THE EXTENSION OF SYSTEM BOUNDARIES IN SHIP DESIGN

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(DOI No: 10.3940/rina.ijme.2010.a1.167)

SUMMARY

In this paper we address the challenges arising from the public pressure to curb greenhouse gas emission from shipping. The shipping industry must expect that inefficiencies or sub-optimality in the transport systems will be curbed or punished severely.

We present available technology to improve energy efficiency, and argue that decisions to apply such technology in a design process have to consider the vessel in its operational setting. We further discuss how this affects existing or introduces new design parameters.

In the new situation, the relationship between a ship and its intended mission cannot be "broken" by a contractual document, such as a requirements specification. A ship designer needs to engage in the use of the ship, moving from being a ship designer to participating directly in a transport system design.In the paper we propose some amendments to existing models, and the framework of design tools, that facilitate this change.

NOMENCLATURE

DNV	Det Norske Veritas
ECA	Environmental Control Area
EEDI	Energy Efficiency Design Index
EIAPP	Engine International Air Pollution Prevention
GHGs	Greenhouse gases
IMO	International Maritime Organisation
KPI	Key performance indicator
MEPC	Marine Environment Protection Committee
PM	Particulate Matter
SEEMP	Ship Energy Efficiency Management Plan

1. INTRODUCTION

The maritime industry is in 2009 facing great challenges on several areas, of which we will point to two.

One is acute and short-term, related to the shock from the financial crisis that culminated in the Autumn 2008, causing massive and extraordinary measures in the world shipping community. The initial panic is starting to turn into an anxiety for the future, forcing a rethink of lots of aspects like ship size, steaming speed, fleet composition, route configuration, scrapping, layup, cancellation, and a host of other issues.

The other is also acute, though longer term. It pertains to the constantly increasing public pressure to cap emissions of greenhouse gases (GHGs). Shipping is estimated to have emitted slightly above one million tonnes of CO_2 in 2007, which corresponds to 3.3% of the global emissions. [1] The general expectation is that the shipping industry must partake in the same manner as other industry segments.

According to DNV and Lloyds Register [2], one may expect to see a need for a 70% drop in emissions by 2050 from a business-as-usual scenario of continued growth with same approaches as until now (see Figure 1). This 70% will not come from a single source. It is not about just picking low-hanging fruits, nor just the high-hanging. It is about exploring and exploiting all practical opportunities to achieve the overall objectives.

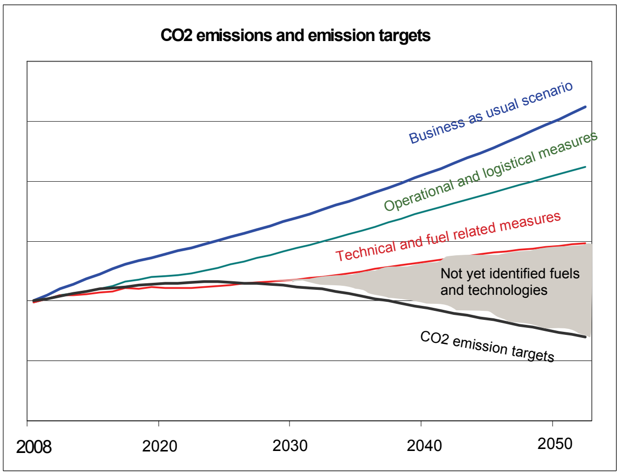

Figure 1 The gap between the generally accepted targets for reduced emissions and the contributions from different measures [1]

Both of these events will contribute to forcing a rethink of shipping into new ways of finding improvements. In this paper we focus on the drive towards reduced emissions. Fortunately, we are in a position that most measures aiming at reduced emissions of GHGs also lead to increased energy efficiency in times of with growing energy costs. For some, it will be profitable to be environmentally conscious and even conscientious.

In this paper we focus on the design of ships but, as will become apparent, in the definite context of the *mission of the ship* in a maritime transport system. We will argue that the shift will lead to several major changes in the ship design process, and shed some light on several of these. We will further describe how these changes may force a rethink, or an adjustment, of some important theoretical frameworks for then to present ongoing work at DNV, which aims to provide new tools to address these new methodological issues.

So – the maritime industry is set for a new era, and arguably a highly challenging one at that. It is at the same time about to part-take in a global concerted effort to dramatically reduce the impact of shipping in terms of GHGs and to position itself in a competitive manner in a period of unprecedented uncertainty and high commercial risks.

But the industry may hardly be said to have an agreed-upon and unified perception of what lies ahead – or even of what the current situation is. Are we seeing a paradigm shift or just a profound change, are the changes evolutionary in nature or is the shipping industry facing a revolution? However one prefers to view the situation, the fact is not debateable; requirements and expectations from the society in general are changing; as are the Rules and Regulations from the IMO, the Classification Societies, and Flag States / Port States.

2. CHANGES, WHAT CHANGES?

Our perception – or postulate – is that we are not facing a paradigm shift or a revolution, but it is arguably the closest thing since the oil crisis in the 1970s. This position is also backed by the observation that many of the industry players are struggling to find the right response to the compound effects of weakened markets (and prospects?) and new "rules of engagement".

In this section we will elaborate on what actually is conceived to facilitate the 70% drop from the business-as-usual scenario in Figure 1, and hence also provide a piece of firmer advice to the industry.

Few (at least not DNV) believe that there is one single, emerging technology that may provide such a feat. Rather, when decomposing the 70% into its different contributors, one will expectedly see a series of larger and smaller developments, implementations of new things in old ways, old things in new ways, and so forth.

Figure 2 represents one way at looking at this. A timely reminder: the 70% drop in emissions is related to the emission efficiency of the transport chain, which is to say that the emissions are measured per unit cargo and not only per vessel or per produced kW in a ship engine.

The big unknown factor [in the 70% reduction equation] is of course the category 'Not yet identified fuels and technologies'. This paper will not address these subjects, but suffice it to say that amongst the most promising prospects in this category, at present, is the still immature fuel cell technologies, battery powering systems that presume energy storage not yet feasible for use in ships, or small-scale CO_2 capture and handling systems that have not yet seen the light of day.

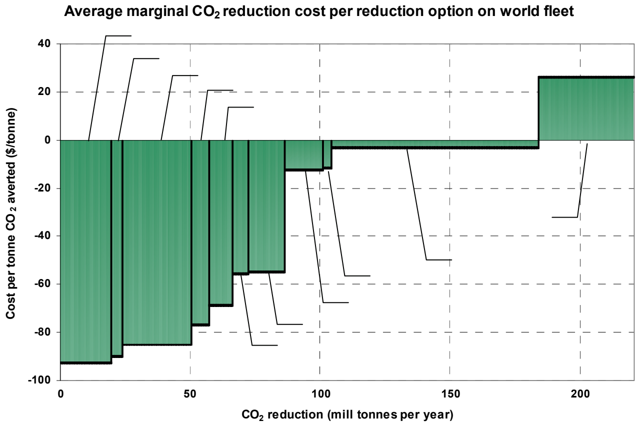

Figure 2 Different elements in a strategy of reducing emission, baseline 950 MT CO_2 per annum [3]

We will instead focus on the options that are already on the radar, and elaborate on how these may be applied in the design process to give their contribution to solving the task at hand:

A. What are examples of available "technical and fuel related measures" that either are not used or are used in an unsustainable (i.e. "less than optimal") manner? What causes are there for this non- or under-utilisation?

B. What are the key elements of "operational and logistical measures"? Why is this relevant in the design process?

And in the extension of these two items we'll move in the direction of a response to the challenges:

C. What are the design requirements, the KPIs that a design is measured against, in the present situation? How will changed objectives change the design of the ships in view of available technology or the foreseen operation of the ship? How does this affect the design process?

2.1. TECHNOLOGY

We start with the entry level question: Have there been (recently) or are there any anticipated groundbreaking or "order of magnitude" technological changes affecting or potentially affecting the ship design process or shipping business? We may stipulate that even a cursory review of the progress in the relevant areas would be able to identify such shifts; our position is supported by the notion that any such event would stand out clearly in both the media and the world of maritime research. Isolating the said review to a select few main areas we may further claim (or at least allege) the following:

2.1 (a) Shipping Business

No radically new technology has emerged over the last decades, but the business surely has changed with new financing methods and tax regimes, the establishment of an FFA (Forward Freight Agreement) market, the onboard IT and communications revolution, and so on.

There is though an increasing awareness that the business as such needs to change in order to reach true improvements in cost efficiency. Brett et al [4] notes that while *"... approximately 20% of the total transport costs is directly related to the ship operation [it] increases to 50% if the port operations [...] are included."* They argue for a *"logistics-based design (LBD) methodology"* that in itself will have to presume changes in the way shipping does business.

2.1 (b) Design Tools

This area spans the software and methodology available for the design team throughout the process.[1] Clearly, improvements within the fields of CFD and FEA, along with new engine technology, have paved the road for new generations of vessels; the emergence of the 'mega container vessels' being the most prominent example (see Figure 2). Nevertheless, this does not represent a radical shift as much as, perhaps, a rapid expansion of the boundaries – the new designs are still made on the back of well-established technology.

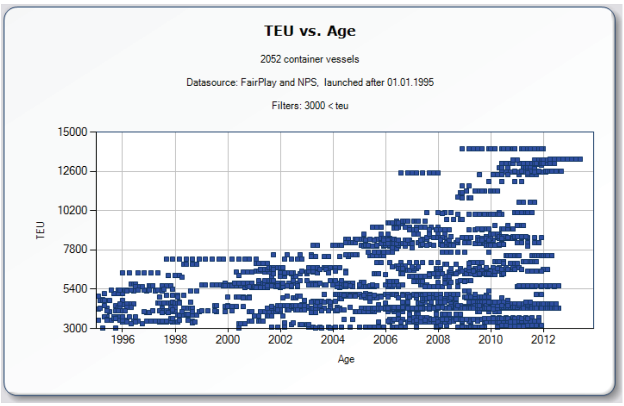

Figure 3 Size development of container vessels, built and contracts reported. [3]

CAD/CAM systems are continually improving, for instance through application of Artificial Intelligence techniques and heuristic modules for an ever larger degree of automation, but again – no radical changes. Over the next few years we might expect the first isogeometric analysis tools [4], i.e. the amalgamation of CAD and FEA and/or CFD tools, or even the 'numeric towing tank', to hit the market. This technology presents a number of interesting features that may allow a completely new view on designs – and on the rules for verification and approval of designs, to take the Class Society view.

2.1 (c) Engine Technology

Life Cycle Cost reductions are achieved through stepwise improvements, gradual sub-systems efficiency gains, and the harvesting of "low hanging fruits" through operational measures. Over the last 40 years or so, to take one example, the average specific fuel oil consumption (SFOC) for marine diesel engines has been reduced by less than 15%, which hardly constitutes a radical technology shift [6]. No emerging and viable alternative fuel technologies are on the horizon for the medium-long term, say before 2025 [1].

2.1 (d) Resistance and Propulsion

Defining this area to cover new propeller or propulsion-related technology, new hull forms and hydrodynamics in general, we find that the "state-of-the-art" performance is steadily improving, but that no radical changes have emerged. The world still waits for a super-slick, maintenance free coating. There are no proliferation of multi-hulled vessels, no shift to ballast-free designs (yet!), no dramatic change in propeller and propulsion arrangements [apart from a variety of pods, vanes, ducts, flow-adjusting and swirl-utilizing solutions, ...]. While described theoretically and applied to scale models, bio-mechanical propulsion (fish tails), magneto-hydrodynamic propulsion and the likes are not (yet) viable options. Solar and wind power remain marginal contributors in the foreseeable future, and nuclear power is certainly not regarded as a viable option in civilian ships.

2.1 (e) Materials Technology

The end of the steel ships era may not yet be prophesised, even if new and lighter materials are on the market. The cost effectiveness of steel, both in production and service, is unrivalled; sandwich constructions (of all kinds), aluminium, concrete and other materials are mainly reserved for special purposes, special vessel types or isolated parts of a vessel.

2.2. OPERATIONS AND LOGISTICS

Technical measures as per the state-of-the-art discussed above are assumed to be applied by all designers so as to maximise the potential performance gains for the ship per se. Such measures will thus not be enough for either designer or the owner to rise above the crowd and, more significantly in the long run, they will not be enough for the shipping industry to meet the demands for CO_2 emission reductions in the years to come.

[1] It has been claimed by some – in jest, for sure – that the most important tools remain the whiteboard and the Excel spreadsheet irrespective of available software systems.

The additional improvements in marine transport efficiency should therefore have to come from a wider systemic change; a rapid (continued) shift from "ship focus" to a "transport system focus"; see Figure 4:

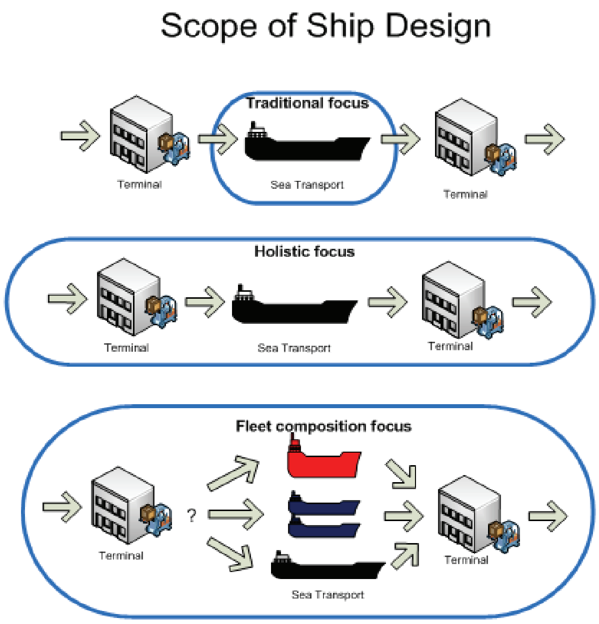

Figure 4 Shifting perspectives, from ship to transport system

The ship must be viewed as a part of a larger transport chain; optimization efforts must consider the total performance in order to avoid sub-optimization. Another illustration is provided in Figure 5; unless the design focus is widened from one leg in the route, the risk of sub-optimizing the transport chain is likely.

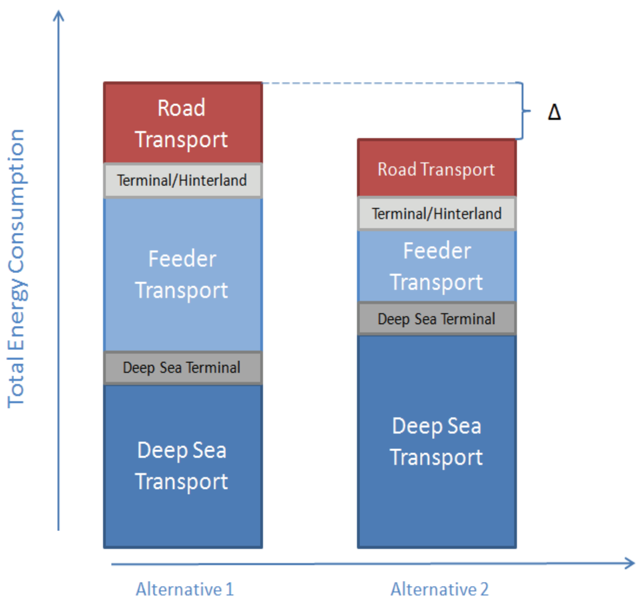

Figure 5 Energy consumption viewed in a transport system context [7]

2.3. SHIP DESIGN REQUIREMENTS

The focus of the shipping business, and hence also on the ship designer (or the design profession / design business), needs, in our opinion, to shift from optimizing the performance of the vessel for a specified transport task to optimizing the performance of the maritime transport chain, be it on a ship-, fleet- or chain level. The overall rationale or driving force for this would be the plain fact that this is a requirement from the society, as represented by the likes of EU and IMO, that the maritime industry satisfies the demands for improvement of the overall environmental performance of maritime transport services.

Environmental performance must be ranked much higher as an evaluation / decision parameter than before, even if shipping in several segments represents the most efficient mode of transportation (in terms of emissions to the environment) [6].

Fortunately, measures improving environmental performance will also tend to contribute to produce a vessel or a transport system that is more energy efficient than the "old" ones, which of course gives a fair ground for optimism on behalf of the environment with an expected fuel cost increased in the long run.

As the design scope changes, so will the success criteria – or KPIs or evaluation parameters or the likes of these – by which the goodness of the solution is measured. We will highlight three groups of evaluation criteria/ parameters that we expect will be more prominently ranked under the revised design regime:

2.3 (a) Societal Expectations

- Triple bottom line accounting: Finance, environment, Corporate Social Responsibility: The ship owner will need to document and account for the environmental footprint of his business along all three axes.
- Green logistics, environmental accounting[2] : The performance of the ship must be documented and the contributions from the sea transport leg of the total environmental footprint identified.

2.3 (b) Enforcement by Authorities

- Direct regulations: As new Regulations come into force, such as IMO SEEMP (MEPC59), fuel quality standards and ECAs, NOx emissions / IMO Tier

[2] "Today companies are held responsible for the environmental impact of the activities within their own part of the value chain. For the future however, the European Commission reveals that manufacturers will be held responsible for the green audit of the whole life cycle of the product from raw material to consumer". [8]

II/III engines, CO2 index, ballast exchange, PM emissions, scrapping - “Green Passports”, the documented vessel performance will be of essence. [7]
- Indirect regulations: Whether or not a system of taxes/levies or Market Based Instruments/ Emissions Trading Scheme (“Cap and Trade”) comes in place, further documentation or even shipboard online measurements will be required. Currently, the IMO EEDI regime is voluntary, but the intentions of MEPC is to make this mandatory.

2.3 (c) Managing Uncertainty

- Changing operating conditions. It will be important to consider performance under varying operating conditions, e.g. cost of energy, cost of modification / upgrades, or the introduction of new regulatory measures.
- Changing market conditions. Multi-purpose project carrier capabilities may be expected to prevail vs. specialisation, in order to enable ships to be commercially viable in fluctuating markets.

The list is obviously not exhaustive. The introduction of new success criteria (evaluation parameters, KPIs) will also affect the nature of the design process. The process to develop a ship conceptual design may for instance have to include the representation of a supply chain (logistics chain) model or transport model with associated simulation or optimization models. This should either be a on a ship-for-ship basis or a fleet basis, a carbon footprint assessment (preferably using the same model) for the transport chain and the ship, scenario-based evaluation of designs, and so on.

It is apparent that the scope of such investigations must be limited strictly so as to reduce problems to a manageable size, and also to reflect the fact that the design project is still in a feasibility study phase, where it is still unclear whether or not the project will come to fruition. The problem is thus a classical conundrum; the needs of the situation require both extremely advanced and work-intensive tools on one hand and a high degree of simplification allowing for numerous quick changes and tweaks to the task at hand at the other.

3. THE CHANGE IN THE DESIGN PROCESS

In this section we present our approach to design in the context of some basic theoretical foundations. When discussing the observed changes and how they affect both methodology and tools, we focus on three particular aspects of the design process:

- **The design within a design.** What is a product in a situation where the product being designed is both a transport system and a ship that is to be a part of the system?
- **The rules of the game.** How to accommodate changed premises; the design requirements upon which the ship design is based may change as the ship is designed?
- **The adaptive design process.** How to handle the fact that increased system complexity and customisation leads to increased need for flexibility in the organisation of the design process (and thus also the tools)?

The first of these represents the main issue and driving force. The two latter are mere important consequences of this.

3.1. DESIGN WITHIN A DESIGN; THE EXTENSION OF SYSTEM BOUNDARIES

As we argued previously, the design domain is expanding. The ship to be designed is not merely an answer to static requirements, but rather will influence its surroundings in such a way that the requirements themselves change. In some sense, the object of the design is expanded from the ship per se to the service or circumstances in which the ship will be placed.

In his seminal work *“The sciences of the artificial”*[9], Simon supports this by pointing to the fact that:

> *“The natural sciences are concerned with how things are. Ordinary systems of logic [...] serve these sciences well. Since the concern of standard logic is with declarative statements, it is well suited for assertions about the world and for inferences from these assertions. Design, on the other hand, is concerned about how things ought to be, with devising artefacts to attain goals.”*

Mistree et al defines designing as “…a process of converting information that characterizes the needs and requirements for a product into knowledge about a product” [10]. This is a quite common and generally accepted definition.

However, there are important qualifications or clarifications to be made here to adopt this definition fully. This clarification pertains to the concept of *product* itself and the concept of *knowledge about a product*.

We assert that the view of the term *product*, as used here, is relative. The main objective of the naval architect has historically been to evolve a ship as the *product*. The “needs and requirements” have largely been formulated as a result from a feasibility study or, for the most cases in practice, simply been handed over from a client through a brief or outline specification stating general requirements for, or expectations of, the vessel. The question of whether or not the ship is “needed” (in the market) is left with the customer, and the requirements are more or less given (though the alert naval architect will challenge those that seem counterproductive to develop a sustainable ship design).

However, as was stated in the introductory chapter, we claim that there is a rapid and persistent development that will have to modify this rather narrow perspective. In order for the naval architect to fully contribute to achieving sustainable designs, in this case meaning sustainable transport systems in which the ships are to operate or be a part of, the design of the transport system will have to be included as an integral part of the design process. It cannot (anymore) be a separate process of developing the "needs and requirements for a product" for then to be captured in a brief specification. It should in principle be possible for the designer to conclude that there is no "need" for the ship!

In some sense the definition of Mistree et al holds water anyway. It is clearly possible to interpret *knowledge about a product* to also include *needs and requirements for a product*. In this view, we implicitly use a model of thinking in which two inter-connected and converging cycles of product development prevail; first a cycle starting with *needs and requirements* for a transport system that develops (converges into) *knowledge about* the system, which then translates into *needs and requirements* for ships, that starts a new cycle aiming to converge into *knowledge about* the ships.

This relative view of what are *needs and requirement* for and what is *knowledge about* a product is also captured in Hagen; "[There] exists an ambiguity [in that] it is difficult to separate the world into one dealing with structure (or 'facts') [knowledge about] and one dealing with functions (or 'expectations') [needs and requirements]. The division is dependent on context and thus may be expected to change as the design process evolves." Here, the design process is implicitly presented as consecutive and converging cycles of generating and proving hypotheses. [11]

Gualeni and Dazzi capture this in [12]

> *"The ship can be read as a system of systems", and a wider vision can be suggested in addition: "System performance depends critically on how parts fit and work together, not merely how well each performs independently. Furthermore, a system's performance depends on how it relates to its environment, the larger system of which it is a part, and to other systems in that environment."*

This has significant implications on how actually a system's performance is assessed or predicted. This is, after all, one of the major tasks of a designer. Simply analysing the relationship between the physical or technical nature of the ship to its physical behaviour in a pre-defined sea-state and loading condition won't do. The ship as a physical entity in its own right must be viewed as an object, or input factor, in an overall system.

In Figure 6 we have schematically modelled this relationship. The traditional focus of the naval architect is in the middle, here simplified to providing the ship with a functional hull design and performance, as well as a propulsive system to bring it through the water.

However, on the upper part of the figure the mission of the ship is modelled. The hull design and performance, and the engine configuration, are traditionally set up to meet needs and requirements for one particular operating scenario, or operating profile.

In real life, the ship will not only operate in one such scenario. In fact, one might in some cases never see the scenario for which the ship was optimised (which might be flat sea, perfect hull and propeller condition, a certain sea temperature, at a certain trim, and other idealisations.

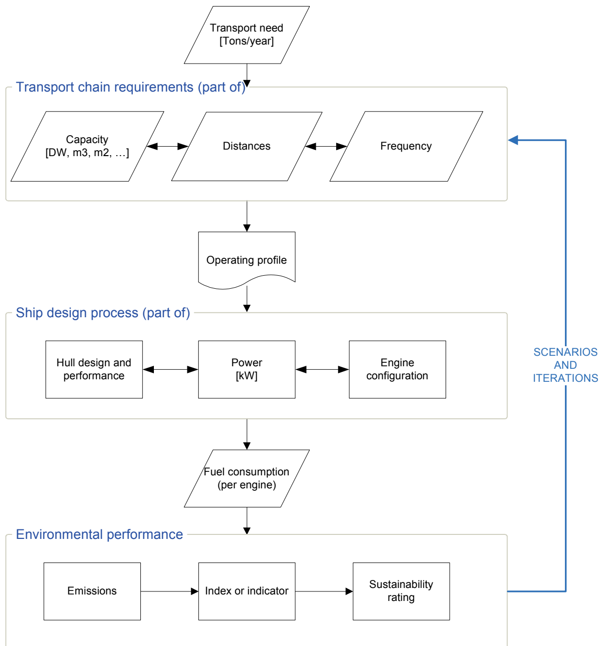

Figure 6 Simplified model combining a mission perspective with a ship perspective

In order to calculate our way through from a very general 'mission of the ship' to the timely 'emission from the ship', we need some mapping between the different concepts. Coarsely described, it might look something like this:

I. From annual transportation need, develop assumption on ship and thus capacity and speed;
II. From the above, identify frequencies, number of travels, time in different operational modes);
III. From required speed and ship size identify still-water resistance;
IV. From the routes, identify sea margin to the resistance;
V. From this and speed, identify propulsive needs;

VI. From mission, identify need for auxiliary power;
VII. From total power need and ship propulsive system, estimate total power production;
VIII. From total power production and knowledge about machinery configuration, identify MCR for each engine;
IX. From MCR and fuel type identify fuel consumption and emission to air;
X. From the above, identify the IMO or Classification Society sustainability rating.

Again – this is a sample only that might fit one specific design task. As indicated earlier in the section, the design process itself may not be perceived as being static. We'll revert to this in section 3.3

3.2. THE RULES OF THE GAME; ENTRY, RE-ENTRY AND THE CYCLES OF DESIGN

50 years ago, Evans introduced the design spiral to describe the cyclic nature of the design process [13]. The model has proven very powerful in capturing major aspects of the design process. It has since its birth been subject to refinements as the development has moved forward on design theory in general and ship design theory in specific.

These refinements have had several objectives, including to introduce also non-technical design criteria and to develop more refined ways at looking at the spiralling and converging processes at the end of which is a manifest ship design.

Some very enlightening contributions along this road have been made by Andrews 25 years ago [14], as reproduced in Figure 7, and in more recent years by the work of Mistree and others [10]. Dillon [15] also presents an excellent visualisation and discussion of the design spiral, as reproduced in the same Figure 7.

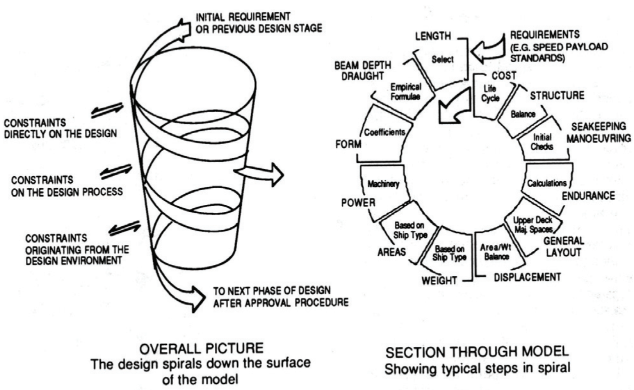

Figure 7 Representation of the design spiral showing external constraints on what is usually considered a closed spiral [14]

However, most prevailing models on the cyclic and converging nature of design attempt to define more or less clearly defined stages, stages in which an end forms the starting point of a new cycle. This is a pedagogic and grossly correct view, and particularly so if considering common practice where the duration and segregation of these cycles also are influenced by contractual milestones and obligation or the scope, responsibility and mandate of particular dedicated teams. Someone develops the *needs and requirements*, while someone else converts this into *knowledge about a product*. "Owners requirement", as seen to be the starting point in Dillon [15], is itself the result of a design process on a higher level.

We postulated earlier that the complexity of the product and the design process increase along several dimensions, both due to the uncertainties of the future, the multi-objective (and partly conflicting) key performance indicators, and the need for a more holistic view.

The less the ship being designed is viewed in its context, the higher is the risk of sub-optimisation in the search for sustainable maritime transport systems. As argued in Section 2, such sub-optimisation can be expected to be more punished and less accepted than historically.

This is also the core idea in [4], where Brett et al argue for a logistics-based design (LBD) methodology. The problem is that "vessel design, in many cases, currently [is] conducted as a sub-optimal and decoupled task in a technical department/shipyard isolated from the business development and logistics department." A more holistic view will, in an LBD-context, reduce the risk of such sub-optimisation as described above.

In the context of this, it should be non-controversial to claim that it may be sub-optimal to fix once and for all the *needs and requirements* to a ship as they result from an initial logistics or transport system study. Andrews [16] discusses this issue in a refreshing way by referring to requirements elucidation. "[Complex] design has been characterised as a 'wicked problem' … where identifying what is the nature of the problem (i.e. defining the requirements) is the main problem." (Page 72)

In other words, after having completed one cycle of development to find the requirements for the next cycle of product development, the latter may bring knowledge to the table that might entirely change the premises for the original requirements, justifying an 'outward spin'. But rather than cycling outward the opposite way, we might want to have some rapid re-entry into the outer cycle. We look for a wormhole through which it is possibly to get an indication whether a change at the present level of design knowledge actually has the potential to change the premises for the current stage when reviewed at a higher level. We need an impact assessment facility.

In principle, we are looking for partial differentiation of one big function. The ideal would be a method through which the designer may isolate the effect of one specific design decision on the performance of an overall objective function. For several reasons, however, this is most often not possible. The most important of these is that it, in our opinion, will be too costly (if not impossible) to develop such a mapping function. The mapping function Yoshikawa [17] described may exist in theory, but not at this level in practice.

Thus, to avoid the expensive and disruptive outwards spins or full iterations we are using what we term unit change matrices (UCM).

The principle behind UCM is not to be elaborated in full here, but it is based on an assumption that if a parameter change is infinitely small, then second- or higher-order effects may be ignored when evaluating the effect of the change on the function monitored.[3]

Locking all other parameters and changing one only slightly will in many cases give a hint as to the influence of that parameter. In essence, this approximates the partial derivative of the objective function on the parameter.

This is systematization, and a pragmatic one at that, aimed at representing a mapping function away from the present design point. It can be derived by statistical means (such as ANOVA-analyses; see Erikstad [18]), theoretical using direct partial derivation on formulae or numerical by iteration on programmed functions.

However, this alone is not necessarily what we want to achieve. The ultimate objective is to see the potential influence on any other value, all others locked, whether that value is the objective function itself or not.

To illustrate, we have created a UCM for a ship for the sake of investigating changes that may affect the propulsive power.

The sample is based on a tanker, using for the sake of simplicity the admiralty coefficient[4] as a function to define the relationship between displacement (Δ), speed (V) and power (P_B), representing the ship-related aspects:

Parameter	Baseline value
Deadweight	300 000 tons
Displacement	345 000 tons
Speed	15 knots
Engine power	24 000 kW
Admiralty Coefficient	692

Table 1 Main parameters of the baseline ship

A similar baseline is established for the mission as such, representing the operational aspects:

Parameter	Baseline value
Distance	6000 nm
Days in port	8 days total R/T
Return cargo	None (Ballast)

Table 2 Main parameters of the baseline mission

Combining the baseline ship and mission, assuming the ship is sailing (both legs) at its baseline speed, this gives:

Parameter	Baseline value
Time at sea/leg	17 days
Roundtrip duration	42 days
Annual roundtrips	9
Annual cargo	2 650 000 tons
Annual time at sea	7100 hours

Table 3 Calculated baseline values from the combination of a ship and its mission

Note that figures are rounded and that the sample is significantly simplified for the sake of illustration.

On the ship, the Admiralty-Coefficient is held constant (as pivot), which will be approximately correct when the hull and other conditions are subject to (very) small changes. Making a 1% change in each input parameter and seeing how each of the other parameters have to

[3] Such higher-order effects are well-known in ship design; design parameters are rarely uncoupled from or without influence on other parameters. This effect may be deterministic, i.e. an effect will follow as a logical consequence; increase the vessel length and the displacement increases, or it may be defined or programmed into the design process as a restriction, i.e. the vessel must be able to transit the Panama Canal, which represents a firm boundary for some parameters while others are available for variation by the designer.

In both cases, the changes to a parameter not done directly, but as a result of changes to another parameter that is connected through a deterministic or defined relation, is termed a second-order effect. Higher order effects will also occur through any extension of the "chain of relations".

[4] Admiralty Coefficient $C = \frac{\Delta^{2/3} \cdot V^3}{P_B}$

change to accomplish this, gives the unit matrix shown in Table 4:[5]

	1% increase in				
	240	*3400*	*0,15*	*3000*	*26600*
	KW	**Disp**	**V**	**DWT**	**Annual cap**
KW	NA	170	720	144	Undef
Disp	5 000	NA	(15 500)	3 000	3 000
V	0,050	(0,033)	NA	(0,029)	0,190
DWT	5 000	3 400	(15 500)	NA	3 000
Annual cap	Undef	30 000	21 000	26 000	NA

Table 4 Shows a unit change matrix (UCM) from the combination of ship and mission in absolute values. 1% increase in the parameter to be monitored is shown on top of each column, and the required reduction in one other parameter (all others kept constant) in the row. 240 KW increase in power allows for 5000 tons extra cargo. 3000 tons of extra cargo gives 26,000 extra tons delivered per year.

Thus, a 1% (3000 t) increase in DWT will increase displacement by 0.87%, which will reduce speed by 0.19% (0.029 knots), power held constant. It will increase power demand by 144 kW, speed held constant. The 1% increased deadweight will also increase annual cargo capacity by 26 000 tons, of course exactly 1%, if speed is constant.[6] A 1% increase in speed, by 0.15 knots, gives a need for increased power output by 720 kW.[7]

Inversely, aiming for a 1% increase (26 500 tons) in annual cargo carried will either require a 1.27% increase in speed or a 1% increase in DWT. The approximate cost of this increase in speed in terms of required engine power is 910 kW (1.27x720), while the "power cost" of the increased necessary deadweight capacity is 144 kW (1x144).

In other words, this approach is based upon one value to be kept constant either based upon physical facts or design decisions. Assuming we have three parameters of interest, A_1 to A_3. We let A_1 be constant and then predict the effect from a potential design change of A_2 on A_3 by evaluating how a unit change on A_2 influences the other parameters. We are in this case looking at the gradient at the design point of the curve plotted between A_2 along one axis and A_3 along the other (assuming the curve is linear at the design point and a region +/- 1%). This approximates a partial derivative, and can be used as guidance.[8]

	1% increase in				
	240	*3400*	*0,15*	*3000*	*26600*
	KW	**Disp**	**V**	**DWT**	**Annual cap**
KW	NA	0,71 %	3,00 %	0,60 %	Undef
Disp	1,45 %	NA	-4,49 %	0,87 %	0,87 %
V	0,33 %	-0,22 %	NA	-0,19 %	1,27 %
DWT	1,67 %	1,13 %	-5,17 %	NA	1,00 %
Annual cap	Undef	1,13 %	0,79 %	0,98 %	NA

Table 5 Similar to table 4, but showing a unit change matrix (UCM) from the combination of ship and mission in relative values. 1% increase in power allows for 1.45% increase in DWT.

	Increased speed, deadweight fixed	**Increased deadweight, speed fixed**
Changed annual transport capacity	26 500	26 500
Change in required engine power	910 kW	144 kW
Changed time spend sailing	-17 hours	0 hours
Change kWh spent at sea annually	6.3 million kWh	1 million kWh
Changed fuel spent annually (0.2 kg/kWh)	1 270 tons	196 tons
Changed fuel cost annually (500 USD/tons)	630 000 USD	98 000 USD
Fuel cost per additional cargo ton delivered	24 USD	3.7 USD
Changed CO_2 emission annually (3.2 g/g fuel)	4 100 tons	630 tons

Table 6 Using UCM to calculate scenarios for increasing annual capacity on selected KPIs[9]

What is not shown in table 5 is that the increased capacity of 26,500 tons requires about 1 million kWh annually when speed is held constant, while the same increase when speed is increased and deadweight is constant is 6.3 million kWh annually (increased power

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[5] In this case we might use first principles directly, and doing partial derivation on the Admiralty Coefficient.

Finding the partial derivative of power on speed, we would then get: $\frac{\partial P_B}{\partial V} = 3 \cdot \frac{\Delta^{2/3} \cdot V^2}{C}$

to calculate the overall effect of an infinitesimal change in speed on required power. However, the sample in the text is to illustrate an approach that does not presume knowledge of the parametric representation of a relationship, but can rather apply any means to detect the unit change effect (for instance simulation or regressions).

[6] Changed lightship weights due to larger hull and heavier engines are ignored in the sample.

[7] The effect of, for instance, increased power on annual capacity is undefined since it is not obvious whether the excess power may be used for increasing the displacement or for increasing the speed. It might rather be defined as a range of opportunity.

[8] Of course, it is not clear what happens at a change of 2%. The method thus should be used with caution so as not to direct searches to purely local optimum.

[9] This is certainly only a part of the analysis. Both other costs, capital cost utilisation and effect of increased speed on achievable freight rates are relevant in a complete analysis.

demand, slightly less time at sea). Some key figures are extracted in the table 6.

In a design situation, UCMs can be calculated for each baseline vessel and baseline mission, for all critical and relevant indicators and decision variables. Parsing the unit change matrices enables us to indicate the sensitivity to design decisions, not giving the exact answer but giving an indication whether a change causes so large an impact on important indicators that a full new iteration or complete exit to the outer cycle has to be performed. It may be used as an impact assessment facility.

3.3. THE ADAPTIVE DESIGN PROCESS; CUSTOMISING AND CONFIGURING THE DESIGN WORKFLOW

As discussed above, there is a need for a (mostly temporary) exit from the current cycle to revisit the process that develops the *needs and requirements*. Likewise, while progressing along the current cycle, knowledge will be developed that may affect the outcome of tasks already done, thus also altering design decisions previously taken. This iterative nature of design is commonly known, and captured in several models. Asimow [19] presents a very complex and detailed such, where the design process is represented by sequences of decisions where there are ample possibilities to jump back a step or more. Mistree [10] takes this even further, and views the decisions as the main building blocks of the design process.

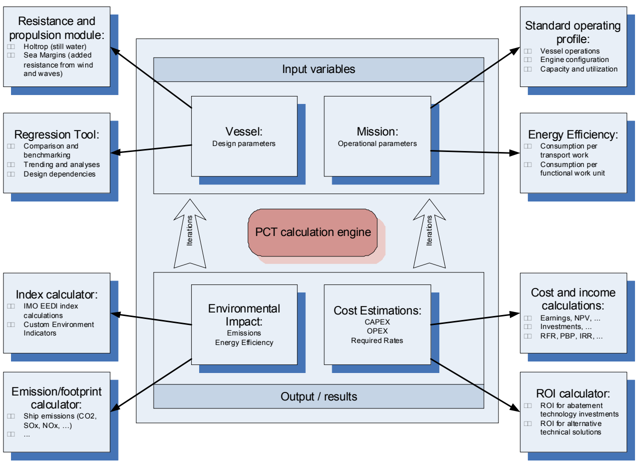

Figure 8 Software architecture, mission and vessel as two objects

These ways of viewing design provide good guidance. However, they model design as a (mostly locally) iterative and (grossly fundamentally) sequential process, and tend to build rigour into it. This is partly intended, since several models have had this as a motivation to stimulate design efficiency and control. The sequential nature (though with several options to step back at various decision points) is implicitly a way of reducing the complexity in the process and, in some models, also a way to prescribe "the correct way of doing things". If focussing on the descriptive models, they tend to support the strategy of what Goel and Pirolli [20] call Limited Commitment Mode Control Strategy (LCMCS), in which complexity is handled through more or less pragmatically focussing on the tasks at hand while momentarily 'forgetting' other aspects that in theory may be affected by these tasks.

However, while this of course also becomes more important as complexity increases, it also introduces an increased challenge. Predefined processes obviously tend to predefine the most important tasks to be completed at various steps. Implicitly, this also will tend to second-guess what is the intention is of the designer in these steps. Ultimately, in the worst case, this presumes which goals or objective functions drive the process.

The handling of complexity is partly also the motivation behind the Set-Based Design approach that Lamb and Kotinis present in [21], enabling "the sensitivity of any design characteristic [to] be individually determined, without occurring any 'hidden effect' of, or on, other design characteristics." In Set-Based Design a range (set) of a selected main parameter is established, after which other parameters are evaluated in feasible ranges to find a "best match" for each member of the original set. This may reduce the overhead related to moving towards an optimum, but still is sequential in that it treats "the segments individually and in the correct sequence."

As the problem complexity increases and as the design objectives become increasingly multi-objective as in the trade-off between functional performance, technical integrity, commercial soundness, environmental sustainability and robustness to meet an uncertain future, it is not easy to know what tasks the designer will focus on at any one point in the process. While tools made to design a ship, as a predominantly technical system may fairly easily build a 'good' process into the tool, this is not anymore an obvious option. The designer needs to be able to alter the process consecutively by calling on a wide range of analytical resources on demand.

In 2008 we presented a framework and essence of a service-oriented tool in development that addresses this issue, noting that "(new) designs will be more adaptive or flexible, (thus also causing) the design process (to shift) from a more pre-defined path or process towards a flexible and configurable process." [22] This is essentially in line with several theories also described here, except that we see little way of building a path, or implicitly a 'best practice', into the tool without being able to freely deviate from this practice. The process would seem to become too complex for that.

4. CONCLUDING REMARKS

In this paper we have shown that there are strong driving forces, both commercial and environmental, that necessitates a rethink of what is ship design. Our contention is that it will become impossible, in the future, to continue with the sub-optimisation inherent in designing a ship to fixed requirements based on old design indicators.

Rather than accepting such sub-optimisation, we then need to be able to design the ship for optimal, total, performance under uncertain scenarios. In order to facilitate this, the traditional way of designing ship needs to change significantly. The naval architect must be able to understand the impact of design-stage decisions on the overall performance of the transport system, and ideally also to change the configuration of that system when that radically increases sustainability or robustness.

This implies that the spiralling and converging nature of ship design, as manifested in models from Evans, has to be amended even more than that which has been excellently formulated by Andrews and later on Mistree. Though the result is converging, we must be able to break rapidly away and force an outward spin at any point in the process.

We have presented an approach in which a complete (often expensive) outward spin can be avoided. We look to a toolkit and process in which we can model the main concepts, or objects, of the design – the ship and the mission of the ship – and call upon analytical services when needed.

To detect the impact on the overall transport system of particular decisions, we have introduced an impact assessment facility in the Unit Change Matrices as a pragmatic way to indicate the effect of changing selected design parameters. By monitoring these parameters, we will then be able to assist the designer in analysing the true impact on a design decision, and thus also give the decision support needed for that designer to design the design process.

By broadening the perspective and increasing the flexibility of the design process, we claim that the ship designer will have more means at hand to make the right decisions. We claim this will reduce the risk of sub-optimisation while maintaining the necessary control and efficiency in the process as such.

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