DYNAMIC ENERGY MODELING – A NEW APPROACH TO ENERGY EFFICIENCY AND COST EFFECTIVENESS IN SHIPPING OPERATIONS

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ABSTRACT

One of the primary drivers in ship design and operation is the requirement for fuel efficiency. Wide fluctuation of fuel prices, periodic market downturns and new environmental legislation force the shipping industry to look at alternative ways to manage energy costs. Traditionally, standard design practices consider worse case operational conditions in order to safeguard against the unexpected. As a result the components / systems installed onboard a ship are destined to operate away from their optimum point for extended periods of time considering the infrequent occurrence of extreme situations. This paper introduces a methodology of assessing the dynamic energy performance of a ship at global level for any given period of time. For this purpose, all energy systems onboard are modelled and integrated into an overall energy model, which is subjected to a set of environmental conditions and operational requirements. In this manner the energy flows onboard the ship are presented as a function of time. The paper concludes with discussion on the applicability of the proposed methodology in the phases of ship design, operation and retrofitting followed by a roadmap for further development. The proposed methodology will be implemented in the project *Targeted Advanced Research for Global Efficiency of Transportation Shipping* (TARGETS, www.targets-project.eu), which is jointly funded by the 7th Framework Programme and the industry.

Keywords: Dynamic energy modelling, Energy efficiency, Life-cycle assessment, Energy optimisation, Environmental sustainability

1. INTRODUCTION

The maritime industry is often addressed as a high risk business due to the exposure of ships and cargoes to the naturally hostile ocean environment, the increasing demand of society for services and products, the competition that incurs in the shipping market as a result, and the periodical intervals of economic recession. Such a combination of physical and financial / social parameter results in a dynamic environment where it is rational to expect that cost-effectiveness is among major concerns of shipping operations.

On the other hand, environmental considerations are also among the major concerns of governments and international organisations. Despite the imminent need for environmental friendliness of all human-oriented activities, it is also acknowledged that this can be achieved only with step changes in science and technology, which are not expected to occur in the immediate future. Therefore, before such changes become widely available and adopted by the industry, a regulatory framework is prepared in order to ensure that the greening of any industrial activities, among them shipping operations, will progressively comply and contribute to international targets for green house gas emission (GHG) reduction and control.

The combination of these above two aspects and the substantial dependency of the shipping operations on fossil-based fuels, the prices of which may fluctuate rapidly in short time intervals, force the industry to seek alternative ways to manage more efficiently its energy costs. Moreover, in a setup of intense environmental discussion with the introduction of MARPOL Annex XI it has recently dawned that energy efficiency and environmental sustainability (which traditionally has never been an issue as stringent regulations were never in place) are such congruent targets that one cannot be targeted without affecting the other.

With this realisation in mind, effort is spend in understanding how the systems onboard a ship interact with each other from a design and operational point of view, and which are their effects on fuel consumption. In this manner and the majority of cases, the simplified approach of static energy balances and worst case scenarios that are traditionally followed during ship design result in configurations which are destined to cope with rarely met conditions in daily operations. In other cases, more detailed studies will consider a range of operational conditions but the complexity of the global ship system (i.e. the interactions among its sub-systems) and its performance is never addressed to a sufficient extent. As a result, the energy systems onboard are destined to operate away from their optimum point (maximum efficiency) for a large proportion of their useful lives, and more importantly, they do not offer the much needed capability in energy and cost management.

This fragmented approach and the evident gap it creates is not without remedy. Contrary to the poor global treatment of the onboard energy systems, the modelling and performance of individual energy components enjoys a high degree of understanding. For example, naval architects have been studying hydrodynamic resistance since W. Froude's time and despite the difficulty of the problem they poses enough understanding and experience which allows the design of ships with the endeavoured hydrodynamic performance. The same is valid for the performance assessment of other systems onboard, like the internal combustion engine, which is equally well studied and understood to a large extent.

In response to the need for imminent answers regarding energy efficiency and environmental friendliness, the objective of the Dynamic Energy Modelling (DEM) methodology is to integrate the existing knowledge of component-level to ship-system level by defining the interactions among the energy systems (in the broad sense of the term) onboard and modelling the energy flows as a function of time. In this manner, the life-cycle energy performance of a ship (in terms of GHG emissions and fuel costs) will be addressed in much more comprehensive way during the design stage and it will be assessed alongside other design objectives (like cargo carrying capacity, stability, etc.). Moreover, rational representation of a ship as an autonomous energy system will provide valuable insight in operational practices and cost-effective retrofitting.

This paper elaborates on the basic philosophy of DEM, followed by its implementation methodology and applicability, and it concludes with the future steps for its establishment as a widely acknowledged tool in the maritime industry.

2. THE CONCEPT OF DEM

From a foundation of mature knowledge of the energy systems that comprise a ship DEM offers the integration environment where the interactions among various systems are captured holistically. By definition DEM is related to energy transfer, conversion and storage and their coupling as a function of time. The energy domains which are considered (for the current stage of development) are (Figure 1):

- **Mechanical energy models**, e.g., ship resistance and propulsion in various sea states;

- **Thermal energy models**, e.g., HVAC performance as function of external climate;

- **Electrical energy models**, e.g., electric power demand with respect to time of day, longitude / latitude, occupancy profile.

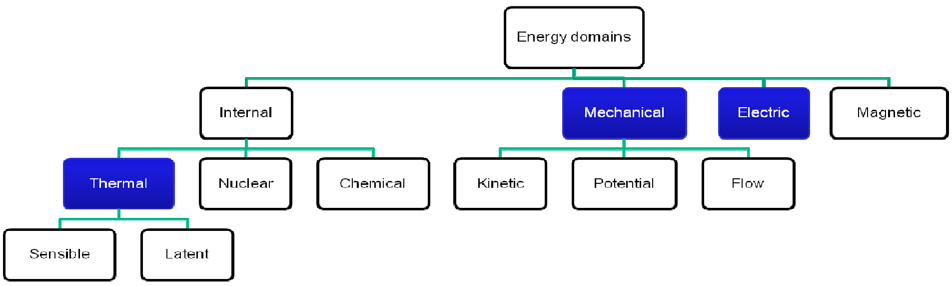

Figure 1: Energy Domains

The result is the holistic treatment of energy generation and utilisation onboard a ship, as it is elaborated in more detail next.

2.1 SHIP ENERGY SYSTEMS

The notion of a ship as an autonomous energy system pertains to the fact that energy is manipulated and utilised onboard without any external supplement. In this sense, the chemical energy that is converted by the main engine is transmitted to the propeller, the rotation of which produces sufficient thrust to overcome the hydrodynamic resistance experienced by the ship. In the context of DEM the "hydrodynamic resistance" is treated as an energy component, which is coupled to the propeller performance, the transmission losses through the shafting and gearing system, and the main engine performance.

This example demonstrates a series of considerations which have been included in the development of DEM:

- *Integration*: although the ship energy systems are identified very early in the design process (through a blend of past experience, cost and maintenance considerations) they are rarely treated as a total. This inherent deficiency is addressed from the outset in DEM as its fundamental feature, and it is very important as the economic and environmental life-cycle performance is concerned with the ship as one system rather than as a collection of individual systems.

- *Modular approach*: In order to treat the energy system onboard as a collection of sub-systems that dynamically interact with each other, each sub-system is modelled separately and according to its special nature and function (Figure 2). For example, the time domain performance of the internal combustion engines takes into account other energy systems which are connected at their boundaries (e.g. air cooler, economiser, etc.).

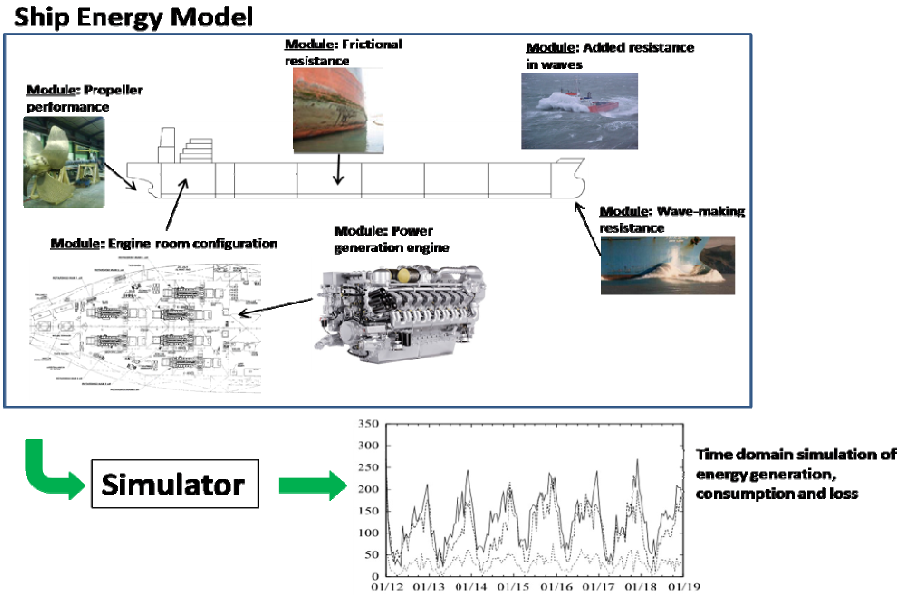

Figure 2: The modular approach of DEM

- *Alternative configurations*: The modular approach allows the definition of a library of system modules. That is, pumps, air compressors, diesel engine with 6 cylinders, diesel engine with 8 cylinders, wave resistance, air resistance, propeller, etc. Following this, the definition of various combinations that will correspond to the energy needs of the operational profile of the ship can be assessed.

- *Innovative energy systems*: The modular approach that is followed in DEM also allows the definition of energy modules like wind turbines, fuel cells, and solar panels. Such modules can be included in the configuration variations and integrated in the global ship model. In this manner their effect in the energy performance / footprint of the ship can be identified.

- *Rational representation of the operational profile*: Traditionally in the design process of a ship the sea environment where it is expected to operate is taken into consideration in the form of wave characteristics alone. In the DEM context however, this requirement is enhanced further by incorporation of ambient air temperature and humidity, sea water temperature, sunshine intervals, etc., all of which define the interaction of the systems onboard with the surrounding environment. Contrary to stationary platforms like offshore rigs and buildings, ships are travelling for a substantial proportion of their lives and the encountered environmental conditions cannot be taken into consideration in generalised format of average values. The rational treatment (i.e. the time domain simulation of energy flows) offered by DEM can cater for this requirement as well.

2.2 FROM THE RULE-OF-THUMB TO MULTI-OBJECTIVE OPTIMISATION

The existing practice for selection of the marine engineering systems for a new ship is frequently thought as an interactive procedure between the ship owner and the naval architect. The ship owner will decide about the main engine and other power plant machinery based primarily on past experience and economic considerations. Past experience reflects the ship owner's knowledge about issues like crew familiarity and training, spare part inventories and service support, (Molland, 2008). The economic considerations are mainly related to specification of fuel type, fuel consumption, installation and maintenance costs, etc.

The naval architect (design office and / or shipyard) on the other hand is mostly concerned with issues of propulsive efficiency, required electric power, etc., along with physical aspects like size, weight and location of the machinery installation. Above all, the designer should deliver a design which fulfils the contractual specifications and complies with rules and regulations. Although the engine and plant selection started like an interactive procedure, in reality it is sequential and leaves little margin, if any, for compromise, i.e. identification of "common ground" as every party protects its own interests alone, (Nurmi, 2008).

DEM can facilitate an improvement of this archaic process by offering the possibility to take life-cycle considerations into account and, on the basis of this, the platform for multi-objective optimisation for the new ship. That is, because the whole concept builds on a dynamic representation of the energy flows onboard as a function of one or more systems configurations and operational profile, the optimal solution can be found according to soft (experience and operational practice) and hard (emissions and fuel cost savings) objectives and criteria that mutually satisfy all involved parties. Moreover, because of the virtual representation of the onboard systems configuration testing of alternative systems (that fall outside the zone of past experience) is cheap and can be readily explored. For example, alternatives of four diesel generators (instead of three) of equivalent capacity, installation of solar panels on the accommodation block, fuel cells, etc.

2.3 ENERGY EFFICIENCY CONSIDERATIONS AT IMO

MEPC at its 58th session made noteworthy progress in developing technical and operational measures to address GHG emissions. The outcome was the development of the Energy Efficiency Design Index (EEDI) for new ships, and the Energy Efficiency Operational Index (EEOI) and the Efficiency Management Plan for all ships. In total these developments constitute a voluntary code on best practice in energy efficiency of ship operations, (MEPC, 2008).

At its 59th session MEPC disseminated interim guidelines on the method of calculation, and verification of EEDI for new ships, along with guidance on the development of a Ship Energy Efficiency Management Plan (SEEMP), and for voluntary use of the EEOI for new and existing ships.

Although the establishment of EEDI is a straightforward and encouraging step towards the greening of ship operations, and it builds on a holistic approach as it addresses the issues from the design stage, it still suffers from a series of deficiencies in its implementation:

- It represents the ship transportation CO_2 efficiency at a single point during the life span of the ship.

- The specific fuel consumption of auxiliary engines, which is used in the calculation formula, has minimal impact on EEDI. This can be misleading since the installed electric power capacity depends on other requirements like mission objectives and various safety margins.

- Larger cargo carrying capacity (payload) of the ship leads to improved EEDI since the capacity term is in the denominator. This renders larger ships more environmentally friendly than smaller ones.

- The generator power in the formulation depends on the installed main engine power. This can be misleading since the installed electric power capacity depends on the ship mission, various safety margins, classification rules, etc. As a result the less comprehensive approach under-sized machinery may appear beneficial.

EEDI is intended to stimulate innovation, technical development and operational improvement of all elements influencing the energy efficiency of a ship at regulatory level. This effort and development deserves and require further support by the industry and academic community. Along these lines DEM can offer the much needed realistic simulation of ship energy systems, which when it is benchmarked against real time measurements, it can set a rational foundation for EEDI and a comprehensive implementation process.

3. METHODOLOGY

The methodology of DEM will be presented in the following paragraphs in a top down manner. That is, from the ship's mission and functions to the systems and components representation.

3.1 THE SHIP'S MISSION

The ship mission can be decomposed into platform, hotel, general support and mission specific functions, (Woud et al, 2008). That is,

- *Platform functions*: carrying capacity, mobility and survivability
- *Hotel functions*: accommodation and protections from the sea elements, fresh water and air, sanitation services, heating and air conditioning, etc.
- *General support functions*: electric power supply, fuel circulation and supply, cooling and fresh water supply, compressed air supply, etc.
- *Mission specific functions*: anchor handling, fire fighting, lifting capacity, etc.

An example is depicted in Table 1, where the mission of a bulk carrier and an offshore supply vessel can be decomposed in a set of operational profiles and states, (Gaspar et al, 2009). For the portion of the time that the ship is operating at these states, a number of the above mentioned functions have to be performed.

Table 1: Mission, operational profile and operational states

Vessel Type	**Bulk Carrier**	**OSV**		
Mission	Cargo Transportation	Anchor Handling, Towing and Supply		
Operational Profile	Cargo Delivery	Anchor Handling	Towing	Supply
Operational States	At sea laden, at port loading etc.	Stand-by, alongside, A/H operations etc.	Towing, alongside, stand-by etc.	At sea laden, alongside unloading etc.

3.2 SHIP'S FUNCTIONS AND REPRESENTATION OF SYSTEMS AND COMPONENTS

In the DEM context a system is defined as a combination of machinery, equipment and hydrodynamic components, which along with their interconnections perform a task indicated by a function, (Woud et al, 2008). Table 2 presents some examples of mission specific energy systems of tankers, container ships, bulk carriers and Ro-Ro as a function of their operational profiles.

For modelling purposes, a system can be further decomposed (in a hierarchical manner) into *subsystems* and *components* (including their physical connections). A component can be further decomposed into many levels depending on the underlying functionality that define its behaviour. From a simulation point of view a component is regarded as the indivisible building block of an energy system and it may be physical in nature or fictitious. Its internal behaviour, i.e. the state of the component, can be modelled as a set of differential and/or algebraic equations, an explicit function or tabular data.

Many alternative techniques exist for the dynamic modelling of physical energy systems. Two of them are adopted in the current work: (i) the lumped and distributed parameter models, and (ii) the simultaneous and sequential models.

<u>Lumped and distributed parameter models</u>

The former approach assumes no spatial variation in states within the balance volume and the only objective is the time varying behaviour of the model, (Hangos et al, 2001). Contrary to this, the distributed parameter models include the spatial variation of states within the balance volume. The choice between the two approaches depends on the specific case requirements.

<u>Simultaneous and sequential models</u>

In the simultaneous approach all the equations of the system are implemented in one routine. This method allows the user to impose extra manipulations and simplifications to the equations and generally is faster than the sequential approach, (Colona et al, 2007). On the other hand, the sequential approach allows the standardisation of energy components, which can be stored in a library and recalled accordingly.

In the sequential approach a further differentiation can be made between causal and non-causal models with respect to their interactions. The causal components / systems have predefined interactions (input/output variables), contrary to the non-causal models, which allow for simplifications and rearrangement of the governing equations, (Colona et al, 2007).

So far, the development of DEM is largely based on the sequential and causal approach, whilst in some cases other approaches have been adopted (e.g. non-causal models).

3.3 MATHEMATICAL MODELLING OF SYSTEMS AND COMPONENTS

The output (or states) of physical components can be described with the application of mathematical functions given a number of inputs, parameters and initial states, (Grimmelius, 2003). Generally, there are three types of model classification: (i) black box, (ii) white box, and (iii) grey box models.

- *Black box* models use transfer functions, neural networks, etc. An essential requirement for this type of models is measured data from an existing component/system. They are not computationally intensive and the provided results are accurate but limited to the specific component / system, where the measurements originate from.

- *White box* models are based on first principles (usually together with constitutive equations) and they require mainly physical system parameters. They are computationally intensive due to the required spatial and temporal discretisation.

- *Grey box* models are a combination of the black and white box models. They require both physical parameters and some measured data and, depending on the type of problem and available background information, they perform accordingly.

In the modelling process of a system the following need to be identified:

- Whether the system / component performs energy conversion, transmission or storage;

- The system boundaries;

- The input, output and the states, which express the behaviour of the system / component; and

- The specific physical characteristics and constraints of the system (rated power, number of operational states, weight, maximum rpm, etc).

Finally, the boundaries of the system can be physical or abstract. The input to a system (or its constituents) can be subdivided into (i) *control* (input that can be controlled, e.g. control systems), (ii) *disturbances* (input that cannot be controlled e.g. environment), and *operational* (input influenced by ship's operations or other energy systems, e.g. cargo carried).

Table 2: Energy systems of tankers, container ships, bulk carriers and Ro-Ro as a function of their operational profile

		Operational Profile					
Mission Specific Functions	**Energy Systems**	Anchor	Port Loading	Port Unloading	Port Idle	Sailing	Man/ring
Tankers							
Provide cargo unloading capabilities	Cargo system		✓	✓			
Provide tank heating	Tank heating system	✓ (L)	✓	✓	✓ (L)	✓ (L)	✓ (L)
Provide tank cleaning capabilities	Tank cleaning system			✓			
Provide inert gas and ventilation to cargo tanks	Inert gas and ventilation system	✓ (L)	✓	✓	✓ (L)	✓ (L)	✓ (L)
Provide pump room ventilation	Pump room ventilation system		✓	✓			
Containerships							
Provide electric power to reefer containers	Electric power sub-system	✓ (L)	✓	✓	✓ (L)	✓ (L)	✓ (L)
Provide cargo hold ventilation	Cargo hold ventilation system	✓ (L)	✓	✓	✓ (L)	✓ (L)	✓ (L)
Bulk Carriers							
Hatch Cover Operation	Hydraulic Power Pack		✓	✓			
Deck crane operation	Deck cranes		✓	✓			
Cargo Hold cleaning	Fire & holds' bilge system					✓ (B)	
ROROs							
Provide electric power to reefer containers	Electric power for refrigeration system	✓ (L)	✓	✓	✓ (L)	✓ (L)	✓ (L)
Provide car deck ventilation	Car deck ventilation system		✓	✓			✓ (L)
Provide hydraulic power for	Deck hydraulic system		✓	✓	✓		

equipment in port							

(L): Partially of fully loaded condition
(B): Ballast condition

4. DEM IMPLEMENTATION

Application of the above models and modelling techniques for the energy systems onboard a ship will result in arrangements like the one presented in Figure 3. From the strength point of view offered by such a representation, DEM can be implemented in the design, operation and retrofitting stages as it is explained next. It should be noted that some components depicted in Figure 3 can be further decomposed in a hierarchical manner (e.g. main engine, auxiliary boiler etc.), as described earlier.

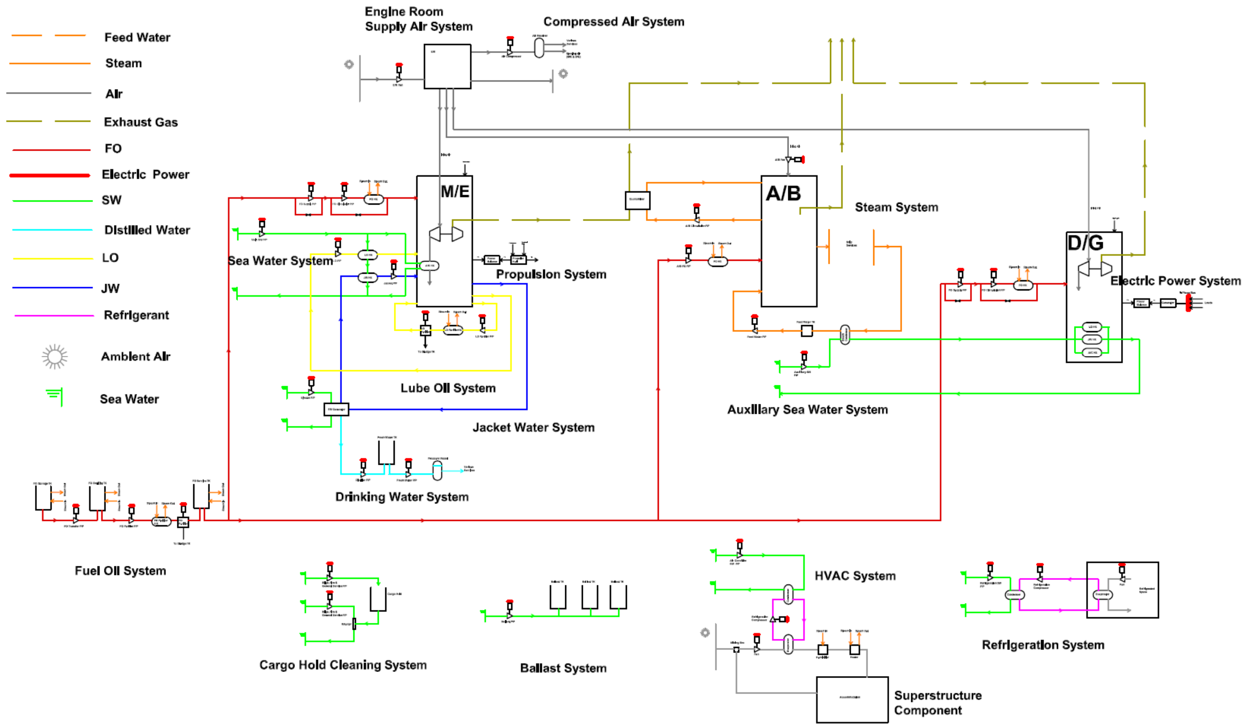

Figure 3: Simplified energy systems representation

4.1 DESIGN

DEM can be used for the assessment of the energy efficiency of a large number of designs in terms of system / component selection, power plant configuration, environmental conditions and associated operational profiles. Whilst DEM can be a multi-objective optimisation tool by itself (by addressing the energy performance of various sub-systems), it can also be part of a larger ship design optimisation framework by introducing the design for energy efficiency and minimum environmental impact alongside other design objectives. Thus, DEM facilitates a more thorough exploration of the design space and results like fuel consumption, engine emissions, power plant configuration, etc. can be directly associated to structural performance, stability characteristics, operational speed, etc.

4.2 OPERATION

Considering that the energy systems configuration of an existing ship is fixed for most of its operational life, DEM can offer the framework for energy management, thus providing a decision-support tool in real time that will indicate the best energy savings strategy during operation. This can be achieved since the DEM models are comprised by many individual sub-systems / components forming the whole ship-system. Thus, when DEM is used as an energy management tool, the focus will be shifted towards the environmental conditions and the operational profile of the ship and how the most energy efficient strategy can be achieved.

4.3 RETROFITTING

In the case of retrofitting, where some characteristics of the ship will be well known and defined like spatial arrangement and hull form, the evaluation of energy performance will be faster (narrower solution space). The DEM contribution in a retrofitting exercise is twofold:

- It can be used as a tool to identify poor performance of systems / components by assessing not only the performance of the particular item but how this affects the overall ship-system performance, and

- It can provide the necessary solutions for improvement by considering many alternative configurations within given boundaries and cost-effectiveness constraints.

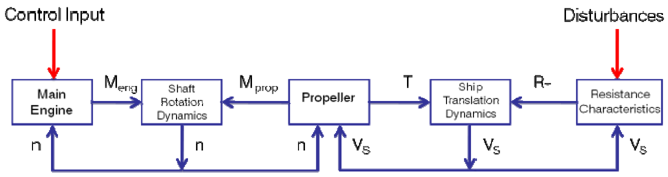

Figure 4: Propulsion system block diagram, (Schulten, 2005)

5. APPLICATION EXAMPLES

Example 1: Propulsion system

The modelling of a propulsion system (Figure 4) is subjected to the following requirements and considerations:

- *Function*: Conversion of chemical to kinetic energy
- *Input*: Chemical energy, control input etc
- *Disturbances*: Waves, wind etc.
- *Output*: Ship's Speed
- *Internal behaviour*: Prime mover - propeller (torque) balance, hull – propeller (force) balance, etc.

The Simulink model of the propulsion system is presented in Figure 5.

Example 2: Sea water cooling system

The sea water cooling system presented in Figure 6 has the following requirements and considerations:

- *Function*: Transfer of thermal energy
- *Input*: Pressure flow energy, shaft work, heat
- *Disturbances*: SW temperature
- *Output*: Dumped heat
- *Internal behaviour*: Motor-pump and pump-system power balance, e-NTU method, control system, etc.

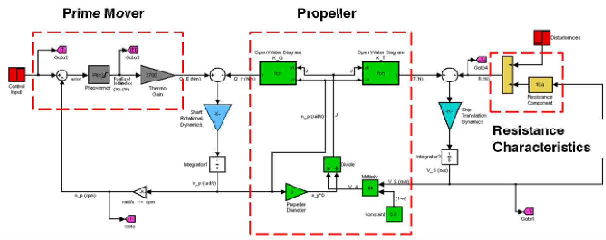

Figure 5: Functional diagram of the propulsion system

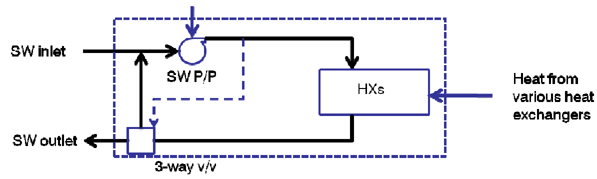

Figure 6: The sea water cooling system block diagram

The Simulink model of the sea water cooling system is presented in Figure 7.

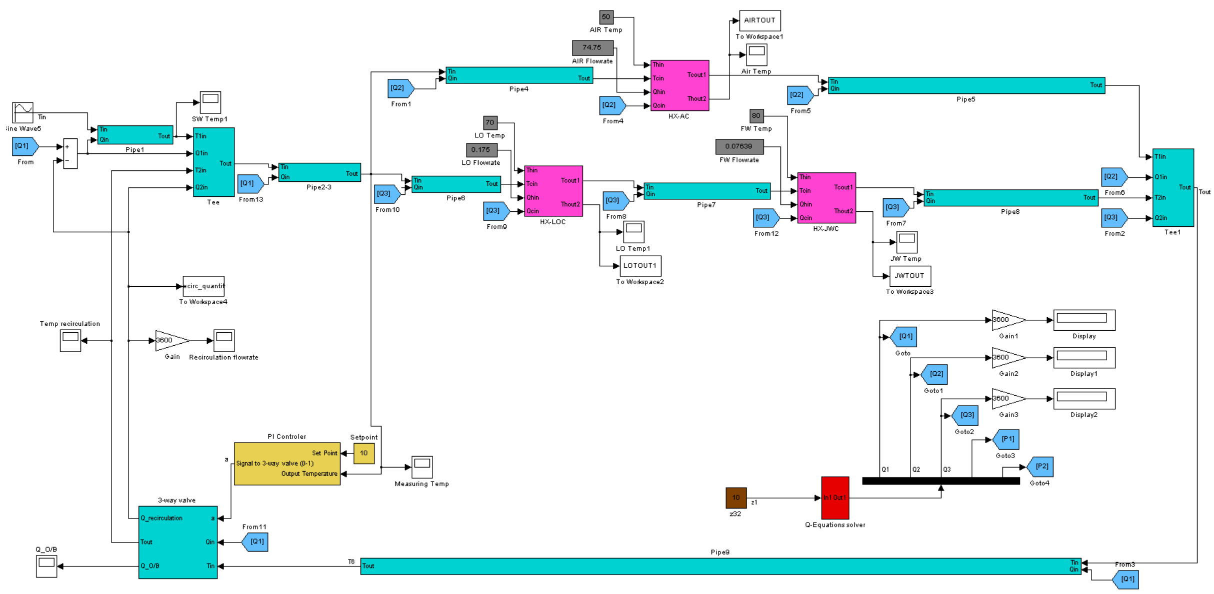

Figure 7: Functional diagram of the sea water cooling system

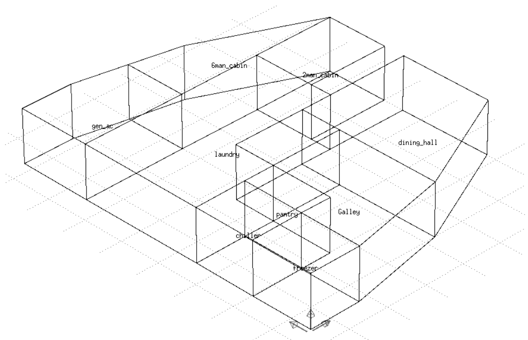

Figure 8: ESP-r model of the accommodation block

Example 3: Accommodation block

Example no. 3 presents a model where the thermal energy variation in an accommodation block is studied over a period of one week. In this case, the external environment, the occupational status and the lighting demand of the galley and the dining room respectively are taken into consideration. The necessary modelling and simulation in this case takes place in the ESP-r software (www.esru.strath.ac.uk/Programs/ESP-r.htm). Figure 8 presents the model and

Figure 1 the power demand variation for the interval under consideration.

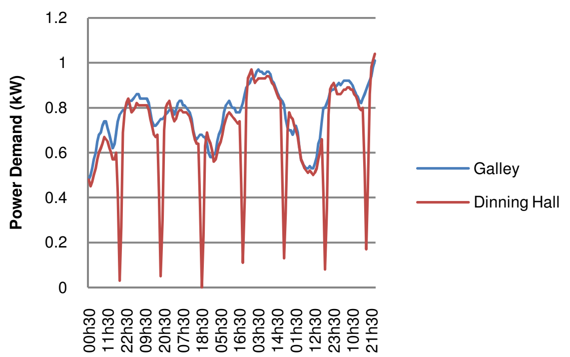

Figure 1: Temporal variation of the power demand in the two spaces under consideration

6. FURTHER DEVELOPMENT OF DEM

Despite the very promising nature of DEM and the ground that has been covered so far in its development, a number of issues are still pending to be addressed for the establishment of the method as a robust way to address cost and energy management onboard.

In particular the following major topics will be elaborated upon in the course of the TARGETS project:

- *Integration of hydrodynamic components*: the mature knowledge of the hydrodynamic performance of ships allows the development of knowledge intensive models (e.g. neural networks) to be integrated in the existing DEM routines. In this manner a progressively more complete picture of the lifecycle energy flow variations of typical ship types will be obtained.

- *Actual ship modelling*: Development of models of specific ships for which energy audits will be conducted onboard and will provide benchmarking and calibration data for the simulation results. These models will have various degrees of complexity in order to demonstrate the application in design, operation or retrofitting of a ship.

- *Uncertainty quantification*: Considering the highly complex nature of the systems treated in DEM, the uncertainty originating from (i) the lack of knowledge about the physics of the systems modelled, and (ii) the mathematical assumptions and approximations in the course of modelling will be quantified.

- *Energy efficiency optimisation*: When the models of the dominant energy components become available and the DEM models are benchmarked with real measurements, optimisation of the energy efficiency will be conducted in order to demonstrate how the newly acquired knowledge can be readily taken into consideration in the design stage.

- *Submission to IMO*: By the time the above actions are completed there will be sufficient data available for an information paper which will be submitted to IMO in order to contribute to the ongoing discussion on the energy efficiency indices.

7. CONCLUSIONS

Similar to any other commercial activity, shipping operations entail cost management practices, which were never specifically targeted to the fuel consumption. This was attributed to low fuel costs and the lack of stringent environmental regulations.

However, this situation is bound to change in the foreseeable future. Under these circumstances environmental performance and energy efficiency are interlinked to such extent that one cannot be addressed in isolation of the other. Moreover, the forthcoming environmental regulations made apparent that traditional practices for dealing with energy efficiency in the design, operation and retrofitting stages are not adequate any longer. This issue has been acknowledged at IMO, where energy efficiency indices have been recently developed, despite the fact that they are at a very early stage of their development.

In light of this situation, the DEM methodology has been conceptualised and is currently under development. In DEM the energy performance of a ship is not treated as an average, a worst case condition or a steady state physical performance of the systems onboard. Instead the systems installed on a ship are treated as the components of the ship energy system, and emphasis is placed equally on their individual performance as well as their interconnectivity. When these two aspects are considered together a life cycle assessment of the energy performance of a ship can be achieved. It is believed that this knowledge will not only assist the industry to respond to the future challenges but also the IMO in the course of developing regulations that will nurture innovation across the industry.

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