HANDLING TEMPORAL COMPLEXITY IN THE DESIGN OF NON-TRANSPORT SHIPS USING EPOCH-ERA ANALYSIS

(DOI No: 10.3940/rina.ijme.2012.a3.230)

H M Gaspar and **S O Erikstad,** Norwegian University of Science and Technology, Norway
A M Ross, Massachusetts Institute of Technology,

SUMMARY

A core aspect of temporal complexity in the design of non-transport vessels is the uncertainty related to the future market and contract opportunities, and the corresponding changeability that should be incorporated into the ship design to meet this uncertainty. The development of an appropriate design specification for a new ship represents a core strategic decision for ship owners as part of a fleet renewal or expansion programme, with a high financial risk and a long time horizon of typically 20-30 years. This type of temporal complexity is one out of several complexity aspects to be handled as part of a ship design process.

In this paper we model possible realizations of an uncertain future for a vessel using the Epoch-Era Analysis (EEA) method. Here, we use the *epochs* as the primary instrument for capturing major market developments, such as the opening of new offshore areas, new emission regulatory regimes, or the availability of new, disruptive technologies. From these, more specific *epoch variables* are derived, for which specific contract opportunities can be generated. The epoch-specific performance of the vessels is found by solving a Ship Design and Deployment Problem (SDDP) of concurrently identifying both a preferable ship design and the corresponding path of consecutive contracts that maximizes total revenue.

We present a case study related to the design of an Anchor Handling Tug Supply (AHTS) vessel. The study illustrates the complexity in striking the correct balance between optimizing the vessel for an initial scenario, while at the same time providing addition performance capabilities to be competitive in the context of future market requirements.

1. INTRODUCTION

1.1 THE SHIP DESIGN PROBLEM FOR NON-TRANSPORT VESSELS

The fleet renewal programme is a core strategic process for shipowners, for which the determination of the appropriate design specification for a new ship is a key decision point. This decision is taken in a context characterized by a high degree of uncertainty, involving both a high financial risk and a long time horizon, typically in the range of 20-30 years.

For transport ships, the fleet renewal problem can be modelled as an extension of a routing problem with a predefined demand for transportation services. This problem can be modelled for the design of a single ship, Jansson and Shneerson [1], Garrod and Miklius [2], or for a fleet of ships determining the optimal mix of vessels with different sizes and speeds, Dantzig and Fulkerson [3], Bellmore [4], Fagerholt [5]. For non-transport ships, such as offshore support vessels (OSVs) and floating production, storage and off-loading vessels (FPSOs), the routing problem approach is less relevant. Here, we may instead model the future operating context of the vessel as a set of contracts to which the vessel might be assigned during its economic life. These contracts may vary in their duration, from far-term contracts lasting the lifetime of the vessel, to near-term contracts lasting for a year, a season, or less. The contracts also have different requirements for vessel capabilities and capacities. The general tendency is that these requirements become more demanding over time.

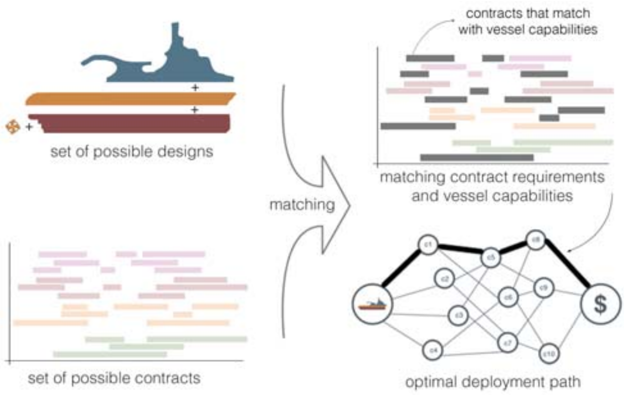


Figure 1: Vessel capabilities are matched with contract requirements to form vessel specific contract scenarios for which the optimal deployment path can be found

The decision problem associated with this situation can be modelled as a Ship Design and Deployment Problem (SDDP), Erikstad et al [6]. The SDDP formulation supports the concurrent identification of the optimal ship design and the corresponding optimal deployment of the vessel. This is a key strategic decision problem primarily for shipowners, but also for stakeholders such as offshore contractors, often entering into far-term leasing contracts of 5-10 years, and ship design consultants that increasingly take a more active role in the development of the outline specification in close collaboration with the customer, Ulstein and Brett [7]. In Andrews [8] this is referred to as *requirements elucidation,* aimed at finding a balance between opportunity revenue and vessel capability cost.

Thus, the basic trade-off in the development of the outline specification for a new vessel is between optimizing the vessel for its (likely) first, while investing in additional performance capabilities that provide a sufficient degree of capability and flexibility to meet a range of possible future contract requirements. Figure 1 illustrates the problem.

1.2 ASPECTS OF COMPLEXITY IN SHIP DESIGN

A systematic approach for defining complexity in ship design will be based on the ideas introduced by Rhodes and Ross ([9],[10]). Here, the complexity of a system is captured through five main aspects, namely:

- Structural (structure and relationships)
- Behavioural (performance)
- Contextual (circumstances)
- Temporal (changes in context / uncertainties)
- Perceptual (stakeholders)

The *structural* aspect is related to the arrangement and interrelationship of the functional and physical objects in the ship. This complexity is directly related to the ship as a large, self-contained system with a high number of highly integrated systems and with many parts. All basic systems must be provided by the vessel itself within a very limited contained volume, and changes to any part of the system tend to interact and influence other systems through complex relationships.

The *behavioural* complexity derives from the form-to-function mapping. Technical performance analysis, such as resistance and propulsion, seakeeping, manoeuvring, stability and structural, are both mathematically complex and computationally intensive. Those analyses rely to a large degree on advanced engineering analysis tools such as finite element analysis and computational fluid dynamics. Adding to this the economical, risk, safety and environmental performances results in a behaviour evaluation function that is both complex and inherently multi-objective.

The *contextual* aspect defines external operating circumstances to which the system is subjected. It consists of the external entities, interfaces and factors that affect the behaviour of the system, and should be taken into account when designing it. Examples of contextual aspects are the market variables (e.g., demand, contract, taxes, prices), regulations, rules and preferences. Some elements of the ship requirements can also be taken into account from the context into the system. For instance, the specification of what type of mission the ship should perform, as observed by Hagen and Grimstad [11].

The *temporal* aspect of complexity refers to changes over time during the system lifespan. Shifts and uncertainties in the context are also handled in this aspect. For instance the uncertainty related to the operational profile of the ship, or due to future contract scenarios. One of the traditional engineering methods to approach these uncertainties is scenario development / planning (Roberts et al [12]).

The *perceptual* aspect relates to how the system is interpreted from the perspective of system stakeholders. It considers individual stakeholder preferences, and how preferences vary across stakeholders. It must answer the question *How is decision X perceived by stakeholder Y?*

Figure 2 presents an overview of the 5 aspects, within the traditional ship design boundary, that must be incorporated in a complex systems approach. In the rest of this paper, we will primarily focus on the *temporal* aspects of complexity in the ship design process.

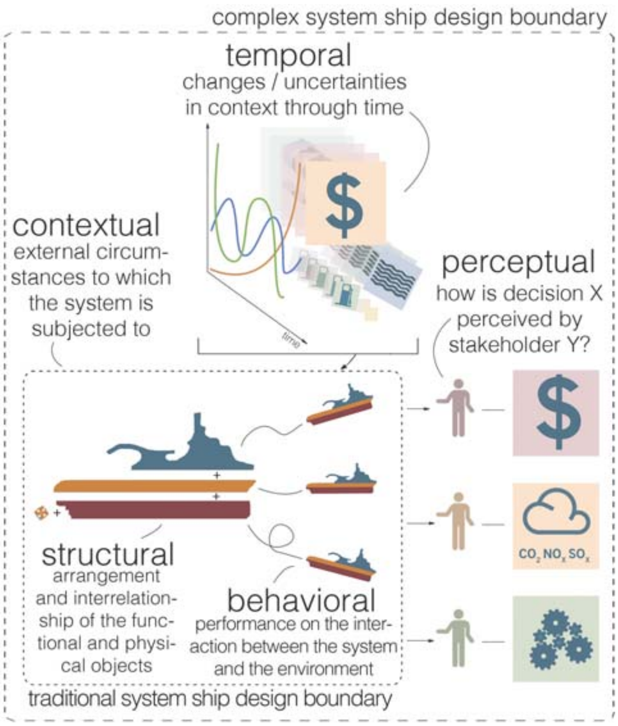


Figure 2: Five aspects of complex system applied to ship design

1.3 DESIGN OF NON-TRANSPORT VESSELS – SHIP DESIGN AND DEPLOYMENT PROBLEM (SDDP)

The SDDP is a binary integer programming model used to support the development of the contract specification for non-transport vessels. The SDDP model addresses the selection of an optimum design configuration for a vessel, while at the same time considering future contracts for which the vessel could be deployed (Erikstad et al, [6]).

The approach taken here is based on the assumption that we are able to create one or several scenarios that capture the expectations about the future operating context for the vessel(s), as observed in Figure 3.

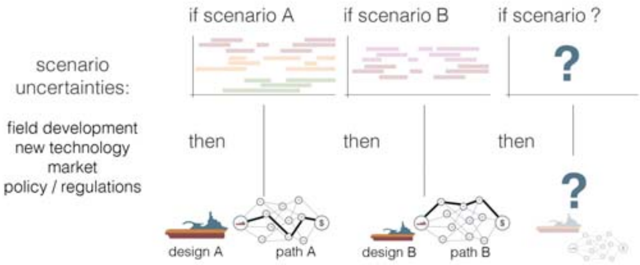


Figure 3: Context uncertainties for the ship design and deployment problem

For a given scenario, we have to match the corresponding contract's requirements with that of the vessel design capabilities. For each design we can thus derive a set of available contracts, for which we can generate a vessel- and contract-specific network model as is illustrated in Figure 1. The size-related complexity of this network will naturally depend on the capability level of the vessel, since highly specified vessels are able to serve more contracts than lower specified ones.

Each scenario can be described by a set of governing parameters. From these, a set of possible contracts can be generated, which will form the basis for evaluating a specific vessel design within this period of time. Each contract will specify a set of requirements for vessel capabilities, such as cargo capacity, deck area, bollard pull, operating depth, so that only a subset of the contracts will be available for the vessel.

Thus, each scenario S will have a set of contracts N_e, each one described by the following attributes:

$$\{T_i^S, D_i, R_i, [\varphi_i^1, \varphi_i^2, \dots, \varphi_i^n]\},$$

where T_i^S is the starting time, D_i is the duration, and R_i is the revenue of contract i. $[\varphi_i^1, \varphi_i^2, \dots, \varphi_i^n]$ is contract i's set of capability requirements for the vessel to serve the contract, where n is the total number of requirements.

In addition, we have a set of vessel types V, each described by:

$$\{C_v, [\vartheta_v^1, \vartheta_v^2, \dots, \vartheta_v^n]\}$$

where C_v is the cost of acquiring vessel v, and $[\vartheta_v^1, \vartheta_v^2, \dots, \vartheta_v^n]$ is a set of vessel capabilities. A vessel type v is said to be compatible with contract i if its capability ϑ_v^k is sufficient to match the corresponding contract capability requirement φ_i^k for all requirements, i.e. for $k = 1,2,\dots,n$. Erikstad et al. ([6]) presents the complete formulation of the problem with examples.

Naturally, there is a substantial degree of uncertainty related to the definitions of these scenarios. For a short term planning horizon, the variables may be based on actual contracts available in the market, or specific markets or offshore areas expected to become available. For scenarios further in future, the contracts may be generated randomly from a chosen distribution or via a *story telling* process, thus representing a realistic, though not a real, scenario.

In the next section we discuss the Epoch-Era Analysis (EEA) as a method to handle the temporal complexity aspects related to the shifts and uncertainties in the characteristics of future operating contexts. Section 3 applies the EEA to the SDDP problem, for both a short and long run. Section 4 presents a case study, and a discussion on the approach is made in Section 5, followed by concluding remarks in Section 6.

2. HANDLING FUTURE MARKET UNCERTAINTY

2.1 FUTURE MARKET UNCERTAINTY

Uncertainties are things that are not known, or known only imprecisely, as defined by McManus and Hastings [13]. In order to understand uncertainties, these authors develop a framework (Figure 4) connecting the lack of knowledge to the risk, then to mitigation/exploitation techniques which seek a more robust outcome.

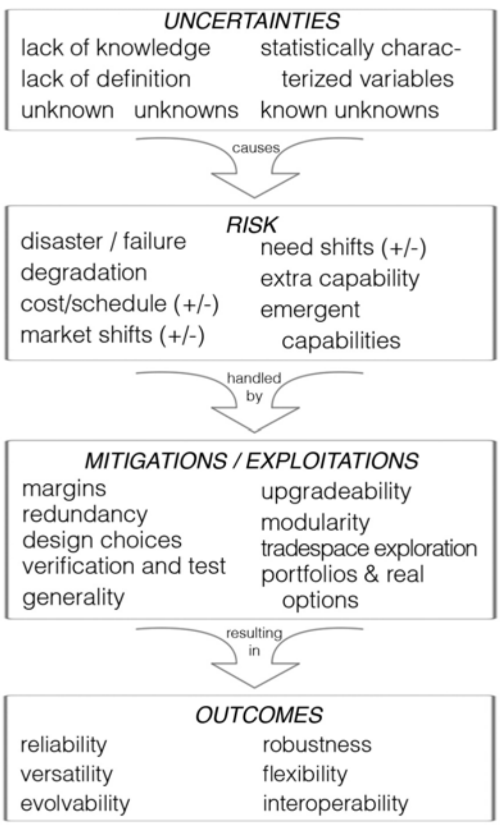


Figure 4: Framework for handling uncertainties and their effects McManus and Hastings [13]

In light of these definitions, we can rephrase the current SDDP as, for instance, uncertainties related to the lack of knowledge of future scenarios causes a cost/schedule risk to the shipowner; it can be handled by refinement of design choices, resulting in a more value-robust ship.

2.2 EPOCH-ERA ANALYSIS

The EEA method proposes a useful representation of the context, as an interval of time with a static set of contextual factors forming an epoch - from the Greek *epokhé*, which means a fixed period in time. Several epochs create a dynamic interval of time, a time-ordered set of contexts defined as an *era*.

EEA handles the temporal aspect by dividing the system lifespan into a series of epochs. Significant changes in contextual factors will trigger the start of a new epoch. Changes can include different context parameter values, which can be certain or uncertain. In the case of the design of non-transport vessels, these parameters are related to the following categories:

- Field Development: The opening of a new market may require different technology to be on board, such as ice class for an oil and gas field in the Arctic or ultra deep water equipment for operation in the Brazilian pre-salt offshore market.
- Technology Development: A new technology may require a different type of fuel, or strengthened steel foundations on the hull and main deck, altering the capabilities of a vessel.
- Policy / Regulations: Future regulations may create a new emission control area (ECA), such as limitation in SO_X or NO_X levels (SECA/NECA); or new rules related to dynamic positioning or fire-fighting, or even a mandatory air control method to prevent environmentally harmful emissions.
- Market: Shifts in the market can also trigger a new epoch, with alterations in the fuel and freight price, high or low demand condition and potential spot market options.

The EEA formulation is outlined in Figure 5. Each epoch E_e contains a set of scenario parameters $\{\varepsilon_e^1, \varepsilon_e^2, \ldots, \varepsilon_e^n\}$, defined as *epoch variables* (Ross and Rhodes [14]). The future scenarios are represented by the discretization of the parameters, from a range that takes into account the uncertainties and expectations. The sum of all epochs defines an epoch space.

Expectation categories are discretized into a vector of epoch variables, or group of uncertainties. The next step consists of enumerating the variable, which could include selecting a unit for the variable, and its range of minimum and maximum values, the number of steps and, optionally, weighting factors related to the impact of a given epoch variable compared to others. An example of the epoch vectors is presented in Table 1.

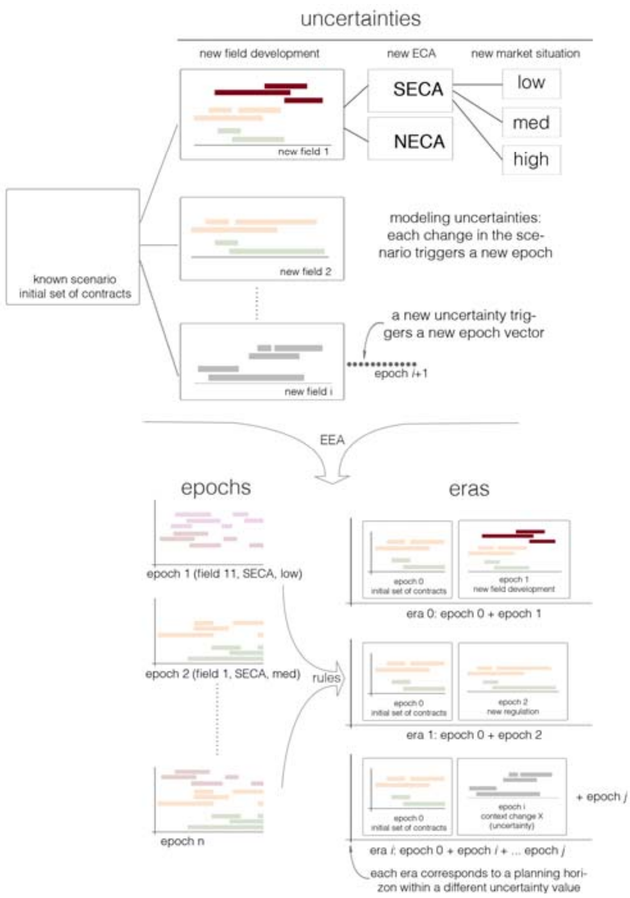


Figure 5: Epoch-Era formulation based on context shifts

Category	Epoch Variable ε_e^n	Unit	Scale (continuous or discrete)	Range (min-max)	Steps	Weight
Field development	New field (e.g. Brazilian pre-salt)	Field	Discrete	1 – 3	3 4	1 1
	Start Year	Year	Continuous	2015 - 2030		
Technology Development	New Technology (e.g Fuel Cells commercially available)	Technology	Discrete	1-3	3 4	1 1
	Start Year	Year	Continuous	2015 - 2030		
Policy/ Regulations	New ECA	ECA	Discrete	1-3	3	1
	Start Year	Year	Continuous	2015-2030	4	1
Market Conditions	New Condition	Condition	Discrete	1-3	3	1
	Start Year	Year	Continuous	2015-2030	4	1

Table 1: Epoch variables example

Each epoch variable represents a possible categorical change in a contractual scenario, and is instrument in the mapping between context parameters and vessel performance. For instance, considering the example in Table 1, a possible contextual change category can be the development of a new offshore area (from one to three concurrent fields), or a new starting date for the development of a field (possibilities are drawn from 4 equal steps starting from 2015, i.e., 2015, 2020, 2025 and 2030). For example, a unique epoch vector with three fields can be written as:

$$E_1 = \{Field\ 1, 2015;\ Technology\ 1, 2015; ECA\ 1, 2015;\ Condition\ 1, 2015\}$$

and a change in any of the values in the vector means a different context and therefore a new epoch. The process of epoch characterization as in the Table 1 example is illustrated in Figure 6.

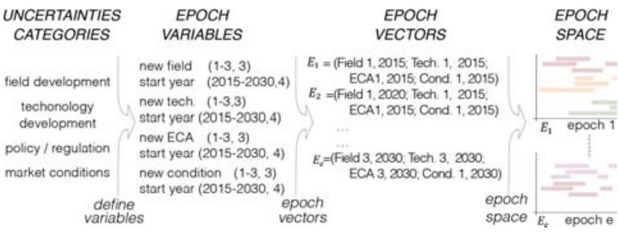


Figure 6: Epoch space characterization process

An era ξ_j represents the full lifespan of the system, and it is constructed by a time-ordered sequence of a given set of epochs $\xi_j\{E_e, \ldots, E_f\}$. This sequencing must obey consistency rules in the epoch variables, such as continuity constraints in the end of an epoch e and beginning of an epoch f, and consistency in the progression of epoch variables. For instance, a new oil and gas field, which starts operating in 2015, will likely not disappear in 2020 and reappear in 2025. However, it is possible to have an era during which such a field starts in 2015, another in 2020 and a third one in 2025. Stakeholder preferences, such as *all/no eras must contain X* can also be incorporated. Figure 7 illustrates the process of era construction from Table 1 epochs.

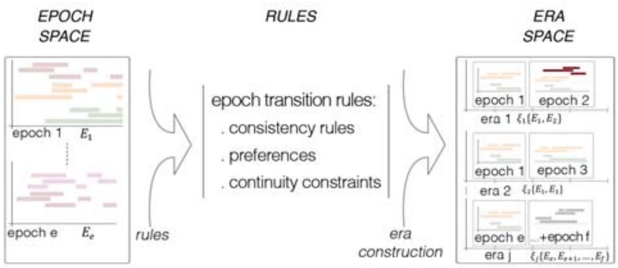


Figure 7: Era space construction process

3. SHORT AND LONG RUN OF SDDP WITH EPOCH-ERA FORMULATION

3.1 SHORT AND LONG RUN ANALYSIS

Ross and Rhodes [15] operationalized the economic concepts of short run and long run analyses (Pindyck and Rubinfeld [16], Goodwin [17]) in the EEA methodology. The short run is characterized by a time period during which the context parameters are fixed, and do not change, that is, an epoch. The long run is characterized by the lifetime period across which parameters may change, that is, an era.

The ability to incorporate changes in the lifetime of the system through the assembling of epochs gives to the era a more variable facet. It leads to the long run analysis, incorporating *the amount of time needed to make all production inputs available,* which in our case is the whole contract/design deployment.

Each of the analyses requires formulation of different questions. The short run takes into account the static problem, where the objective is to maximize revenue by the SDDP longest path problem.

The long run deals with the maximization of profit over an extended period of time. In addition to the problem of how to assure the correct assembling of an era, with the discontinuities and constraints of the given context changes, the main problem becomes the era space. Since the potential era space grows exponentially with the number of epochs, sampling or constraint-based strategies should be used to manage the number of evaluated eras. The following subsections cover approaches using stakeholder preferences as constraints, the *story telling* process and the efficient selection of particular eras.

3.2 SHORT RUN OF SDDP – EPOCH ANALYSIS

The short run problem consists of running the SDDP presented by Erikstad et al. [6] across the epoch space, and in each run transforming each epoch E_e in a scenario S. As a result, it is possible to rank the best designs by revenue in each of the epochs, using as utility parameters the total revenue of the path. A probability weight can be given to each epoch, reflecting the likelihood of its occurrence.

For illustrative purposes, let us consider a simple example, with few uncertainties. The example consists of a non-transport vessel to be designed towards a base contract set in the first 8 years, plus the uncertainty of whether or not two new fields will be developed in the future, with two possible dates to start the development. Table 2 translates the context parameters uncertainties into epoch variables.

Category	Epoch Variable ε_e^n	Unit	Scale (continuous or discrete)	Range (min-max)	Steps	Weight
Field development	Base contract set*	Field	Discrete	1	1	1
	New field: Brazilian pre-salt North Sea	Field	Discrete	1-3	3	1
Contract Period	Time Period	Year	Discrete	2012-2028	2	1

* - only in first period, from 2012-2020

Table 2: Uncertainties translated in epoch variables

Each field determines a set of contracts. In the example, the set will have a fixed number of 5 contracts per field. Each contract has the following parameters: contract number i, starting date T_i, duration D_i, revenue R_i and requirements value φ_i^1. Table 3 presents the contracts generated for each different context.

Context	Contract Number - i	Starting Date T_i^S	Duration (years) - D_i	Revenue R_i	Requirement Value - φ_i^1
Base Contract Set	1	2012	8	16	1
	2	2013	3	10	4
	3	2015	5	14	3
	4	2012	3	7	2
	5	2018	2	6	3
Brazilian Pre-salt	6	SY	3	9	3
	7	SY+3	3	10	3
	8	SY+5	2	5	2
	9	SY+1	7	17	2
	10	SY+4	4	13	3
North Sea	11	SY	5	20	5
	12	SY+2	4	15	4
	13	SY+4	4	16	5
	14	SY	2	7	4
	15	SY+5	3	12	5

Table 3: Contexts' contracts

Figure 8 translates Table 3 into epochs, based on the epoch vectors of Table 2.

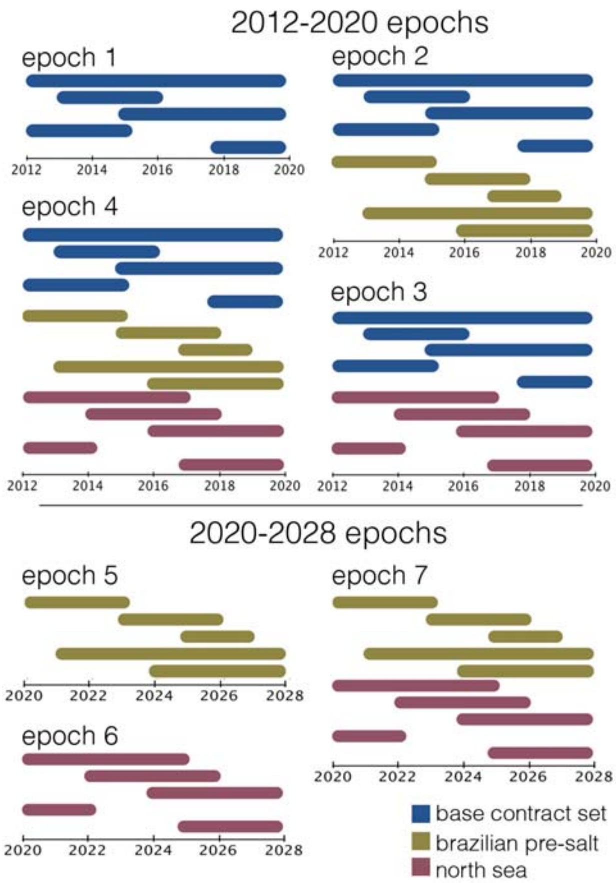


Figure 8: Seven possible epochs for the example

For the sake of clarity, the requirements φ_i^n in this example are converted into a *requirement value* φ_i^1 ranging from 1 to 5. A vessel with capability value ϑ_v^1 equal to or greater than φ_i^1 is able to meet to the contract, whilst vessels with lesser capability value are unable to meet it. The design alternatives are presented in Table 4.

Vessel ID v	Cost C_v	Capability Value - ϑ_v^1
A	15	1
B	20	2
C	25	3
D	30	4
E	35	5

Table 4: Design alternatives

For each epoch a SDDP run is performed (Figure 1). Results of these runs are obtained giving an optimum path, with the highest revenue, listed in Table 5.

	Designs				
Epochs	A	B	C	D	E
E_1 – Base Contract Set (2012-2020)	1	1	3, 2	3, 2	3, 2
E_2 – Base Contract Set + Brazilian Pre-salt (2012-2020)	1	9	5, 7, 6	5, 7, 6	5,7,6
E_3 – Base Contract Set + North Sea (2012-2020)	1	1	3,4	3,2	11,5
E_4 – Know Scenario + Brazilian Pre-salt + North Sea (2012-2020)	1	9	5, 7, 6	5, 7, 6	11, 5
E_5 –Brazilian Pre-salt (2020-2028)	-	9	10, 6	10, 6	10, 6
E_6 –North Sea (2020-2028)	-	-	-	12, 14	13, 14
E_7 –Brazilian Pre-salt + North Sea (2020-2028)	-	9	10, 6	10, 6	13, 6

Table 5 – Optimum contract path for each design in each epoch

The revenue for each vessel in each epoch is obtained by solving the optimum contract path problem. Figure 9 plots the sum of the revenue, for all epochs and organized by contract period and field development.

3.3 LONG RUN OF SDDP – ERA ANALYSIS

In the long run the epochs are used as modules that can be combined to create the full lifetime of the system, that is, the eras. It is assumed that the profit for an era can be estimated by summating the epoch revenues of that era minus the cost of the ship. Assuming addition is a simplification, which works well with the assumption that the duration of the contracts are always within the epoch period. Variation on those assumptions is discussed in Section 5. Ideally, we could skip the epoch analysis, and just create the eras, applying SDDP in each of them. However, the potential era space size grows exponentially, and cases such as the ones observed in Table 2 can easily be as high as hundreds of thousands of cases. When an era space is too large, it should be refined by selecting more likely values for the context parameters, narrowing down the number of eras to include those epochs with a higher likelihood of occurrence.

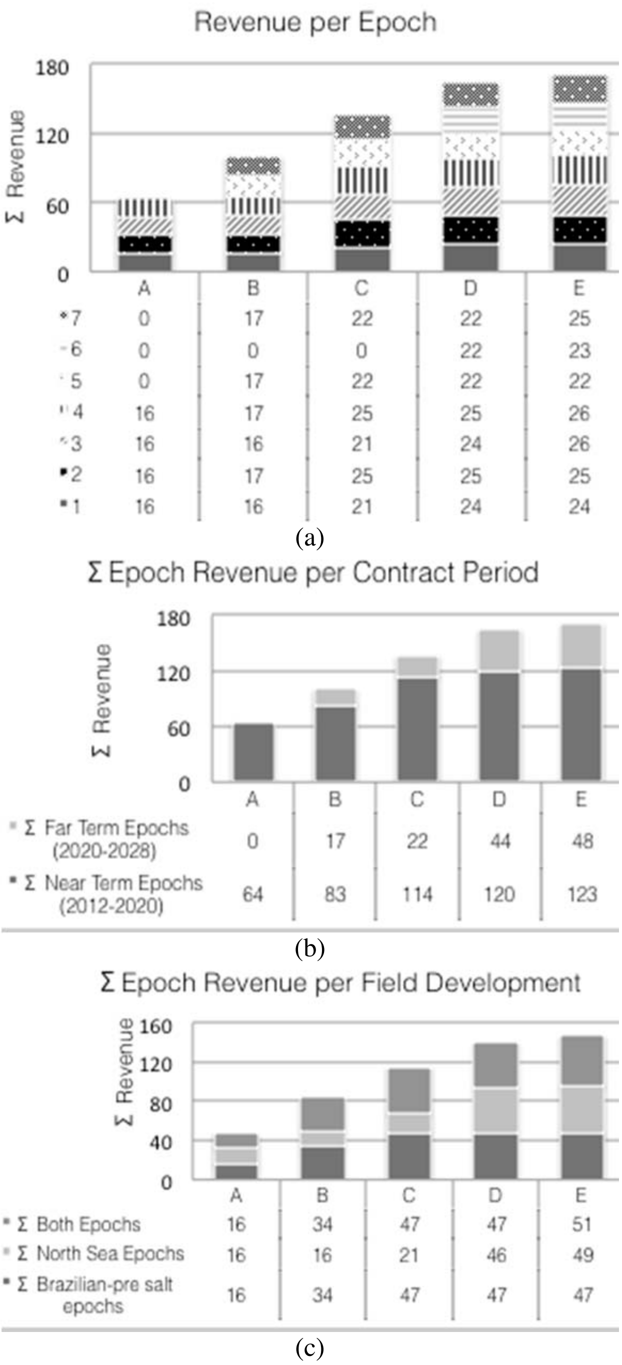


Figure 9: Sum of the revenues for all epochs (a), and organized by contract period (b) and field development (c)

The construction of an era starts with the definition of the *epoch transition rules,* which imposes continuity constraints and variable consistency, as discussed in Section 2.2. In this illustrative example, the number of eras is reduced. However, in more complex problems, a large number of eras may possibly be created. In those cases, a set of desired epochs (scenario expectations and/or uncertainties to be evaluated) can be selected, based on the results of the epoch analysis.

Our example considers all possible eras ξ_j (Figure 10) given two simple epoch transition rules: All eras must include the base contract set; All eras must cover the period from 2012-2028.

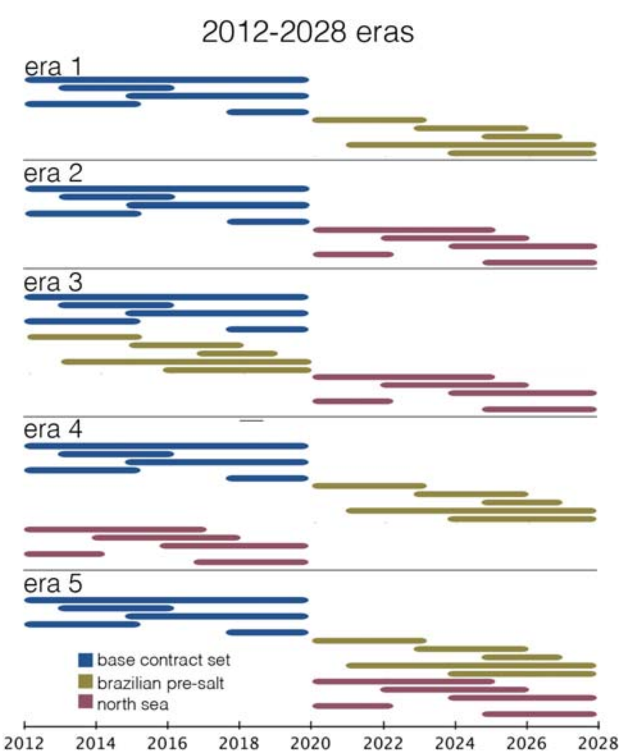


Figure 10: All 5 possible eras given the epoch transition rules

It is possible to calculate the profit per design in each era by summing up the revenue of the epochs. The result is presented in Table 6.

	Designs				
Eras	A	B	C	D	E
ξ_1 $\{E_1, E_5\}$	1	13	18	16	11
ξ_2 $\{E_1, E_6\}$	1	-4	-4	16	12
ξ_3 $\{E_1, E_7\}$	1	13	18	16	14
ξ_4 $\{E_2, E_6\}$	1	-3	0	17	13
ξ_5 $\{E_3, E_5\}$	1	13	18	16	13
Profit Average per Design	1 ± 0	6.4 ± 9.0	10 ± 11.0	16.2 ± 0.4	$12.6 \pm 1{,}1$

Table 6: Profit for each design in each of the eras

A quick evaluation shows that higher capability designs (D) were able to make the most profit and were most predictable under varying circumstances, but if that some situations could eliminate the risk from, and hence make optimal, somewhat lower capability ships (C). Although this was a *toy* problem, it illustrates a principle: extra capacity may be valuable under high uncertainty, while if some uncertainty can be eliminated, a more optimal solution may be found.

It is essential to note that this example has a small number of uncertain parameters related to only two possible field developments, plus a base contract set, which leads to a low number of eras to compute. Larger problems deal with an unfeasible number of eras, requiring much more attention to the epoch analysis and the selection of the epochs in order to construct an efficient era space.

4. CASE STUDY – ANCHOR HANDLING TUG SUPPLY (ATHS) DESIGN

The case study examines an AHTS design for a 24-year period, starting in 2012. The ship should be robust enough to deal with selected uncertain future scenarios, based on figure 5.

The approach intends to capture uncertain future scenarios via a *story telling* process. It relies on generating a base contract set that embraces a probabilistic distribution of five capability requirements that are essential to the AHTS's design. Different scenarios are created when a percentage of the base contract set are forced to have a minimum value in one or more of the capability requirements φ_i^n. Given those principles, the following assumptions are considered:

- The base contract contains 100 contracts, distributed in an 8-year period (2012-2020)
- The base contract set is generated based on a probabilistic distribution of five capability requirements: $\varphi_i^1 = SECA$, $\varphi_i^2 = NECA$, $\varphi_i^3 = Ice\ Class$, $\varphi_i^4 = Depth$, $\varphi_i^5 = Speed$
- The base contract defines an *epoch* 0
- Each change in this base contract set triggers a new epoch, also covering an 8-year period
- Changes are added in a given percentage of the base contract set, forcing selected capability requirements in at least X% of the contracts of the set
- The revenue R_i of each contract is proportional to its duration D_i and capabilities requirements φ_i^n
- Alternative ship designs are motivated by the contracts' potential requirements
- A total of 4000 designs are analysed, with different capability values ϑ_v^n assigned to the design variables.
- The cost C_v of each vessel is proportional to its capabilities ϑ_v^n

Figure 11 exemplifies the base contract set generation concept, in order to capture diverse future contexts, based on the probabilistic distribution of φ_i^n.

Table 7 lists the capability requirements φ_i^n of each contract transformed into epoch variables ε_e^n, including the desired percentage value of change in the total of base contract set (ε_e^1- percentage of contracts)

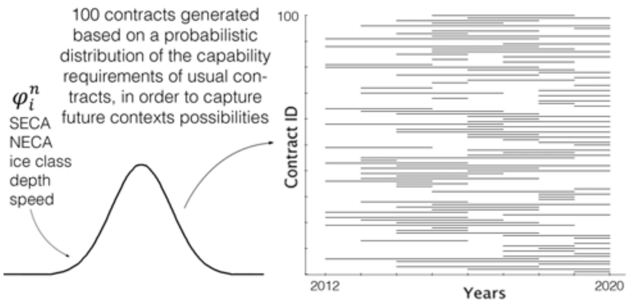


Figure 11: Base contract set, with 100 contracts capturing a probabilistic distribution of the usual capability requirements φ_i^n in an 8-year period (2012-2020)

Epoch Variable ε_e^n	Unit	Scale	Range (min-max)	Steps	Action
Percentage of contracts	%	Discrete	25 - 100	4	Alter randomly the given percentage on the initial set of contracts, requiring that at least the given percentage of contracts contains the following capabilities requirements
New ECA	ECA	Discrete	no yes SECA NECA	4	Add a SO_X and/or a NO_X control requirement in the contracts, allowing only vessels that comply with it to get the contracts
New Market Condition	Condition	Discrete	normal low high	3	Changes the revenue of contracts in a rate of: normal: no change, low: -30%, high: +30%,
Ice Class	Class	Discrete	0-3	4	Add an Ice Class requirement in the contracts, allowing only vessels that comply with this class to get the contract
Ocean Depth	Meters	Continuous	1000 -3000	3	Add a depth requirement in the contracts, allowing only vessels that comply with the minimal depth to get the contract
Speed	knots	Continuous	12-24	4	Add a design speed requirement in the contracts, allowing only vessels that comply with the minimal design speed to get the contract
				Potential Epoch Space:	*2304 Epochs + 1 Base Contract Set*

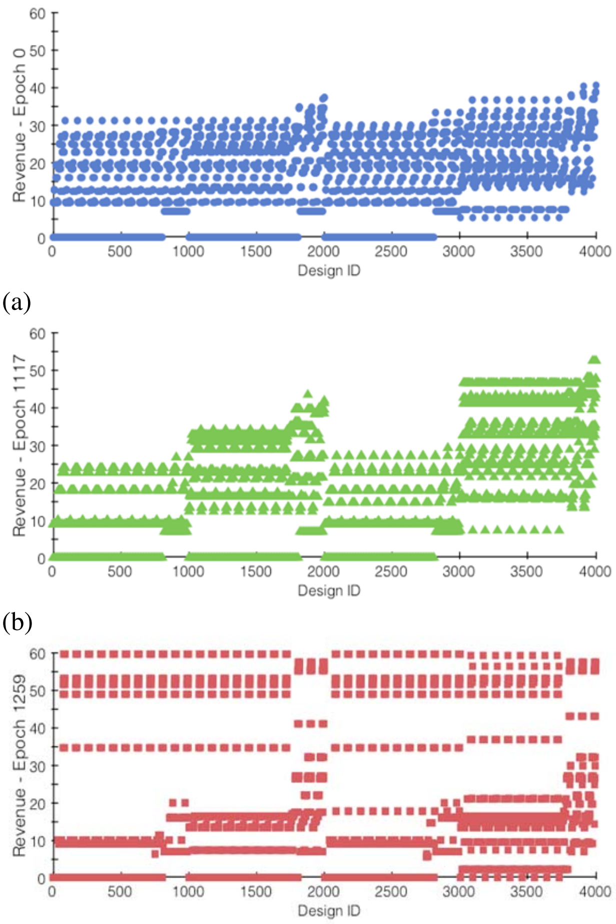
Table 7 – Case study epoch variables ε_e^n

The potential epoch space is calculated by multiplying all the possible combinations of the epoch variables, plus the base contract set (*epoch 0)*. The following epochs represent a change in a percentage of the contracts of the base set, forcing the epochs through the *story telling* process. It means the possibility of modelling an eventual scenario where *25% of the contracts require ice-class*, due to an Arctic field, or another scenario where *50% of the offered contracts will require SECA and anchor handling in 3000m depth*. For instance, epoch 1: $E_1 =$ *{25, no SECA/no NECA, normal, 0, 1000, 12}* assures that at least 25% of the contracts are modified to include: no ECA requirements, no change in the revenue, no ice class requirement, minimal depth of 1000m and design speed of 12 knots.

Non-transport ship designs are mainly driven by their functional work, rather than just the transportation capability (Gaspar et al. [18]). Formulating the AHTS design problem by the decomposition of functional capabilities (ϑ_v^n) allows for estimation of the behaviour of a design in any scenario covered by the selected discretization. The only isoperformance indicator in this case is economical: revenue for epochs and profit for eras.

Short run analysis calculates the optimum contract path regarding maximum revenue for each vessel in each of the epochs. It means that all 4000 designs are evaluated through the epoch space (2305 epochs), and it is possible to obtain outputs similar to the ones in Figure 9 to each design in each epoch. For illustrative purposes, Figure 12 plots the revenue for each design in 3 distinct epochs:

a) E_0 (base contract set)
b) E_{1117} *={50, SECA + NECA, high, 1, 1000, 12}* (50% of the contracts with both ECA, high market, ice-class=1, minimum depth and speed, as if for an Arctic field)
c) E_{1259} *={75, no SECA/ no NECA, high, 0, 3000, 20}* (75% of the contracts with no ECA, high market, no ice-class, maximum depth and minimal speed of 20knots, as if for a Brazilian pre-salt field).



(a)
(b)
(c)

Figure 12: Revenue for epoch 0 (a); epoch 1117 (b); and epoch 1259 (c)

Turning to the long run, it is necessary to commit to a set of preferred scenarios to carry on in the era analysis, once the era space is too large to be totally covered. Each era covers the period of 2012-2036, and it requires 3 epochs in its vector: $\xi_j = \{E_e, E_f, E_g\}$. Figure 13 illustrates this part of the methodology, with the construction of 2 eras.

It is of interest to note that the *story telling* process may be helpful. By *check-marking* epoch variable values in the table for a given period (Figure 13), we can observe how the scenario changes through time, adapting it to a real case. For instance: era 1 ($\xi_1 = \{E_0, E_{683}, E_{1259}\}$) starts the first period with the base contact set, and it is expected both ECA and ice class requirements, with high market condition, in at least half of all contracts from 2020-2028, and it becomes at least 75% of the contracts in the last period, until 2036; era 2 ($\xi_2 = \{E_0, E_{1117}, E_{1693}\}$) consists of the initial scenario in the first period, followed by half of the contracts with no ECA or ice-class, but with high market condition, 3000m depth and 20-knot minimum speed requirements in half of all contracts in the second period, with those requirements growing to 75% in the last period.

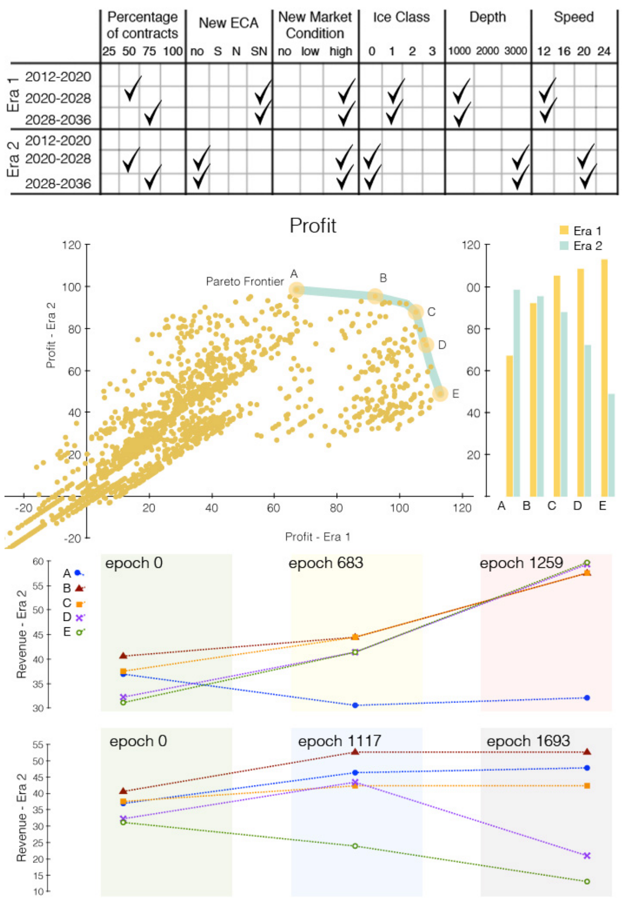


Figure 13: *Story telling* process for the construction of 2 eras, with revenue and profit for 5 designs in the Pareto frontier.

Given those eras, it is possible to plot profit for all of the designs, by summing up the revenue of each epoch that belongs to the era minus the vessel cost. This operation is has a low computational cost, once the SDDP is calculated for all epochs, and Pareto frontiers can be plotted when comparing two eras, as in Figure 13. For illustrative purposes, Figure 13 also plots the revenue and profit for 5 (A, B, C, D and E) designs that are in the Pareto frontier.

The same type of insight as the one presented in Figure 9 can be used for evaluating designs within the era space, for example creating 10 or 20 likely-to-happen eras and evaluating the maximum and minimum of each design in it. The refinement of the design space is also a possible next step. Since each case requires specific outputs, more research in the *perceptual aspect* (Section 1.2) is required in the future. An alternative of developing a more elaborated isoperformance value, rather than profit, is discussed by De Weck and Jones [19].

5. SDDP + EEA DISCUSSION

The EEA technique brings an explicit benefit to scenario planning problems, such as the SDDP. In these cases, the selection of a design in the conceptual phase is driven mainly by the correct assessment of the economic return of such a choice in an uncertain future. EEA is a tool malleable enough to deal not only with non-transport ships, but also with the majority of the temporal aspects of ship design scenario planning problems.

The EEA approach presented was selected in order to exemplify context parameter decomposition and possible future estimation. However, the methodology may vary according to necessity. One possible change would be to decompose even more, breaking the contract sets, allowing each contract a separate entity. This extreme decomposition would transform each one of the contracts into an epoch, and create eras based on probabilistic methods - where the era space would be even larger due to the higher number of epochs. The SDDP could be applied to the era space only. This approach focuses more on single scenarios, and is weak in elucidating the effect of a single context change on the whole lifetime.

A second possible modification is to put aside the *short/long run* division, by breaking up the problem in small pieces of epoch and era combined, and then run SDDP during the process. The task would then evaluate one group of context parameters per time, creating epochs and possible eras on the go. The final result would be the design performances in each of the era sub-spaces, one set for each parameter group.

Another consideration is to realize that the case presented is a theoretical study. Shipping involves a high degree of risk, and probability distributions of the profit for a case with real data and assumptions should contain much more information than a single profit plot as Figure 13. For instance, how most likely to happen epochs influence designs' performances; or, similarly, changes in the probability distribution of the contracts should be considered.

With additional statistical analysis, this serves as a tool for decision makers to better understand the implications of different beliefs. For example, *invest in an ICE-1 vessel if you believe that Shotkman Arctic offshore field is open with a probability higher than 48% in 2021, or 79% in 2018*.

6. CONCLUDING REMARKS

In this paper we have presented a design method that explicitly takes into account the uncertainty related to the future operating context of the ship.

The Epoch Era Analysis provides a way to handle the complexity of this decision support problem. The EEA captures alternative expectations about the future by formulating distinct epochs with a fixed operating context, for which the performance of each alternative design can be analysed. These epochs can then be combined into many possible eras, each representing a possible lifecycle scenario for the vessel.

The EEA approach represents a *divide-and-conquer* approach for handling temporal complexity. The shipowner, facing a 20-30 year uncertain future with possible variations in a number of dimensions, can use the EEA approach to form manageable *chunks* in the form of epochs. These epochs provide the foundation for a quantitative performance evaluation of the alternative designs, while, at the same time, they offer a suitable means for communicating about future expectations as part of a *story-telling* process.

Within an epoch, the SDDP is used as a means for translating the context parameter values into a form suitable for performance analysis, the epoch variables, by generating a contract scenario for which a given design will optimize its revenue.

When combining these epochs into eras, the lifecycle performance of a given design can be found by aggregating the performance of the epochs it contains.

Thus, our conclusion is that the combination of the SDDP and the EEA method presented here is an efficient approach to handle temporal complexity problem in early ship design, providing a modular approach to handle uncertainty both from a computational perspectives as well as capturing expectations about the future into manageable *chunks*.

7. ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding for this research provided through SHIP-4C KMB project (NTNU, Norway), Jansons Legat scholarship (Norway) and MIT System Engineering Advancement Research

Initiative (SEAri, USA). The authors would also like to thank Matthew Fitzgerald (MIT), Stian Erichsen and Edgar McGuinness (NTNU) for their contribution during the research.

8. REFERENCES

1. JANSON, J. O. AND D. SHNEERSON, The optimal ship size. *J. Transp Econ Policy 16(3), 217-238*, 1982

2. GARROLD, P. AND M. MIKLIUS, The optimal ship size: a comment. *J Transp Econ Policy 19(1), 83-91*, 1985

3. DANTZIG, G. B. AND D. R. FULKERSON, Minimizing the numbers of tankers to meet a fixed schedule. *Nav REs Logist Q 15, 403-411*, 1954

4. BELMORE, M., A maximum utility solution to a vehicle constrained tanker scheduling problem. *Nav Res Logist Q 15, 403-411*, 1968

5. FAGERHOLT, K., Optimal fleet design in a ship routing problem. *Int Trans Oper Res 6(5), 453-464*, 1999

6. ERIKSTAD, S.O., S. SOLEM AND K. FAGERHOLT, A Ship Design and Deployment Model for Non-Transport Vessels. *Ship Technology Research*, Accepted for publication, 2011

7. ULSTEIN, T. AND P. O. BRETT. Seeing what's next in design solutions: Developing the capability to develop a commercial growth engine in marine design. *In: proceeding of the 10th International Maritime Design Conference (IMDC) 2009, Trondheim, Norway*, 2009

8. ANDREWS, D. J., Marine design - requirement elucidation rather than requirement engineering. *In: IMDC 2003 - proceedings of the 8th International Maritime Design Conference (IMDC) 2003, Athens, Greece*, 2003

9. RHODES, D.H., AND ROSS, A.M., Five Aspects of Engineering Complex Systems: Emerging Constructs and Methods, *4th Annual IEEE Systems Conference, San Diego, CA, April*, 2010

10. RHODES, D.H., AND ROSS, A.M., Shaping Socio-technical System Innovation Strategies using a Five Aspects Taxonomy, *EuSEC 2010, Stockholm, Sweden*, May 2010.

11. HAGEN, A. AND GRIMSTAD, A., The Extension of System Boundaries in Ship Design. *Transactions of RINA, vol. 152*, 2010

12. ROBERTS, C.J., RICHARDS, M.G., ROSS, A.M., RHODES, D.H., AND HASTINGS, D.E., Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration, *3rd Annual IEEE Systems Conference, Vancouver, Canada*, March 2009.

13. MCMANUS, H. AND HASTINGS, D.E., A Framework for Understanding Uncertainty and Its Mitigation and Exploitation in Complex Systems, *IEEE Engineering Management Review, Vol. 34, No. 3, pp. 81-94*, Third Quarter 2006.

14. ROSS, A.M., MCMANUS, H.L., RHODES, D.H., HASTINGS, D.E., AND LONG, A.M., Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System, *AIAA Space 2009, Pasadena, CA*, September 2009.

15. ROSS, A.M., AND RHODES, D.H., Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis, *INCOSE International Symposium 2008, Utrecht, the Netherlands*, June 2008.

16. PINDYCK, R. S. AND RUBINFELD, D. L., Microeconomics. *Saddle River, NJ, Prentice Hall*, 2001

17. GOODWIN, P. B., A review on new demand elasticities with special reference to short and long run effects of price changes. *J. Transp Econ Policy Volume 26 (2), 155-169*, 1992

18. GASPAR, H. M. NEUMANN-LARSEN, E., GRIMSTAD, A., ERIKSTAD, S.O. Efficient Design of Advanced Machinery Systems for Complex Operational Profiles. 9th International Conference on Computer and IT Applications in the Maritime Industries – COMPIT, 2010

19. DE WECK, O. L. AND JONES, M. B. Isoperformance: Analysis and Design of Complex Systems with Desired Outcomes. *Systems Engineering, Vol 9 (1), 45-61*, 2006