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COMPUTATIONAL SUSTAINABILITY: A LIFE CYCLE PERSPECTIVE FOR ECODESIGN AND LARGE YACHTS PRODUCTION

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SUMMARY

We all know that beneath its glamorous façade, a yacht is essentially an industrial machine. A yacht moving through the waters generates its own electricity and water, processes most of its waste, and produces enough power to transport itself and its passengers to nearly any place on Earth with access to the sea.

Like most high energy industrial workspaces, the working areas of a large yacht produce smoke, heat, fumes, noise and vibrations. Unlike most industrial operations, a yacht regularly moves between many of the Earth's most pristine, beautiful and environmentally sensitive sites.

Much has been written in the past decade about the "green yacht" but just a few of this litterature was then implemented and tested in its operational phase.

By adopting the *Computational Sustainability* approach it was for the first time possible to implement a management support system that provide a comprehensive framework in which the best sustainability practices can be adopted from the design stage and, more importantly, their impact constantly assessed and certified.

The *Computational Sustainability* approach in the yacht building sector in now a ***design decision support system*** and a management tool. It's the result of the collaboration between Eulabor Institute, the Italian super yacht builder VSY and the University of Bologna.

1. INTRODUCTION

The European shipbuilding industry is globally renowned for its innovative nature and capability to deliver high quality vessels. Today Europe has a lead position in high value segments such as cruise ships, dredgers and other ship types. To react to the recent economic crisis, a substantial push towards environmental-friendly products, production lifecycle and services can create opportunities for the shipbuilding industry, introducing new challenges that encompass the value chain of the products as a whole. Our *Computational Sustainability* project focused on the production of luxury yachts, a market segment of high added value which has been identified by BESST (Breakthrough in European Ship and Shipbuilding Technologies, a Large Scale Integrating R&D Project under the umbrella of EC Seven Framework Programme) as a target for innovation in decreased cycle cost, reduced environmental impact and improved safety.

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The objectives of our project were to:

1. Design a decision support system for the production cycle of the vessel, taking into account cost, energy and environmental impacts, from production to the shipping phase and up to dismantling and recycling.

2. Collect data on existing products that have already adopted green solutions to assess their effectiveness and real impact. The collected data will feed the decision support system and calibrate it.

3. Provide guidelines for certifications by relying both on the decision support system and the data collected.

4. Evaluate the decision support system on a number of business cases that include economic, strategic and commercial aspects and business models developed.

The impact of the *Computational Sustainability* project is manyfold from several point of views. It aims:

1. to face a number of environmental, climate change and sustainable development (green growth) issues that are affecting the shipbuilding industry;

2. to implement a holistic approach to ship construction and evaluating the cost/benefict indicators: it could give the shipbuilding industry the opportunity of not only setting its own environmental agenda (rather than be forced by government or public pressure) but to also deal with such impacts more effectively, and even benefit commercially from associated innovations.

3. to generate new business through opening the sustainability data and to expand the use of sustainability to the whole life-cycle;

4. to support structured ocean responsibility reinvesting in conservation programs, actively protecting our natural capital and embracing the Sustainable Development Goal n.14.

2. IDENTIFYING SUSTAINABILITY

Our project relies on the definition of *sustainability* provided in Executive Order 13514 - Planning for Federal Sustainability in the Next Decade (B. Obama, 2015) “to create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations”. The definition indicates that the term sustainability is both a process and a goal. The *Computational Sustainability* focuses its efforts on sustainability as a process, rather than a goal or a prescriptive end state. The industry pursuit of sustainability is fully compatible with its duty to protect human health and the environment. But we have to admit that its traditional approaches to risk reduction and pollution control cannot fully achieve many of its current objectives and long-term and broad environmental quality goals.

Such megatrends as climate change, greater consumption of natural resources, and continuing demands for existing and new materials for industrial applications in a global economy are causing all organizations —both public and private— to re-think their roles, strategies and capabilities.

Sustainability has evolved from a theory and an ambition to a growing body of practices. The evolution includes a transition from the development of broad goals toward the implementation of specific policies and programs (Figure1) for achieving them and the use of indicators and metrics for measuring progress.

Fig. 1 The Sustainable Development Goals are a UN Initiative. The Sustainable Development Goals (SDGs), officially known as *Transforming our world: the 2030 Agenda for Sustainable Development*, are an intergovernmental set of aspiration Goals

Without losing focus on the goals of the yacht building industry, our project is incorporating sustainability considerations into our decision-making process about potential environmental, social, and economic outcomes. This involves shifting from a focus on specific pollutants in an environmental medium (air, water, or land) to a broader assessment of interactions among human, natural, and manufactured systems in a more efficient way. Many businesses and nonprofit organizations have adopted the Triple Bottom Line (TBL) sustainability framework to evaluate their performance, and a similar approach has gained currency with governments at the federal, state and local levels (Elkington, 1994; Battacharya,et al. 2010) and other tools to evaluate the ramifications of their decisions from a truly long-run perspective. (Figure 2).

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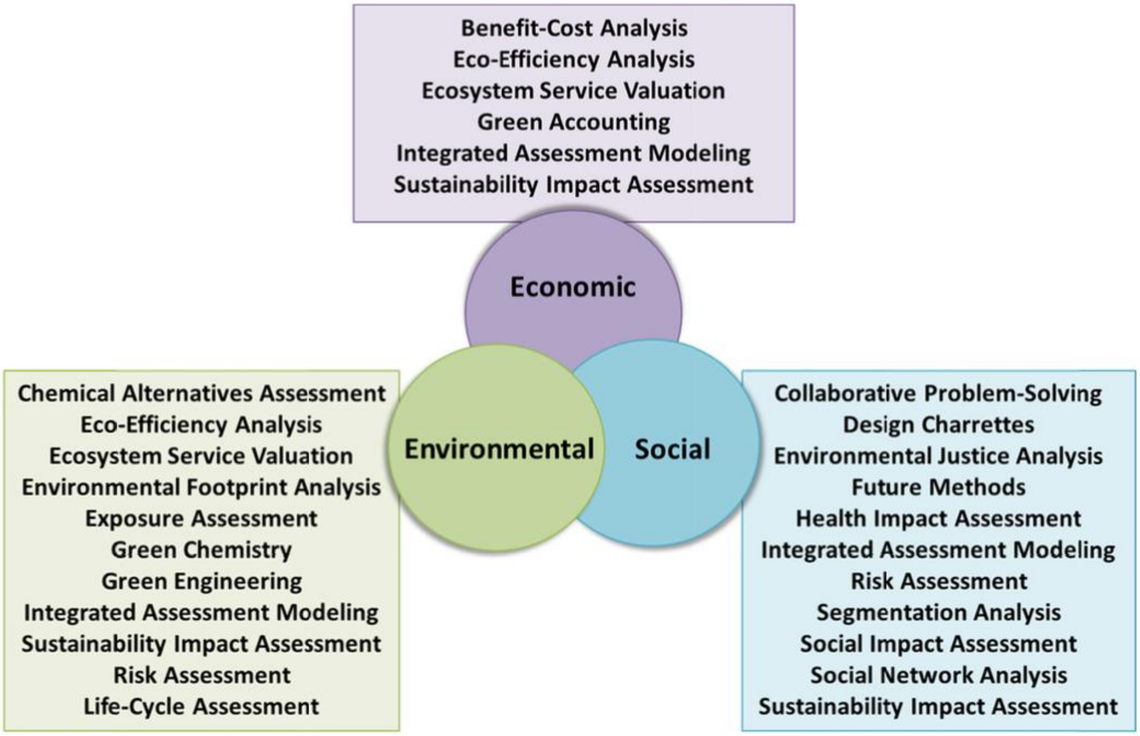

Fig. 2 Sustainability in the industry

2.1 The evolution of Sustainability Science

Perhaps the most rapid implementation of sustainability practice in the last decade has been in the private sector. Sustainability has become a greater business imperative, a source of competitive advantage, and an enabler of innovation. Leading companies are pioneering ways to lower their costs while building more efficient and sustainable processes, products, and services. The focus of sustainability takes companies beyond mere conformity with government laws or regulations to the creation of innovative products and services that give rise to new markets.

The scientific foundation and analytic tools used to support decisions in a sustainability context— regardless of whether the decisions are made by governments, businesses, non-government organizations, or individuals—will benefit greatly from new knowledge and better use of existing knowledge (NRC 1999; NRC 2011a). Such scientific capabilities are helping to build connections between the research domains of environmental sciences, economics, and sociology (Anastas 2012). Those advances are enhancing the development of sustainability science, a field of research recommended by the international policies.

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2.2 Systems thinking

The industry today should always use concepts of sustainability to strengthen a systems-thinking approach in using current and future tools and approaches, as necessary, to support its process decision-making. The yacht building sector has many opportunities to incorporate sustainability considerations by applying those tools and approaches across the spectrum of its activities and it should do so rapidly. Systems thinking involves a comprehensive understanding of the mechanisms and feedback effects of interrelated parts or subsystems that work together to perform a function. From an operational perspective, “applying a systems approach to sustainability provides a rigorous way to analyze the potential consequences of human intervention...it may reveal how actions taken by industry and consumers affect the environment, how efforts to protect the environment impact industry and consumers, or how impacts on one system can affect others and the larger whole” (US Environmental Protection Agency 2013a, p. 11). Understanding such connections has long been a central principle of industrial ecology (Allenby 2009). Also, “cradle-to-cradle” (rather than “cradle-to-grave”) design tenets popularized by McDonough and Braungart with the slogan “waste equals food” (McDonough and Braungart 1998, 2002) and The Natural Step Framework for Strategic Sustainable Development (Natural Step 2014) demonstrate the idea that business operations are deeply integrated into natural systems and vice-versa. Life cycle assessment (LCA) approaches have advanced over the last 20 years to provide a methodological framework for ensuring that an improvement in one sustainability issue (for example, energy consumption) would not create an unanticipated impact in another area or life cycle stage.

3. COMPUTATIONAL SUSTAINABILITY: OPTIMIZING THE YACHT BUILDING PROCESS

The large yacht construction involves activities like metal working (thermal metal cutting, welding, and grinding), and surface treatment operation (abrasive blasting, coating, and painting). It includes ship maintenance and repair activities, as well as normal functioning. The final dismantling involves the removal of toxic and hazardous materials; moreover, the recycling of high quality steel and other materials characterizes this final phase as being a valuable economic activity, with up to 95% of a ship being virtually recyclable (Hossain et al. 2006; Mikelis 2006).

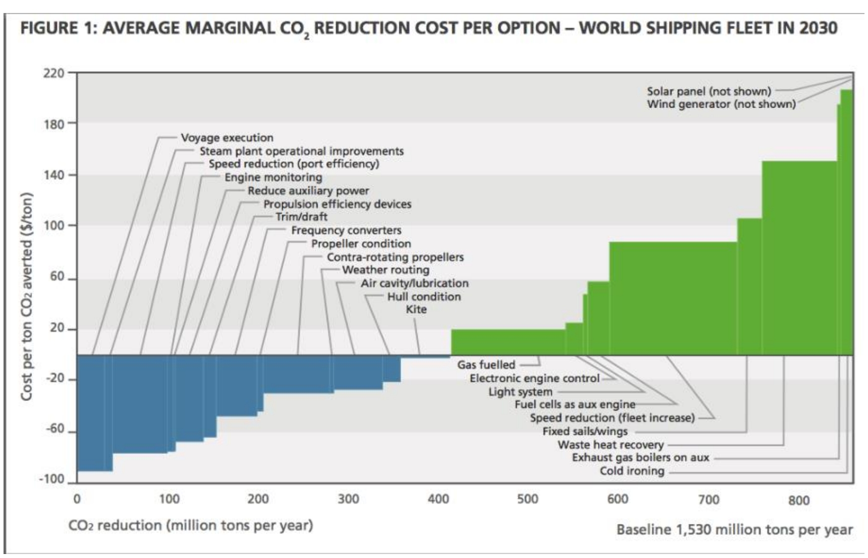

Fig 3 Average marginal CO2 reduction cost per option

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Greener solutions (Figure 3) are already available or will be in the near future. However, given the higher number of choices and possibilities, it is a hard task to decide which technology it is worthy to invest on, as well as to estimate cost, energy, and environmental impact reductions. Moreover, any choice of this type, made in the construction phase, will have huge different impacts on the subsequent phases. As an example, let us consider a recent study by Det Norske Veritas, where a number of technologies have been examined w.r.t. their potential and cost-effectiveness for reducing CO2 emissions. (two reports, one looking at the period up to 2015, and the other looking ahead to 2030). The full list of technologies, as well as their cost-effectiveness and CO2 reduction potential, can be seen in Figure 3 [The list excludes a number of technologies, such as biofuels and hydrogen, as these were not deemed available on a commercial basis until after 2030].

The vast majority of the decision problems in the ship manufacturing market cannot be solved by intuition or experience, and they cannot be tackled through relatively simple calculations. This is particularly true in the maritime sector, where a number of actors contribute to the whole process, quite often bringing specific skills such as naval engineering (e.g., design offices). LCA-related models can be useful whenever the amount of data and relations are too complex to be analysed by human experts, and determining the effects of decisions upon the environment and the product cost is not doable by humans. Models aid designers, customers, and naval builders to compute and especially compare alternative decisions; moreover, they are a mean for aggregating knowledge from different areas and sources.

In the naval engineering there are two fundamental methodologies for modelling processes: mathematical-based simulation, and mathematical modelling. In the design phases both the models are heavily exploited to solve engineering issues. However, our model is not focused on the engineering design task, but rather on the assessment of the industrial processes that characterize the life of a vessel, from the cradle to cradle perspective. In such context mathematical modelling is often used to assess the properties of the industrial processes, quite often in terms of Life Cycle Cost (LCC) perspective.

Among the mathematical models, optimization based modelling can be considered as a goal- oriented approach that is directed toward creating alternatives. Optimization can be driven by a single objective (single-criterion optimization) or several objectives (multi-criteria optimization). Goals are the input and decision variables the outcomes.

Mathematical modelling for decision-making support is the process of creating, analysing, and documenting a model, which is an abstract representation of a problem developed for finding a possibly best solution for a decision problem. Mathematical modelling has been applied in several environmental applications energy-related planning, and optimisation applied to the life-cycle cost in naval building.

Computational Sustainability allowed us to use advances technologies based on multi-criteria optimization techniques, to compute the Pareto optimality curve where alternative and non dominated solutions are located and to help all the actors explore the alternative scenarios while ensuring to optimize the desired targets. In this way our approach merges the global perspective over the product life with the local perspective given by the involved actors and the different targets (mainly economic, environmental, and energy related).

The models developed provide two strategic objectives:

1. a better insight into the ship product-life, from the cradle to cradle perspective. Such insight implicitly provides also a reference model, that once adopted will allow any actor involved to have a precise reference framework for evaluating its own production processes;

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2. tools and techniques that, when adopted in the various steps of the production process, will support the decision process not only by suggesting possible alternatives, but also documenting why some decision are preferable to other.

Indeed, with the objectives 1 and 2 the models will establish a methodological framework that can be taken as a reference. The aim is to exploit the results and to define a set of guidelines and standards that are accessible to all the shipbuilding market players.

3.1 Design a decision support system supporting the production cycle of a vessel, taking into account alternatives and evaluating their cost and environmental impacts

By using the *Computational Sustainability* field it was possible to adopt a systems thinking approach and to embrace an integrated sustainability concept. As a result we have developed a Decision Support System based on constraint programming (Marriot K. Et al., 1998) and hybrid optimization techniques (Milano et al. 2013) to optimize the design process by taking into account a specific objective function to be minimized/maximized. E.g., an objective function might be the total cost (from cradle to cradle) of the vessel, while another might be the energy consumption for the construction phase only. The decision support system is based on a logical and mathematical model of the overall process, taking into account constraints limiting the feasible solution space and stating objective functions representing an evaluation metric on the solutions. For each phase of the production, for each activity/component of the vessel alternatives are identified, evaluating their cost, energy, and environmental footprint. The *Computational Sustainability* decision support system is now implemented and integrated with a database of data stored on activity impacts from existing vessels and from the literature and made accessible through a web interface. The system supports the user in three tasks:

- Describe the design process of the vessel. The process is modelled through an intuitive graph structure.
- Optimize the design process. The *Computational Sustainability* system is fast and reliable. It computes good solutions very quickly and optimal.
- Evaluate the design process of a vessel. The system can evaluate the impacts and the costs of a design process.

3.2 The Design Process Model

The design process of the vessel is described through an intuitive model. The model consists in a set of variables, constraints and in a graph similar to a flow diagram with logic operators regulating the flow.

The graph is composed by nodes and arcs. We have two types of nodes:

- **Activities**: an activity represents an action that could be executed during the construction phase of the vessel (e.g.Installation of the pneumatic actuated valves in the exhaust gas system, painting the external hull below waterline or installing a particular diesel engine). Each activity has its own impacts in terms of:
  - Economic cost
  - Timing cost
  - CO_2 emissions

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  - Water consumption
  - Others environmental and human health indicators
- **Operators**: an operator is a node representing a logical operator:
  - AND: all the out-going arcs have to be considered
  - OR: at least one out-going arc has to be considered
  - XOR: only one out-going arc has to be considered

Each arc represents a dependency between two nodes an can be associated with a condition (when connected to a logic operator).

The system and the designer, during the design process, should take decisions (e.g. the material of the hull, the type of engine, select the treatment of a particular material). These decisions in the model are taken on the variables. Each variable therefore represents a decision that has to be taken during the design phase.

The variables are connected to one or more nodes and their values can be bounded by constraints (e.g. at most two food elevators, the pipes material of the hydraulic system cannot be PVC, the number of decks is 5).

The final process (i.e. the set of activities to be executed) is derived from the decisions on the variables and the logic conditions of the arcs.

3.3 The optimization engine

The aim of the optimization engine is to find the optimal decisions that satisfy the constraints and maximize/minimize the objectives (Figure 4). The objectives are connected with the costs of the activities, such as:

- Minimize the economic cost
- Minimize the time
- Minimize the emissions
- Minimize the water consumption

An advanced algorithm extracts from the design process model a mathematical model which is used in the optimization engine. The optimization engine is based on the Constraint Programming paradigm which is an advanced artificial intelligence optimization technique used to solve hard combinatorial problems.

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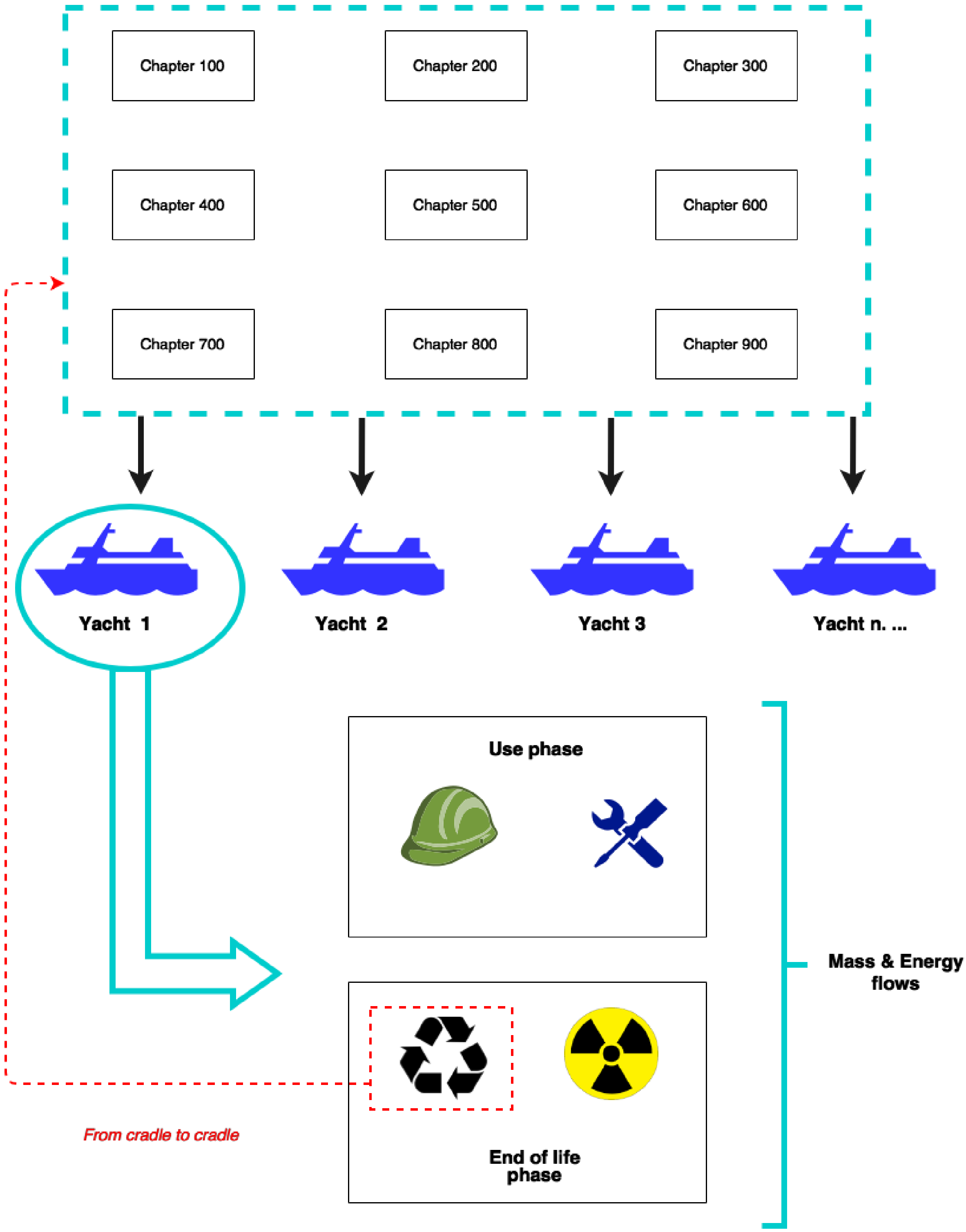
Fig 4 System Border and Chapters



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4. CONCLUSIONS

There is a clear and timely need for strengthening the focus on environmental information and transparency in the international agenda in general and in the shipbuilding industry, including as how the industry is linked to impacts of environmental concern following from its use of raw materials, and through shipping and ship recycling operations.

In this sense Yachting 2.0 could provide a reference framework where best greener practices can be adopted and, more important, constantly certified thanks to the developed tools. This in turn will be an important innovation step for the EU-based industry, thus enabling a competitive advantage over concurrent industries.

The implementation of the *Computational Sustainability* tool allowed VSY to break down every stage of the production process of its yacths and then to assess the sustainability components at each stage while providing cost benefit indicators. By adopting the computational sustainability design tool, VSY demonstrated that preservation of resources and high performance is not a contradiction at all. With the Yachting 2.0 program VSY achieved a 20% reduction of C02 emissions and energy consumption in the production process, a 10% reduction in costs and a significant reduction of the owner´s operating and maintenance costs.
The implementation of this model translates also into significant cost savings, a part of which is reinvested into marine conservation programs, e.g. marine protected area planning and financing. This model has a name - Waterevolution - and it has already been recognised as a Blue Solutions from the key nature conservation organisations such as UNEP and IUCN. http://www.solutionsexplorer.org/solutions/waterevolution-an-integrated-approach-to-maritime-cluster-sustainability.

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