ARALFUTUR PROJECT: Energy efficiency of deep sea trawlers for South Atlantic fisheries

Adrián Sarasquete Fernández[1], Valentina Ruiz Toulemonde[1], Alfonso Jurado Fuentes[1], Daniel Rojas Rodríguez[1], Aitor Juandó Iturrioz[1], Javier Rodríguez Rey[1], Oscar Fernández Acevedo[2], José Irisarri Castro[3], Pablo Carceller[4], Jesús Doval Gandoy[5]

1. Vicus Desarrollos Tecnológicos S.L., Vigo, Spain.
2. ARVI (Cooperativa de Armadores de Pesca del Puerto de Vigo), Vigo, Spain.
3. Optimar Fodema S.A., Vigo, Spain.
4. Faustino Carceller S.L., Vigo, Spain.
5. Universidad de Vigo, Spain.

Abstract—**This project is focused on the optimization of deep sea stern trawlers, to offer an advanced and viable technological answer on four basic questions about the competitiveness of the freezer trawler fleet: energy optimization (by increasing the hydrodynamic efficiency of the ship, developing new and more efficient systems and equipment and establishing procedures to be integrated into the ship's design), on board activities fishing & processing optimization, safety and ergonomics in the ship. The aim is to approach the whole design from different points of view to present a new concept of tomorrow's trawler fleet.**

Keywords: trawler vessel; optimization; operational profile; energy efficiency; fisheries; viscous CFD; hydrodynamics; simulink; permanent magnet synchronous machine; freezing tunnels system.

I. INTRODUCTION

Spain is the major fish producer in the EU and 20th in the world, although it is the second in value because all catches are for human consumption. Likewise, the Spanish fleet is the most important in the EU in terms of capacity. In the early 60's Vigo's shipyards started to build the first freezer trawlers. This was a milestone in the history of the fishing sector for Galicia and for the world because it provided the access to fishing resources which until then were geographically very far but massive and unexploited. Moreover, these areas had been identified in what they called "international waters" with free and total access.

In the early 80's the scenario previously described changed radically. One of the first big international changes was the extension of the EEZ (Exclusive Economic Zone) of the countries signing the UN Convention on the Law of the Sea. From that date countries signing the Convention, i.e. those with the largest extractive platform, enhanced their exclusive zone from 12 to 200 miles.

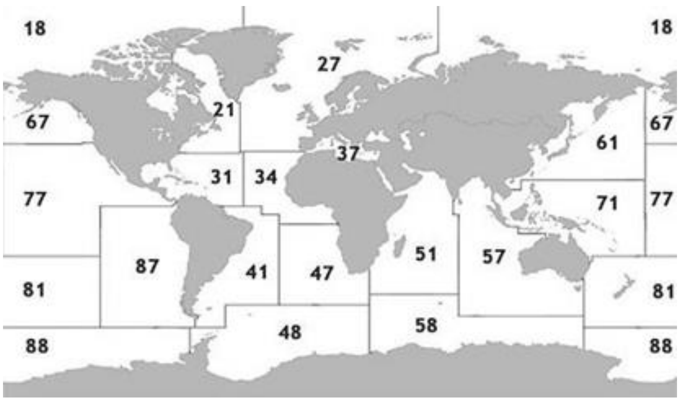

Figure 1. FAO Fishing areas

In this context, many ship owners established joint ventures with partners in third countries with recognized historical rights for fishing... most of them in the Southern Atlantic (FAO 41). This business association had been called ACEMIX.

This remarkable change in the international legal system happened while a new generation of freezing trawler vessels was being built. These new ships were technically conceived following similar criteria as the previous ones, taking for granted that the international scenario wouldn't change in such a way. So, they had standard designs not adapted to the characteristics and features of the fishing areas where they should work, on the contrary they fulfilled the logistic requirements and capacities of a fishing system doomed to failure. But, even more, the newest vessel, built as late as 2004, has not represented the adoption of a new conception, and exploitation costs remain similar.

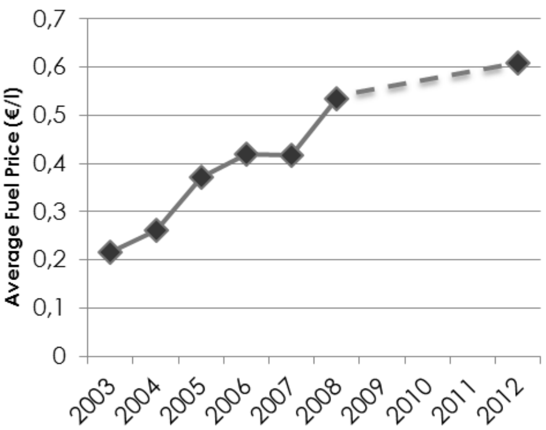

Figure 2. Fuel price since 2003 to 2012

TABLE I. OPERATING COSTS OF A SW ATLANTIC TRAWLER

OPERATING COSTS (vessel type: freezer trawler SW ATLANTIC)						
Costs	**Euros 2005**	**% 2005**	**Euros 2006**	**% 2006**	**Euros 2008**	**% 2008**
MATERIALS	1 611 897	36.6	1 804 723	39.3	2 252 080	44.6
Food	*87 984*	*2.0*	*87 984*	*1.9*	*87 984*	*1.7*
Oil	*1 426 915*	*32.4*	*1 619 742*	*35.2*	*2 067 099*	*41.0*
Lubricant	*6 901*	*0.2*	*6 901*	*0.2*	*6 901*	*0.1*
Other materials	*90 096*	*2.1*	*90 096*	*2.0*	*90 096*	*1.8*
GEAR:	192 140	4.4	192 140	4.2	192 140	3.8
CREW AND ASSOCIATED COST:	1 793 992	40.7	1 793 992	39.0	1 793 992	35.6
PORT CHARGES, LANDINGS, REPAIRS...	731 601	16.6	731 601	15.9	731 601	14.5
INSURANCE AND OTHER:	75 742	1.7	75 742	1.7	75 742	1.5
TOTAL	**4 405 372**	**100.0**	**4 598 198**	**100.0**	**5 045 555**	**100.0**
NET SALES: 4.8 M€/year						

So, at this point fishing units are at risk and a fleet renovation is needed in order to keep on being competitive, focusing on energy efficiency, on board activities optimization, safety and ergonomics in the ship.

It has to be mentioned that this project is funded by *FEDER-INNTERCONECTA GALICIA 2013 program*, *CDTI*, *Xunta de Galicia* and *Ministerio de Economía y Competitividad*.

II. STATE OF THE ART

Political, legislative and technological changes have been developed in recent years; apart from the consequent aging along the time, this fleet lacks of all the innovative systems and equipment which make new vessels more competitive.

- Current vessels were devised when there were no access restrictions to third countries waters. In other words, they were not conceived neither for long working periods –around 6 months- and long distance trips, nor to keep in their holds very high tonnages –around 1.000 Tm-.
- This low capacity means unnecessary fuel consumption generating a clear energetic inefficiency.
- Despite the investments made on board in recent years, fuel is still 40% of the exploitation costs in shipping companies. ACEMIX vessels have engines whose fuel consumption is 20% higher than those of the modern ones to reach the same power. In addition, they use diesel instead of fuel-oil, cheaper than diesel.
- This ageing of the fleet causes trouble and costs which increase exponentially due to malfunction and structural problems like corrosion, breaking of inner screens, communication among tanks, plate wearing out, etc.

Figure 3. One of the oldest freezer trawler still in service (1974)

III. NEW TECHNOLOGIES FOR ENERGY EFFICIENCY OPTIMIZATION

There is a need to address the construction of new ships, including technological improvements that increase their efficiency, reducing operating costs for shipping companies.

The ARALFUTUR project is basically divided in four main tasks: development of ship design; technologies for energy efficiency optimization; optimization on fishing gears, processing and freezing; and optimization and technologies for safety and ergonomic improvement.

Between others, and focusing on energy efficiency, specific goals are defined as:

- Improving the energy efficiency by increasing the hydrodynamic efficiency of the ship
- Achieve also a higher level of energy efficiency by developing new and more efficient systems and equipment –approaching both the generation of energy and also the main consumers- and establishing procedures to integrate them into the ship's design.
- Improving functionality and productivity by integrating the auxiliary machinery for fish processing and freezing into the ship. This will be achieved through the innovation and the setting up of new strategies for the systems' design.

This paper is focused mainly on the technologies for energy efficiency optimization, particularly related with hydrodynamics (hull and propeller) and technologies, including the use of simulation tools for power plant improvement of engine room.

A. Ship design

This task tries to integrate the hydrodynamic optimisation of the hull with different requirements concerning stability, location of equipment –with special attention to ergonomics and safety-, seakeeping considerations, etc. This process counts with the feedback of the other tasks, which will provide the necessary input all along the project.

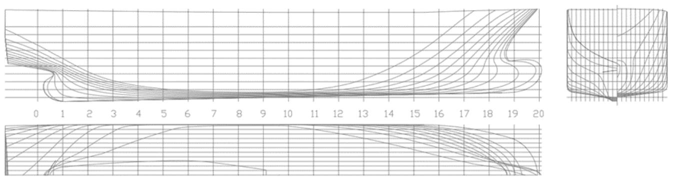

Figure 4. Hull forms with bulbous bow

An initial specification of the ship has been developed, which involves naval architecture issues like an initial shape of the vessel, preliminary stability, and estimations on powering and electric balance with the definition of the main electric consumers.

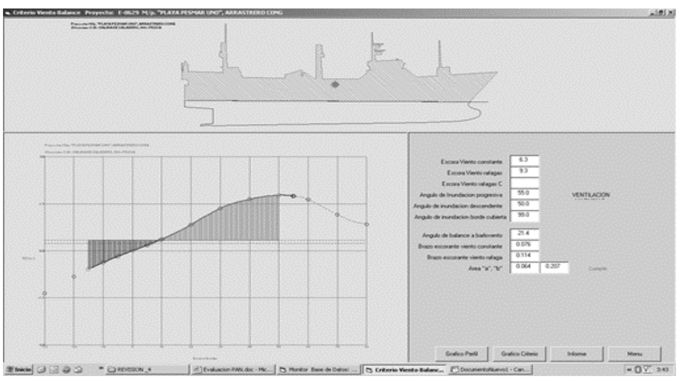

Figure 5. Capture from stability software

B. Energy efficiency optimization

As it is well known, propulsion is the major consumer in a fishing vessel (around 40% of the exploitation costs); in the case of South Atlantic fisheries, it is a common practice to perform the voyage from Spain to SW Atlantic fisheries. The fishing campaign is organized trying to save as much fuel as possible, but taking into account an economic vessel speed is not always implemented. Moreover, if this condition was considered from the initial phase of design, better results could be achieved.

In order to undertake this design, corresponding tasks in this project involves issues related with:

- sea trials and monitoring, that would give a base line defined for actual vessels, provide input for calculations and allow future comparison with new designs
- hydrodynamics, with a complete study of hull and propulsion, including seakeeping
- electric plant design, including state of the art generation devices, as permanent magnets technology
- system integration simulation & performance calculation

Furthermore, during the optimization process, other not technical questions arise, such as current socioeconomics and political requirements: it is necessary to know which are the circumstances and associated problems related with the fishing at this moment.

1) Operational profile definition and main specifications

A study of existing stern trawlers and equipment included on board (propulsion system, power plant, energy distribution and major consumption equipment) is elaborated. Using this information, a database is made with SW Atlantic stern trawler fleet, including main dimensions (L, B, D, T), load magnitudes (displacement, deadweight, lightweight, freezing capacity), naval architecture coefficients and non-dimensional relationships (C_B , L/B, Reynolds number, Froude number…), main propulsion engine parameters (power, rpm, speed…), electrical generation plant (number of generators, power, number of shaft generators, …), main propeller parameters (diameter, pitch, propeller type, propeller clearances, number of blades), main consumers (freezing compressors, fishing winches), and bulbous bow parameters.

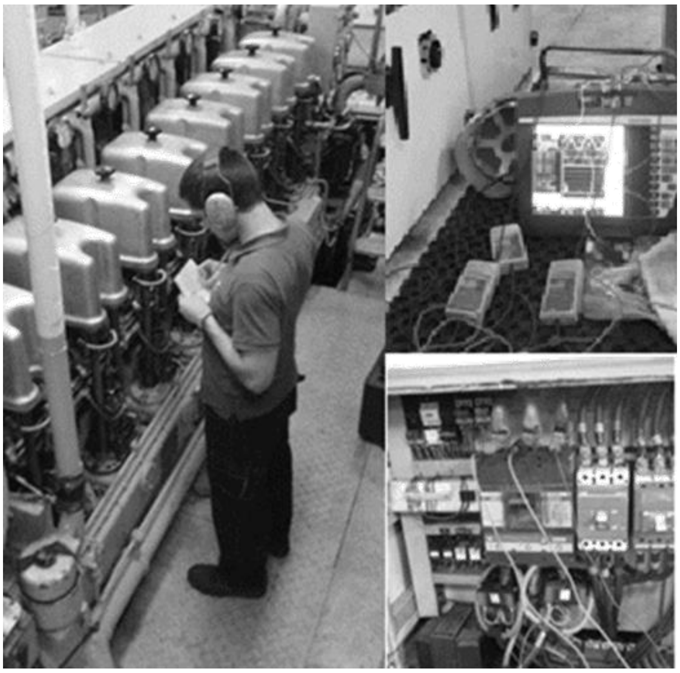

Figure 6. Measurements and monitoring system on board

Meanwhile, sea trials and monitoring were performed in stern trawler vessels of the fleet. These measurements were performed in different operational conditions: navigating, trawling, hauling, scouting and waiting. The data collection included power developed in the propulsion shaft, fuel consumption of main engine and electrical generators, speed, emissions, time in each operational condition… Punctual measurement on sea trials are also completed with remote measurements during the whole campaign, being both of this data analysed statistically.

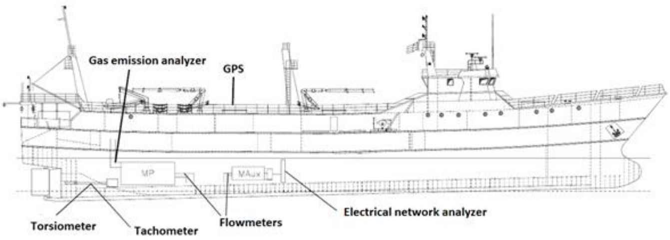

Figure 7. Sensors installed for sea trials

All these data are integrated with more information made available by many owners of the stern trawler fleet who wanted to collaborate with this project.

Therefore, the operational profile is extracted thank to the integration of all this data. Operational conditions such as navigating, trawling, scouting, hauling/setting and waiting are defined with their speed, propeller loading, time spent in this condition, average consumption (litres per hour, litres per day and litres per mile) and electric power plant demanded (auxiliary engines and shaft generators power). Shown ranges correspond to different vessels of the fleet.

TABLE 2. OPERATIONAL PROFILE FOR SW ATLANTIC FLEET

Operational Profile for SW Atlantic Fishery			
Operational condition	**Speed**	**Propeller loading**	**Time (per campaign)**
	kn	**%**	**days**
Navigating	10,5-13,5	90-95	40-50
Trawling	3,5-5,2	80-85	50-80
Scouting	10,5-13,5	90	-
Hauling/Setting	0-1	30	-
Waiting	1	-	-
	Average consumption		
	l/day	**l/h**	**l/mile**
Navigating	6500-17000	270-708	20-67
Trawling	6750-14500	281-604	64-173
Scouting	6500-17000	>270	>22
Hauling/Setting	7983	332,6	-
Waiting	-	-	-
	Electric Power Plant		
	Auxiliary power generation		**Shaft generation**
	kWe		**kWe**
Navigating	>60		>60
Trawling	>240		-
Scouting	>240		-
Hauling/Setting	>240		-
Waiting	>240		-

The time for each *hauling* manoeuvre is around one hour and for *setting* from ten to fifteen minutes. The time for *scouting* and *waiting* is difficult to set because it depends of different circumstances and contingencies. Electric power generation is related to energy needed of each situation, with a strong dependence on main consumers such as freezing system and trawling machinery. The minimum demand is set as 60kW in *navigation* condition, which can be covered by the shaft generator.

Figure 8. Route from Spain to FAO41

In order to have a complete vision of the operating profile, environmental conditions affecting the performance should be kept in mind. During the ship design process, ideal conditions for sea state are taken, and a theoretical margin is added to take into account the effect of the environmental conditioners; but waves, wind and currents have a great effect in the performance of the vessel, having also their impact on safety and ergonomics. To perform seakeeping studies and take into consideration the effect of this external agents, information was collected, defining average and extreme sea conditions on the route and fishing areas.

With this seakeeping analysis we would be able to optimize the behaviour of the vessel in waves, safety and stability on board avoiding resonances with waves, slamming, green water and other problems derived by wind, currents and waves.

The study of sea conditions can be summarized in the following table, where the most probable wave, wind and current from Spain to SW Atlantic are shown: period, significant height and prevailing direction to modelling the wave and speed and prevailing direction to model the wind and stream.

TABLE 3. SEA CONDITIONS

NE Atlantic	**Hs(m)**	**Tp(s)**	**|v|(m/s)**	**Direction**
Waves	3-7	>10	-	From NW
Wind	-	-	6.90	From N,NE
Stream	-	-	0.05	To NW
Atlantic (Ecuador)	**Hs(m)**	**Tp(s)**	**|v|(m/s)**	**Direction**
Waves	2-4	7-10	-	From E
Wind	-	-	5.60	From E
Stream	-	-	1.00	To W
SW Atlantic	**Hs(m)**	**Tp(s)**	**|v|(m/s)**	**Direction**
Waves	3	6-8	-	From SW
Wind	-	-	9.70	From W
Stream	-	-	0.20	To NE

It is also shown some examples of diagrams of currents and wave in FAO41 area and the route from Spain to FAO41 area:

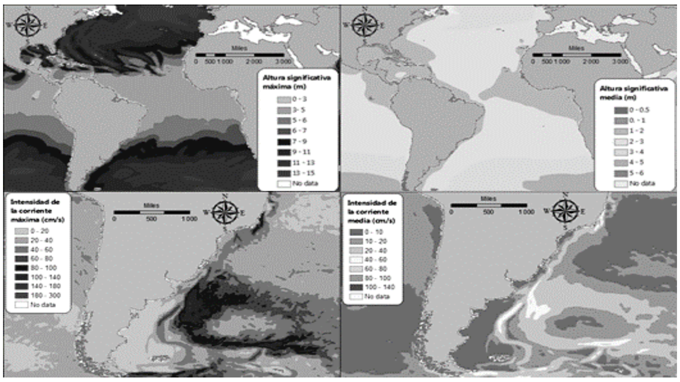

Figure 9. Example of diagrams obtained of sea conditions

2) *Optimization of the hull and propulsion*

The next step is to focus in the hull. First, the different configurations for the hull are studied bearing in mind the possibilities to scope: inclusion of bulbous bow, election between single or twin screw configuration, etc.

Once established this, a parameterization of the hull is made considering a number of parameters of interest through a base vessel geometry. These parameters were studied trying to analyse their individually effect on the resistance of the vessel by a resistance statistic based software, keeping displacement as constant. The parameters subjected to variation are length, beam, waterplane half angle of entrance, dead rise and bilge radius.

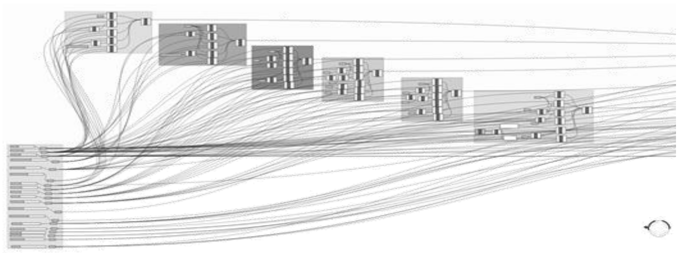

Figure 10. Parameterization model for hulls

More than 220 geometries are evaluated using viscous CFD software. The objective of these calculations is to know which is the best geometry in terms of resistance. After this, the best geometries are set as the base hulls to start the next step of optimization.

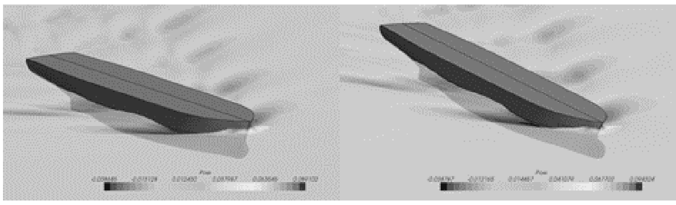

Figure 11. Viscous CFD captures

The optimization of the hull follows studying different bow and stern shape designs, essential issues due to the presented operational profile and the possibility of operation under rough seas and the good. Also, a solution has to be achieved to make the best use of propulsion energy both in the operating condition of *navigation* and *trawling*.

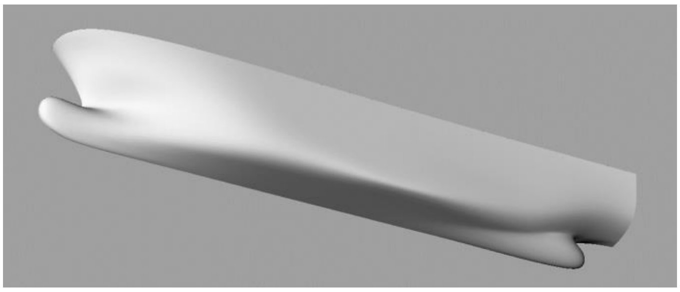

Figure 12. Trawler hull 3D CAD capture

This circumstance alongside propulsion system, seakeeping, manoeuvrability and streamlines and appendages studies is necessary to optimize the hydrodynamic behaviour of the ship.

Referring to propulsion, the propeller design has to be efficient both in route speed and trawling speed. It is studied the convenience of CPP (Controllable Pitch Propeller) or FPP (Fixed Pitch Propeller), with diameter dimensioning and rpm optimization, existence of nozzle or not and the best position of the propeller in respect of the hull. All the possibilities have to be considered.

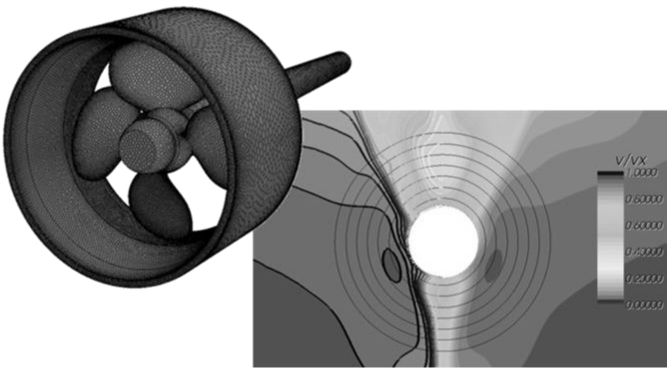

Figure 13. Propeller with nozzle 3D CAD capture and propeller without nozzle wake diagram

Manoeuvrability and seakeeping is very important in the process of optimization. The rudder has to give enough transversal thrust to be able to change the course at low speeds (as in *trawling* operating condition) in every sea state when the rig is pulling transversally the ship stern. The ship has to be able to keep the manoeuvring capacity in every circumstance of sea environment. Using the environment information of the route and the fishery area is possible to know the behaviour of the ship in these average conditions and also in extremal conditions. The vessel design has to avoid resonances with the most common waves, because it could be dangerous for the vessel and the crew and cause inadmissible levels of accelerations. The natural periods of the vessel must be different of wave periods, although this situation also depends on the encounter frequency which involves course and speed of the ship and excitation frequency of the wave.

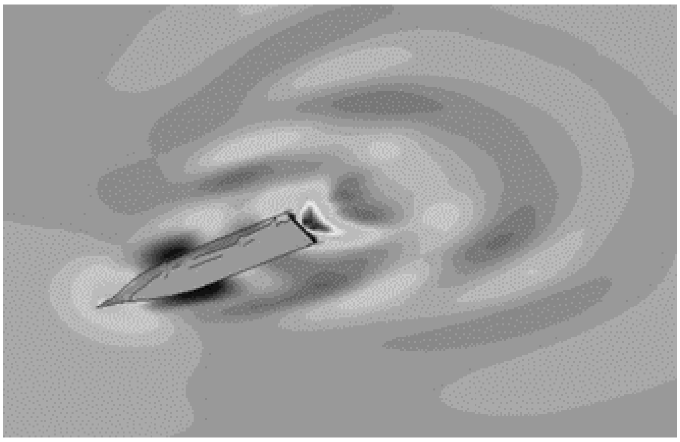

Figure 14. Seakeeping software capture

This frequency analysis is studied with the determination of corresponding RAO's (Response Amplitude Operator), which gives a non-dimensional response of the ship in every freedom degree for a specified range of frequencies defined in a white spectrum wave.

In order to evaluate the impact of all these approaches, achieved results from these studies are used as inputs for simulation tools that permits to evaluate globally and put on value the synergy of this global analysis.

3) *Performance simulation tool*

Simultaneously, a numeric simulation tool is used to obtain power performance, energy demand, gas emissions and fuel consumptions for each configuration. Every decision in the hull shape, propeller, propulsion system, etc. feeds this tool, making possible to predict how would be the behaviour of different ship systems. This way we get an integration of propulsion and hydrodynamics of each configuration defined, under a certain operational profile.

Broadly, inputs are resistance, draught, speed profile and time employed for each condition, propulsive data from the propeller (wake coefficient, thrust deduction fraction, K_T curve, K_Q curve, rpm, propeller performance, etc.), main engines properties, gensets properties, reduction gear performance and electric profile (electric consumers).

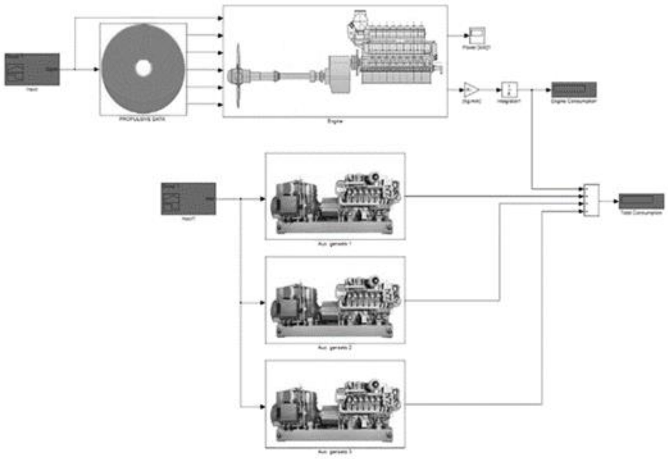

Figure 15. Performance simulation tool capture

4) Technologies for electric power plant optimization

In this project, electric distribution networks, energy storage, generation system of electricity, electric drive and conversion of electric power are developed for the energy efficiency improvement, using simulations and physical testing.

The research and development of distribution networks are related with new solutions of AC and DC technologies. AC technologies are included in conventional fuel power plants and diesel-electric power plants with frequency control for large electricity consumers; new DC technologies are being comparing with AC technologies due to the electric generation frequency independence, keeping in mind for the study the conversion stages required, wire dimensions, efficiency and safety of the systems. This research involves also energy storage and energy hybrid systems like PTI/PTO systems (Power Take In/Power Take Off) that may be installed on the ship shaftline (only for CPP configuration, with fixed revolutions).

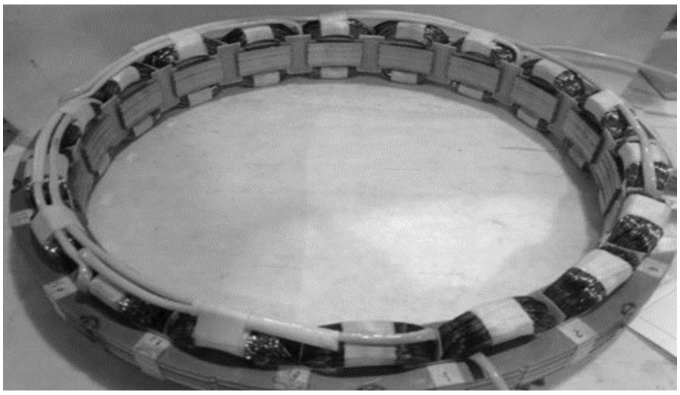

Figure 16. Permanent magnet stator

The studies about electric generation system and electric drive are related with electromagnetic, mechanic and thermal design, based on the development of new concepts of permanent magnet synchronous machine, capable to work as motor or generator in different systems of the vessel

Voltage - frequency power conversion systems are designed depending on each electric distribution defined, being essential the experience of the project partners in various fields like power electronics, control, liquid cooling, etc.

An optimized control strategy is developed by different algorithm implementations performing the most energetically advantageous operation, considering speed of the vessel, power delivered by auxiliary, etc. to increase energy efficiency.

A prototype of the permanent magnet synchronous machine has been made as a demonstrator. In order to operate it, also a prototype of the power converter and the components of the electric distribution network are built.

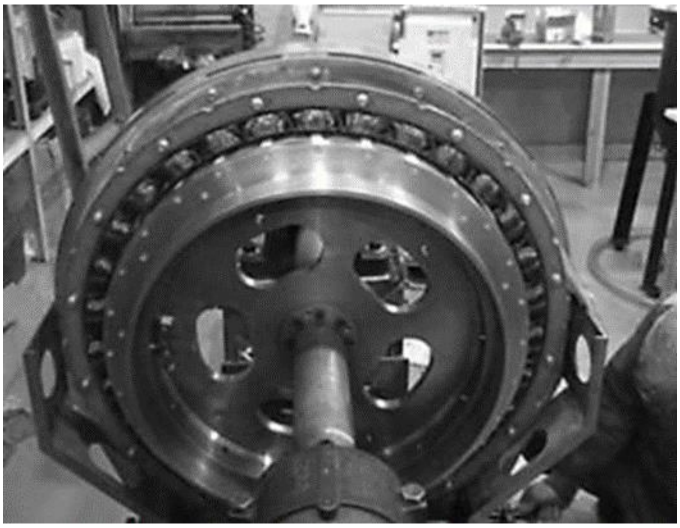

Figure 17. Permanent magnet synchronous machine prototype

To obtain real results of the system and components, different individually testing and global system testing (stationary and transitory regime) are being carried out.

C. Optimization on fishing gears, processing and freezing

The research also addresses on the efficiency in the processing plant, focused on automated loading of freezing tunnels system. This loading and unloading system for freezing trays in static freezing tunnels has been designed; a robotic transferring moving elevator which is displaced along the tunnels is used.

This system allows loading and unloading freezing trays in tunnels completely automatically, avoiding a laborious and difficult task to the crew.

Figure 18. Automated loading of freezing tunnels system

From energetic point of view, this automation allows the location for static freezing tunnels in an isolated enclosure, generating significant energy savings and better environmental conditions in the working vessel factory, being less severe for the crew.

IV. CONCLUSIONS

ARALFUTUR project is currently ongoing and giving good results for the creation of a new design of trawlers under this type of operational profile. On this stage of the project, the conclusions are:

- Advantages thanks to a wide approach of the problem: coordination of different areas covered with specialized companies over a specific scenario.
- Shipowners directly involved in the project and providing their needs in every specific issue.
- Relevance of sailings from Spain to FAO-41 area in the operational profile of the vessel to carry out the best design in energy efficiency
- Promising results in the first half of the project and good expectations in the rest of the project results.

The synergy of this cooperation and the optimizations in many parts of the ship taking into account global impact will make possible a valuable optimization on the whole vessel, giving way to the new concept of deep sea trawlers environmentally friendly and with higher energy efficiency.

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