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The use of a Generic Energy Systems (GES) model for fishing vessels

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***Abstract*— A 'Generic Energy Systems' (GES) model was adapted for fishing vessels in Project "Energy Saving in Fisheries" (ESIF). This model, based on the bond graph method, was developed by TNO and can be used to represent energy flows in physical systems consisting of various components (e.g. electrical, mechanical, hydraulic, acoustical, thermodynamic, material). The model was originally developed for merchant ships and adapted for fishing vessels. The basic features of the model and underlying theory are described. Data were collected from a total of 10 reference vessels cases. A total of 65 technical and operational adaptations were selected for these vessels and analyzed using this model, aimed at saving energy, among which changes in the drag of the (towed) fishing gear, alterations in fishing or steaming speed, optimizing propeller design (e.g. lowering the number of revolutions in a CPP, using a propeller nozzle, or enlarging propeller diameter where possible), improving hull shape, maintaining engines properly, cleaning hulls. Examples of these measures analyzed in GES are given.**

Keywords-component; fisheries; energy saving

I. INTRODUCTION

With the recent sharp rise in fuel costs energy consumption in fisheries became an issue after having been forgotten since 1985 when fuel prices dropped, after the energy crises of 1973 and 1979. Apart from shortage in resources climate change has emerged as a major problem to address, and emissions of greenhouse gases are strongly linked with the use of fossil fuels. Thus there is an economic and environmental drive to cut fuel consumption. In fisheries problems arose for those sectors operating high fuel intensive gears, such as beam and otter trawls. A European study was carried out in 2007-2008 in which the technical and economic evaluation of new technologies and operational adaptations was investigated for major gear types in a variety of European fishing fleets "(Van Marlen et al., 2008)". This paper deals with the use of 'Generic Energy Systems' (GES) models to predict the potential of these measures in terms of savings in fuel consumption.

II. METHODS

A. Principles of the GES-model

The GES model is based on so-called "bond graphs", which is a domain-independent graphical description of dynamic behaviour of physical systems. Using this, systems from different physical domains (cf. electrical, mechanical, hydraulic, acoustical, thermodynamic, material) can be described in the same way. It is a powerful object-oriented tool for modelling engineering systems. Bond graphs are labelled and directed graphs, in which the vertices represent sub-models and the edges represent an ideal energy connection between power ports. The vertices are idealised descriptions of physical phenomena: they are concepts, denoting the relevant aspects of the dynamic behaviour of the system "(Broenink, 1999)".

Technical systems usually consist of various physical components. These components can either generate energy, transfer energy, store energy or use up energy. The system is modelled through energy flows represented by power as a function of time using bond graphs for each component.

For example, in a propulsion system of a ship, energy input comes from the energy content (enthalpy) of diesel oil, which is transferred to rotational energy through the main engine. This energy is passed on to the propeller through a propeller shaft. The propeller converts rotational energy to translational energy, which is used to overcome the vessel's resistance when moving through water. This flow of energy is subject to various losses as the transfer from one system component to the other

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involves losses. In this case we can think of heat losses in the engine, mechanical losses in the propeller shaft, losses due to the propeller dissipating energy in the water, and energy dissipated in the water by the ship's hull. Each component has an energy efficiency defined as the ratio of the incoming energy and the out flowing energy.

The energy flow is described with two variables, called effort and flow. Power is the product of effort and flow, and both effort and flow can be input or output for any component. For the example of a ship's propulsion system we find: energy from the fuel is the product of enthalpy (h) and mass flow (dm/dt), power of the diesel engine and of the propeller shaft is torque (M) times angular velocity (ω), power delivered by the propeller is thrust (F) times vessel speed (v), see Table 1 and Figure 1.

TABLE I. EFFORT AND FLOW DEFINITIONS OD VARIOUS FORMS OF ENERGY

Domain	**Effort**		**FLow**	
Mechanical translation	Force F	[N]	Velocity v	[m/s]
Mechanical rotation	Torque M	[Nm]	Angular velocity ω	[rad/s]
Hydraulic	Total pressure p	[N/m2]	Volume flow rate Q	[m3/s]
Electric	Voltage U	[V]	Current I	[A]
Chemical	Chemical potential μ	[J/mol]	Molar flow dN/dt	[mol/s]
Thermodynamic	Temperature T	[K]	Entropy flow dS/dt	[W/K]
Thermodynamic (stationary)	Specific enthalpy h	[J/kg]	Mass flow dm/dt	[kg/s]

Figure 1: Representation of ship's propulsion system in bond-graphs with effort (above the arrow) and flow (below the arrow) variables.

The GES model was originally developed for merchant ships, and in project ESIF adapted for fishing vessels. Prediction models are used based on first-principles (which means following physical laws, e.g. Newton's Law), semi-empirical data and supplier input and have been verified with empirical data. These models were developed or converted for use in GES by TNO.

An overview of technical components for which quantitative prediction models exist is shown in the table below. Various well-known developed models were applied, e.g. the hull shape model of Holtrop, and the Wageningen B-series, and Ka-series open water diagrams, as well as a range of engine characteristics put in separate accessible libraries.

TABLE II. OVERVIEW OF TECHNICAL COMPONENTS FOR WHICH QUANTITATIVE PREDICTION MODELS ARE AVAILABLE

Item	**Model**	**Variables include**
Vessel design		
hull shape model	Hydrodynamic combined resistance models, semi-empirical	speed, length, draft, beam
hull shape model	Holtrop (systematic empirical series)	speed, length, draft, beam, use of bulbous or axe bows
hull shape model	Fishpow (systematic empirical series)	speed, length, draft, beam
Propulsion systems		
Engine	First principles, semi-empirical	all supplier specs
Shaft	First principles	diameter, length, nominal loss
Diesel electric system components	First principles (incl. switchboards, converters, etc)	all supplier specs
Gear box systems	First principles	gear ratio, nominal loss
Propeller	B-series (systematic empirical series)	diameter, hull clearance, shape and number of blades
Propeller with nozzle	Ka-series (systematic empirical series)	diameter, hull clearance, shape and number of blades, nozzle
Propeller	Design curves (KT,KQ, J diagrams)	Advance speed, RPM, pitch, diameter
Controlled pitch propeller	Design curves (KT,KQ, J diagrams)	Advance speed, RPM, pitch, diameter + pitch controller
On board energy consumers		
Auxiliary engines	First principles, semi-empirical	all supplier specs
Freezing or cooling plants	First principles, basic	cooling specs
Winches	First principles electric motor	motor specs, winch diameter
Blocks	First principles	diameters, line angles
Gear (beam trawl)		
Warps	First principles	diameter, length, number (double or single)
Connecting chains	First principles	chain diameter, chain length
Blocks	First principles	length, weight
Trawl shoes	First principles	length
Beam	First principles	width, height, diameter
Tickler chains	First principles	chain diameter, separated in length groups and numbers
Roller gear	First principles	diameter, weight
Sprout	First principles	number of chains, chain diameter, configuration

B. Examples of detailed models

The model of the propulsion system consists of several components that are depicted in Figure 2, an example for a beam trawler. Starting from the fuel tank connections are made to the main engine, propeller shaft, propeller, vessel's hull and fishing gear, the latter characterized by their drag vs. speed relationships. A suit of different engines, propellers, etc., can be taken from libraries with their own characteristics. The model is very versatile and components and connections can easily be changed.

In the case of a beam trawl the drag vs. speed relationship is derived from its components (Figure 3). Here warps, sprout, beam, trawl shoes, and tickler chains are represented separately, and each of these components can de changed in dimensions, drag coefficient C_D, bottom friction coefficient, etc. The system is very versatile and many variations can be calculated in a short time.

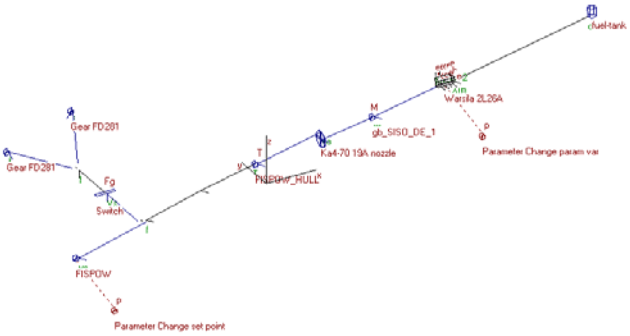

Figure 2. Example of a propulsion train for a beam trawler modelled in GES

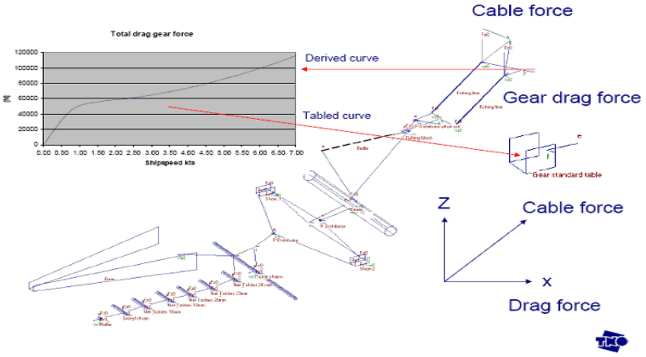

Figure 3. GES model for a beam trawl split in components

For otter and pelagic trawls such a detailed model was not used, but often in these cases a so called 'working point' (i.e. one point of the curve where speed and drag are known) was sufficient and a general drag vs. speed curve was fitted through this point to derive the drags at other speeds. In other cases a complete speed-drag curve could be given from actual drag measurements at full scale "(Sala, 2002; Sala et al., 2008; Ward, Montgomerie, and Lart, 2005)", or from fishing gear simulations using programs like DynamiT™ by IFREMER "(Vilebas, Farruga, Vincent, 2008)".

C. Operational profiles

Another major source of input affecting the energy consumption is what we call the 'operational profile' of a vessel, the distribution over time of various operational modes (e.g. steaming, shooting and hauling gears, fishing, searching, laying in harbour, etc.) with their corresponding sailing or towing speeds over a complete year. An example of such input is given in Figure 4 below. This profile may vary from vessel to vessel depending on the fishing location and thus distance to cover from home port to fishing grounds, but also on the behaviour by the skipper (e.g. sailing and/or fishing with full speed).

No [-]	Name [-]	Description [-]	Duration [hrs]	Distance [nm]	Velocity [kn]
1	Harbour		1.00	0	0.00
2	Steaming to fishing ground		17.00	170	10.00
3	Free gears		0.00	0	1.00
4	Fishing		12.00	60	5.00
5	Pull gears		4.00	0.04	0.01
6	Searching		22.00	220	10.00
7	Steaming to harbour		17.00	170	10.00
8	Harbour operation		12.00	0	0.00
9	End		-1.00		
10					
11					
12					
13					
14					
15					
16			85.00		

Figure 4. Example input of an operational profile in GES (BIM otter trawler midwater OTM 24-40m)

D. GES-output

The GES-program produces a number of outputs, of which some examples are given below. The yearly total fuel consumption is graphically represented in Figure 5 for all operational modes or conditions lumped together.

The efficiency of the installation in various operational modes is depicted in Figure 6 below. In this case we see that fishing and steaming have similar values, while gear handling is much less efficient. Depending on the time used for these activities one can expect them to affect the total energy consumption over a complete year.

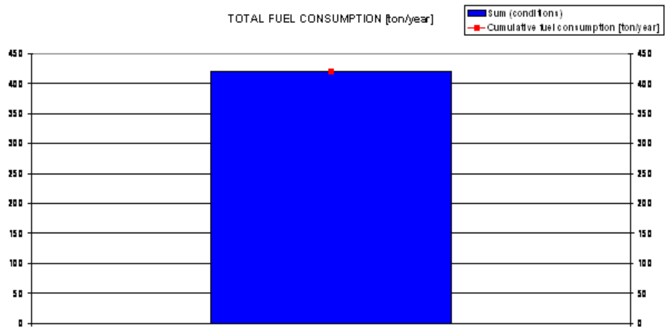

Figure 5. Example of yearly total fuel consumption (FR segment otter bottom trawler OTB: 24-40m)

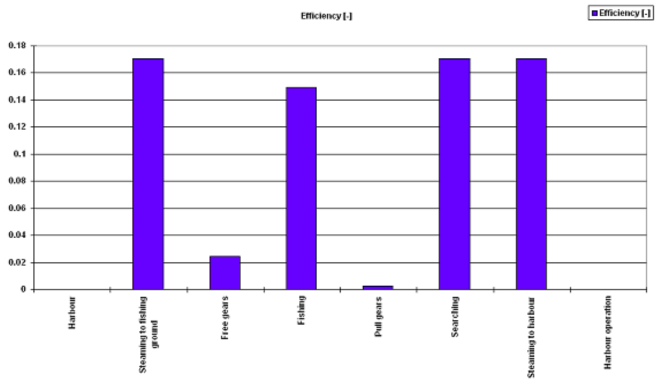

Figure 6. Example output of efficiencies in various operational modes in GES (BIM otter trawler midwater OTM 24-40m)

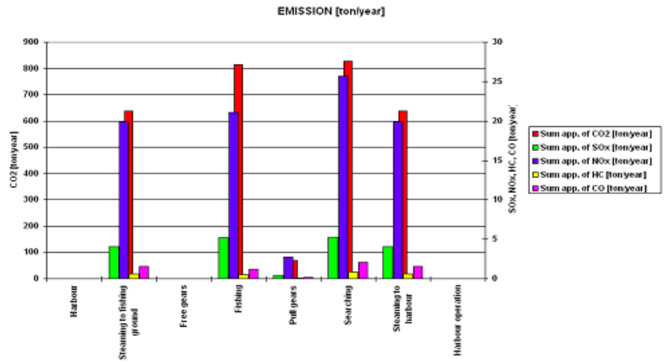

Figure 7. Example output of greenhouse gas emissions in various operational modes in GES (BIM otter trawler midwater OTM 24-40m)

Another interesting output is strongly related to energy consumption, i.e. the emission of greenhouse gases by the engines. A split over various operational modes is given in Figure 7. In merchant shipping more stringent regulations concerning these emissions are expected to come into force from 2011, and fisheries will probably not stay unregulated concerning this aspect.

E. *Cases studied in the ESIF-project*

Data collected from a total of 10 reference vessels cases in the participating nations (Table III). A total of 65 (some in more than one country) technical and operational adaptations were selected for these vessels and analysed using this model. These technical and operational adaptations featured: redesigned fishing gears including all their components to reduce drag (e.g. light material warps, more efficient otterboards, reduction in netting twine area, use of thinner twines "(Sala, 2002; Sala et al., 2008; Vilebas, Farruga, Vincent, 2008 ; Ward, Montgomerie, and Lart, 2005)", use of T90 meshes, hydro-dynamically shaped beams in beam trawls), changing from twin to single rigs "(Rihan, 2004)", converting from trawling to seining or from beam trawls to outrigger trawls, applying alternative stimulation of fish in gears to become susceptible to capture (electric pulses of manipulation of the water flow inside the net) to replace heavy bottom chafing material, optimising propeller design (e.g. using a propeller nozzle, enlarging propeller diameter where possible), improving hull shape, adding a bulbous bow if not fitted, but also of operational nature such as: use of fuel meters, reducing steaming and towing speeds, maintaining engines properly, cleaning hulls more frequently "(van Marlen et al., 2008)".

The percentage change in energy consumption found, estimates of additional investments needed, and effects on catches and earnings were derived as inputs for an economic evaluation.

TABLE III. OVERVIEW OF REFERENCE VESSEL CASES STUDIED IN THE ESIF-PROJECT

Country	FR	NL	BE	IT	UK	IRL
# vessels	1	1	1	2	2	3
# cases	3	8	6	9	11	28

III. RESULTS

A. *Fuel use by gear components*

A first order estimate of fuel savings potential for various components is provided for a typical 2000 hp beam trawler. This is based on deriving the fuel consumption per component by decomposing the energy flows. Interactions between various components have been ignored at this stage. Therefore hard conclusions cannot be derived from it at present.

An example of a so-called Sankey diagram is given in Figure 8. This shows that most energy is lost through heat emission in the main engine. The propeller also dissipates a considerable amount of energy. Further losses are caused by the ship's hull, fishing gear and its components.

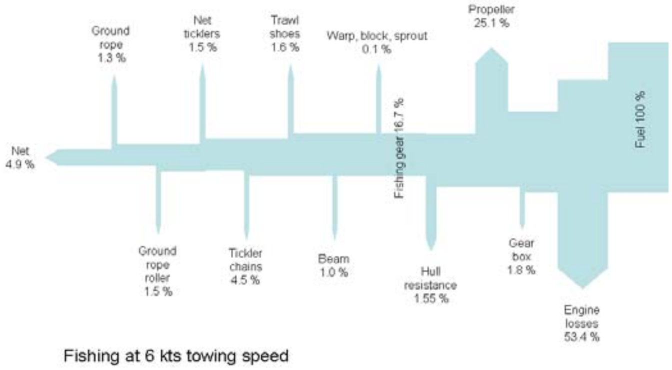

Figure 8. Sankey diagram for a beam trawler

Technical descriptions and data were collected for the selected cases. Part of the description required is quantitative data of technical performance expressed in terms of energy production or consumption. They are dependant on design and/or product specifications.

B. *Fuel use by component as a function of towing speed*

The main engine consumes all of the energy (auxiliaries not included) when speed is zero, and the percentage drops with rising speed. The propeller has a maximum for this example at about 1 knot, then slightly falling back. The gear has a somewhat quadratic contribution rising with speed and reaching a maximum. Components on the bottom have a low contribution, with a maximum for the trawl shoes and some ticklers at about 3 knots. The net itself has an almost linear rising fuel use with speed (Figure 9). In this analysis it is assumed that the gear stays on bottom with increasing speed.

The energy losses from the beam trawl shoes decline with speed, those of tickler chains attached to the shoes have a maximum at low speeds (~1 kt), then are declining. Similarly for net ticklers, but are much lower values. The net, the groundrope with roller, and the beam consume more energy at higher towing speeds (Figure 10).

The percentage savings based on GES-simulations for a range of adaptations in vessels, gears and operational profile was found to vary between 5% and 50%, with the highest rates for the most energy consumptive gears, e.g. demersal beam and otter trawl (Table IV).

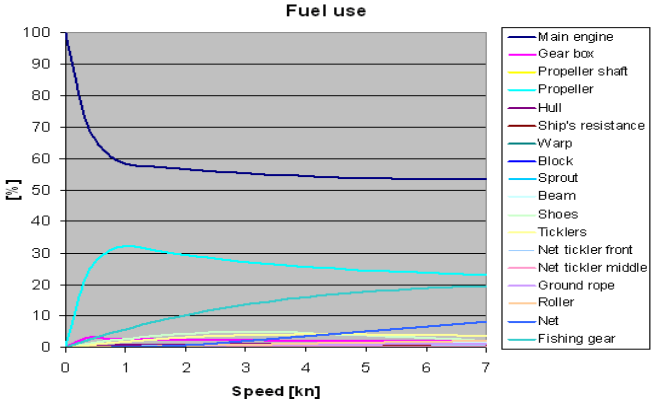

Figure 9. Fuel use by gear component as a function of towing speed for a 2000 hp beam trawler

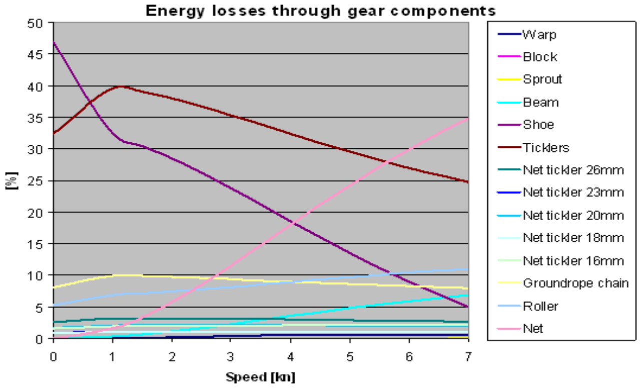

Figure 10. Energy losses by gear component as a function of towing speed for a 2000 hp beam trawler

TABLE IV. SUMMARY OF ENERGY EFFICIENCY AND ROLE OF POTENTIAL SAVINGS

MS / gear	**Length (m)**	**Range of potential savings (%)**
Belgium		
Beam trawl	24-40	5-50%
Denmark		
Demersal trawl	12-24	5-30%
Demersal trawl	24-40	5-30%
France		
Demersal trawl	12-24	15%
Ireland		
Demersal trawl	12-24	8-21%
Demersal trawl	24-40	5-20%
Pelagic trawl	24-40	5-25%
Italy		
Demersal trawl	24-40	8.5%
Netherlands		
Beam trawl	24-40	7-40%
United K.		
Demersal trawl/seine	12-24	5-15%

MS / gear	**Length (m)**	**Range of potential savings (%)**
Demersal trawl/seine	24-40	10%

IV. CONCLUSIONS AND RECOMMENDATIONS

A. *Conclusions*

The GES-model was shown to be a very versatile and flexible tool to predict the energy use of technical components of machinery installations onboard, fishing gear in relation to the operational profile of the vessel. It can help in identifying ways to save energy and reduce greenhouse gas emissions. The range of savings can vary between 5% and 50% depending on gear type and vessel characteristics, with the highest values for energy consumptive bottom trawls (demersal beam and otter trawl).

B. *Recommendations*

New developments can be simulated using GES in order to appraise their energy saving potential. An economic analysis of investments, running costs, and cost savings should be added to make proper decisions. Further use of GES in the development of new fishing vessel and fishing gear technology is therefore advocated.

ACKNOWLEDGMENT

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