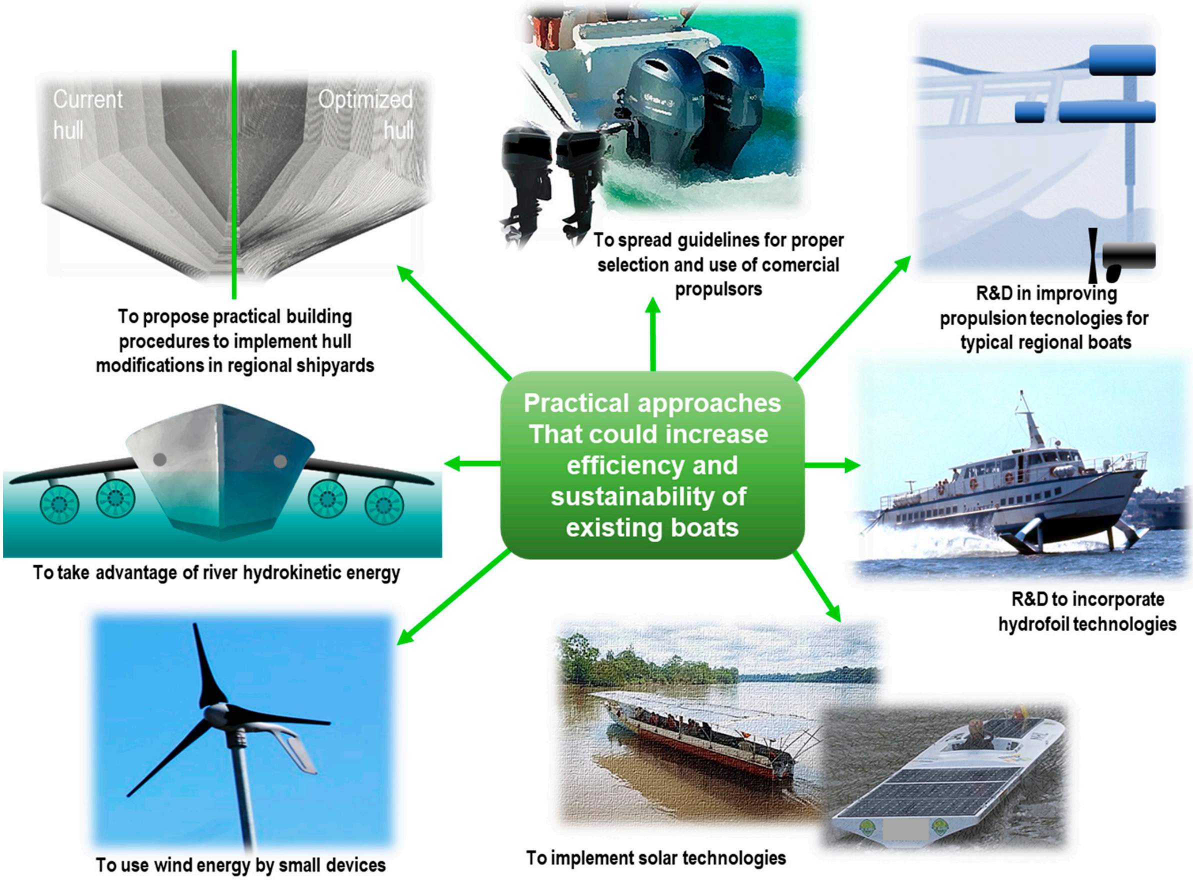

Figure 6. Possible improvements in the efficiency and sustainability of the existing boats used for daily activities in remote regions of the Amazon and similar regions elsewhere. Adapted image credits: commercial propulsors [89]; hydrofoil technologies [90]; solar technologies (left: [80], right: [83]); wind energy [91].

For all these innovations, a feasibility analysis should always be carried out to evaluate possible environmental impacts in the Amazonian environment.

5. Conclusions

Some alternatives for increasing the efficiency and sustainability of river transport in remote regions using small boats were explored in this paper. The focus was on improving the performance of existing boats, thereby contributing to the sustainable development of remote communities. Several means of improving the performance of small boats used for school transport in an Amazon riverine region were described. Improving propulsion and reducing the hydrodynamic resistance of vessels are proposed in the literature to improve their performance, whereas permanent modifications to the boat hulls may provide long-term benefits in terms of efficiency. Hull modifications to existing small boats used for river transport should be feasible. Perhaps these modifications could be carried out by small-scale, local shipbuilders, adding further value to these recommendations through the generation of local employment. Assuming that an improved school boat in the Amazon may have a ~5% reduction in fuel consumption, it was estimated that it would save thousands of liters of fuel per year. This would have socioeconomic and environmental benefits for the communities through the resulting reduction in greenhouse gas emissions.

Other means that could contribute to more sustainable boats in the future were also described. R&D are suggested to develop guidelines for the selection and development of improved propulsion devices, the improvement of hulls in existing boats, and the implementation of hydrofoil technologies. Renewable energy sources available in the region, such as hydrokinetic, solar, and wind energies, were also identified as a means of improving the sustainability of river transport in remote areas.

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