The role of set-based design in successful shipbuilding project execution. Experiences from Umoe.

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Content

• Umoe Mandal
• Experience from actual development programs
  – MCMV
  – Skjold
  – T-Craft
• Experiences with set-based design
  – US Navy: Set-based design
  – T-Craft
• Important success criteria
60 years of naval shipbuilding in Mandal, Norway
Umoe Mandal: Proud builders of Oksøy/Alta Minehunters/sweepers and Skjold Class Corvettes. Probably the most complex ships designed and built in Norway.
# SES MCMVs from Umoe Mandal

## Oksøy class minehunter (MH)

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Type</th>
<th>Builder</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>M341</td>
<td>KNM Karmøy</td>
<td>1994</td>
<td></td>
</tr>
<tr>
<td>M342</td>
<td>KNM Måløy</td>
<td>1995</td>
<td></td>
</tr>
<tr>
<td>M343</td>
<td>KNM Hinnøy</td>
<td>1995</td>
<td></td>
</tr>
</tbody>
</table>

## Måløy class minesweeper (MS)

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Type</th>
<th>Builder</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>M350</td>
<td>KNM Alta</td>
<td>1996</td>
<td></td>
</tr>
<tr>
<td>M351</td>
<td>KNM Otra</td>
<td>1996</td>
<td></td>
</tr>
<tr>
<td>M352</td>
<td>KNM Rauma</td>
<td>1996</td>
<td></td>
</tr>
</tbody>
</table>

## Main data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>396 t</td>
</tr>
<tr>
<td>Length</td>
<td>55.2 m</td>
</tr>
<tr>
<td>Speed</td>
<td>20 kn</td>
</tr>
<tr>
<td>Crew</td>
<td>37 (13/7/17)</td>
</tr>
</tbody>
</table>

## Main weapons

- Mistral SAM

## Main sensors

- MH: ROV, Hugin MRS, sonar
- MS: Elma og Agate sveip

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*Agate influence sweep*  
*Hugin AUV*
## Skjold Class Corvettes in the Navy

### Main data Skjold-class
- **Displacement**: 274 t
- **Length**: 47.5 m
- **Speed**: 60 kn
- **Range**: 800 nm / 40 kn
- **Crew**: 20 (13/4/3)

### Main armament
- NSM
- 76 mm OTO
- Mistral MANPADS

## Skjold-class corvette

<table>
<thead>
<tr>
<th>Ship</th>
<th>Name</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>P961</td>
<td>KNM Storm</td>
<td>2010</td>
</tr>
<tr>
<td>P962</td>
<td>KNM Skudd</td>
<td>2010</td>
</tr>
<tr>
<td>P963</td>
<td>KNM Steil</td>
<td>2011</td>
</tr>
<tr>
<td>P964</td>
<td>KNM Glimt</td>
<td>2012</td>
</tr>
<tr>
<td>P965</td>
<td>KNM Gnist</td>
<td>2012</td>
</tr>
<tr>
<td>P960</td>
<td>KNM Skjold</td>
<td>2013</td>
</tr>
</tbody>
</table>

Built by Umoe Mandal

STRONG performance - LIGHT materials
20 years with air cushion vehicles

• Umoe Mandal is the world leader in Air Cushion and Surface Effect Ships
  – Unrivalled experience in design, building and maintenance of operational high performance naval craft

• Umoe Mandal has extensive experience in design and construction of naval composite structures
  – Umoe Mandal Composite Technology

• Umoe Mandal has the leading experience in high speed craft gas turbine applications

• Umoe Mandal is the leading supplier of advanced high capacity lift fans
  – 4 design generations in service
Umoe Mandal: Leading ship designers

- Leading ship designers for advanced ships and structures with
  - Advanced propulsion solutions
  - Composite materials/light weight solutions
  - Air cushion technologies
  - Military requirements and logistics support
  - Extensive CFD/FEM/3D-CAD capabilities

- Applying lean and efficient design methods and advanced design tools to reduce development time and costs
- Leveraging competitive and successful design work for demanding Norwegian and international Navy customers
- 26 highly skilled engineers within Naval Architecture/Marine Engineering
Extensive CFD capabilities

Umoe Mandal is designing the next generation free fall lifeboats from Harding Safety
Integrated hydrodynamics/structural design

6-DOF, 17 deg list, 90 deg waves, Hit point 2
Solution Time = 0.4 (s)

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STRONG performance - LIGHT materials
SKJOLD Corvettes – a success

• Successful operations in NATO exercises

• Successful first launches of the new Naval Strike Missile

• Last vessel delivered April 2013

• First implementation of RAS (Replenishment-At-Sea) completed

• International promotion focusing on Brazil, Turkey, Singapore and the US
The formidable firepower of the Skjold class

May 2013: NSM fired from Skjold Class corvette «Steil»
Umoe Mandal - a history of innovation

1990-1997

1999-2013

2002-2004

2006-2007

2008-2013....

STRONG performance - LIGHT materials
UM epoxy/carbon lift fan technology

- Fan blades produced with RTM
- Shrouds and centredisk produced with vacuum infusion
- 4 generations of lift fans in operation (>50 units)
- In operation by NAVSEA/LCAC since August 07
Design and production of composite components

- BAe Bofors MK3 Gun Cupola
  - Optimized design by Umoe
  - Increased load capacity
  - Reduced weight
  - Reduced part count
  - Integrated features
The T-Craft Challenge

Vehicle transfer at sea

Fuel Efficiency & Sea Keeping Mode

Vehicle offloading/loading to the beach

High Speed/Shallow Water Mode

Amphibious Mode

T-Craft Vision: One Craft, Multiple Modes of Operation
T-Craft: few requirements – as targets

Capability List:
1. Un-refueled range, in a no cargo condition, of 2,500 nautical miles in a Fuel Efficient Mode.
2. Good Sea Keeping Mode (20 knots, through Sea State 5).
3. Open ocean operations through Sea State 6 (through Sea State 4 in High Speed/Shallow Water Mode) and survivable in Sea State 8.
4. Maximum Speed: full load condition in High Speed, Shallow Water Mode = 40 knots through top end of Sea State 4.
5. Amphibious capability, in Amphibious Mode, to traverse sand bars and mud flats by providing a “feet dry on the beach” capability.
6. Convert between modes at sea without any external assistance.
7. Fuel: 500-600 fuelled range in High Speed/Shallow Water Mode (~500-600)
8. Reduced motions in Sea State 4/5 to enable rapid vehicle transit between the T-CRAFT and a Maritime Prepositioning Ship's logistics connector.

Notional Requirements:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Threshold</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo Payload Weight</td>
<td>300 ft</td>
<td>750 ft</td>
</tr>
<tr>
<td>Cargo Payload Area</td>
<td>2,200 sq ft</td>
<td>5,500 sq ft</td>
</tr>
<tr>
<td>Crew Size</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Beach Slope Climbing Rated</td>
<td>0.5%</td>
<td>2%</td>
</tr>
<tr>
<td>Vehicle Ramp Angle</td>
<td>15.0 degrees</td>
<td>17.5 degrees</td>
</tr>
<tr>
<td>Vehicle Deck Loading</td>
<td>350 psi</td>
<td>550 psi</td>
</tr>
</tbody>
</table>

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The Umoe Response:

Fuel Efficiency & Sea Keeping Mode

High Speed/Shallow Water Mode

Amphibious Mode

T-Craft Vision: One Craft, Multiple Modes of Operation
The Three Modal UM T-Craft Concept

Fulfills all three desired capabilities

1. Fuel economy based on
   - fuel efficient diesel engine powering high efficiency waterjets
   - SES vessel operating between humps

2. High speed and shallow draft
   - CODAG Diesel engine powered waterjets, gas turbine powered air propellers
   - SES vessel operating above hump speed

3. Amphibious mode
   - Gas turbine powered air propellers
   - Large air cushion area with a high air gap (1.5 m) to pass sandbars/mudflats and with beach ascending capability
   - operating below hump speed
Long range good seakeeping and high speed shallow draft mode: SES
Bow tandem connection to an LSD

...at sea cargo transfer made possible
Loading from the WATSON Class side port....
The UM T-Craft.....

...delivering the cargo dry feet on the beach.....
Break-through contract in the US: TEXTRON/Ship to Shore Connector

- Development + Test Craft + 8 vessels
- Ambition to win additional series of 65 vessels 2019-→:
Making Offshore Wind Possible

UM Wave Craft
Speed, Access, Comfort

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SET-BASED DESIGN

(OR KNOWLEDGE-BASED DESIGN)
We have tried two development processes

1. Requirement driven design (Structure-based design):
   - The design process aims to verify that the product will satisfy a large number of (>2k) detailed functional requirements
   - Formal process for evaluation and acceptance
   - Process focused management (rule-based)
     - The process is more important than the technical result
     - Progress reporting based on counting of finished documents

Norwegian naval programs:
Ex: SKJOLD/LSV

2. Set-based design (Knowledge-based design):
   - A low number of requirements – more like targets
   - Focus placed on technical alternative solutions which are accessed and (down)selected at agreed milestones
   - Knowledge-based management

US naval programs:
T-Craft and SSC
Classical Point Ship Design

- Major loopbacks often necessary when starting from scratch....
- Mange rotations are necessary....

Figure 2: Classical Design Spiral. (Evans 1959)
Point design in practice

This is the plan:

- Major unplanned re-engineering occurs
- Costly loop-backs implying late changes on a large number of “finished” documents
Norwegian naval projects: Requirement driven design

• Several thousands functional and performance requirements established by the client
• For Umoe this meant:
  – Focus placed on «closing requirements» throughout the design process
  – Conflicting requirements create demanding processes when discovered
    • Results in major re-engineering and revisions of already issued documents
  – The energy is used on the process and to document the process steps rather than finding the best solutions
    • Counting requirement status and compliance, punches, document nos. and revisions, prove traceability, audit deviations and waivers, changes, progress
• Result: The requirements are satisfied in the end, however,
  • Delayed and to a higher cost
  • Uncertainty whether the result is at all close to the optimum
Requirement Engineering (RE)

• Defining the solution «in abstract» terms
• Used in US since WWII, however now NOT in use in US Navy today
• Continues to be used for naval ship design programs in UK and Norway

Andrews (2011):
• RE is «not appropriate for warships»
• RE is «bad Systems Engineering practice»

US Navy Introduces Set-based Design

• Based on many failed, too late and too expensive ship design efforts since the 1990’ies

• Ship Design and Analysis Tool Goals
  – Letter issued in 2008 by Admiral Paul Sullivan, Commander of the Naval Sea Systems Command,
2009: Set-based design is used by US Navy for the SSC-program:

1. Consider a (large) number of design alternatives by understanding the design space
2. Allow specialists to consider a design from their own perspective and use the intersection between individual sets to optimize a design
3. Establish feasibility before commitment
   a) Narrowing sets gradually while increasing detail
   b) Staying within a set once committed
   c) Maintaining control by managing uncertainty at process gates

Result:
- Conceptually robust designs
- Promises a capacity to adapt quickly to changing requirements and design discoveries.

*What Is Set-Based Design? DJ Singer, N Doerry, ME Buckley - Naval Engineers Journal, 2009*
The UM T-Craft design approach

A knowledge based creative ship design process successfully applied
2009:

• “Everybody” talked LEAN

• I received this book with the order:

READ
## Development Environment

- *The foundation for lasting change –*

### A Continuum

<table>
<thead>
<tr>
<th>Structure-based</th>
<th>Knowledge-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>The basis of the engineering environment is the <strong>structure</strong> of the operational activities: procedures, control, compliance, related training</td>
<td>The basis of the engineering environment is the <strong>knowledge of individual workers</strong>: Understanding of needs, information availability, responsibility and teaming interaction</td>
</tr>
</tbody>
</table>

(Umoe in 2009?)  

(Toyota)
The Lean Development System
(Knowledge-based Development)

An operational value stream emerges from the interaction of four critical culture elements

Fra Kennedy 2003
Decision taken at defined process gates:

- Dates for the process gates are set and agreed by the design team
  - And always kept!
- At the process gates (integrating events):
  - Evaluation and (down)selection of design sets
  - Progress is assessed
T-Craft: Use knowledge-based design:

- During the T-Craft Phase 1 and 2 (2008-2011) we have actively tried out a novel (for UM) product development method
  - inspired by Toyota* product development methods
  - prof. Kai Levander, NTNU (Finland)

- Knowledge Based Design
  - Knowledge based design is based on complete design sets where alternative solutions are tested and selected
  - Other names: Set-based design, Lean product development

Knowledge Based Design:

- Knowledge based design is based on complete design sets where alternative solutions are tested and selected.

**Example:**

- The decision affected the whole ship and “all” drawings.
- Decision to be taken as late as possible at an agreed milestone:
  - Before drawings were made
  - When we had acquired sufficient and quantitative knowledge to take the right decision.
T-Craft main drive alternatives

M-drive:

- 2 MW Bow Thruster Fan
- 2 x 2 MW Lift Fans
- 2.5 MW propulsion fan
- 2.5 MW Water Jet
- 7.4 MW Water Jet
- 13 MW Propulsion Fan

E-drive:

- 2 MW Bow Thruster Fan
- 2 x 2 MW Lift Fans
- 2.5 MW propulsion fan
- 2.5 MW Water Jet
- 7.4 MW Water Jet
- 13 MW Propulsion Fan

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Example: A new ship type is to be developed

- Four new technologies are needed:
  - Transformation from SES to ACV
  - Propulsion system effective at sea and over land
  - Mechanical or electrical Power transmission
  - Cargo transfer system ship to ship
- Assume 80% success rate for each technology

<table>
<thead>
<tr>
<th>Point Design:</th>
<th>Set-based:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 for Transformation x</td>
<td></td>
</tr>
<tr>
<td>0.8 for Propulsion x</td>
<td></td>
</tr>
<tr>
<td>0.8 for Power transmission x</td>
<td></td>
</tr>
<tr>
<td>0.8 for Cargo transfer</td>
<td></td>
</tr>
</tbody>
</table>

Probability for success with all solutions in the project:
\[
0.8^4 = 0.41
\]

Set-based design gives dramatic reduced risk in development projects

Probability of all three solutions for each technology fail:
\[
(1 - 0.8)^3 = 0.008
\]

Probability for success with all solutions in the project:
\[
(1 - 0.008)^4 = 0.97
\]
Knowledge based design vs traditional ship design

<table>
<thead>
<tr>
<th>Knowledge based design process</th>
<th>Traditional design process</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Set–based design process</td>
<td>• Revolving spiral process</td>
</tr>
<tr>
<td>• Always a plan B</td>
<td>• Point design</td>
</tr>
<tr>
<td>• Extensive re-use of knowledge</td>
<td>• Start from scratch</td>
</tr>
<tr>
<td>• Model testing as early as possible to learn</td>
<td>• Model testing as late as possible to verify</td>
</tr>
<tr>
<td>• Milestones are kept</td>
<td>• Milestones are delayed</td>
</tr>
<tr>
<td>• Open development process – all team-members are kept informed and involved</td>
<td>• People are informed on a need to know basis</td>
</tr>
<tr>
<td>• Publish documents (knowledge)</td>
<td>• Archive documents</td>
</tr>
<tr>
<td>• Progress is measured at milestones</td>
<td>• Progress is measured by counting “finished” drawings</td>
</tr>
<tr>
<td>• Active use of the 3-D model, no artificial 2-D presentations of intentions</td>
<td>• 3-D mainly used for artists impressions</td>
</tr>
<tr>
<td>• Drawings are made as late as possible to avoid changes</td>
<td>• Drawings are made as early as possible to show progress</td>
</tr>
<tr>
<td>• Solutions emerge</td>
<td>• Solutions are given</td>
</tr>
</tbody>
</table>

**STRONG** performance – **LIGHT** materials
### Our experience from T-Craft

#### Knowledge based process
- Risk is continuously reduced
- Fully integrate suppliers into the product development system
- Progress estimates are more reliable
- Fewer late design changes
- Team members are involved and motivated – always learning
- Critical milestones never delayed
- Open working environment improves interdisciplinary interaction
- Model tests motivate design improvements

#### Traditional process
- Risks are often ignored – the easy solutions are done first
- Do not include suppliers before they can be contracted
- Progress is overestimated
- Many late design changes – drawings are revised repeatedly
- Team members are frustrated
- Delays are recognized too late
- Interdisciplinary check is a pure formal process
- Late model tests are to be taken as *fait accompli*
The requirement specifications govern the design process

Therefore:

- Always better with few than many requirements
  - Reducing conflicting requirements
- Better with «targets» than absolute requirements
  - Targets facilitate trade-offs and optimizations between conflicting requirements
- Avoid that requirements are formulated too ambitious at “expert level”
  - Will create large problems when some requirements are only partly (or almost) achievable
- Describe what equipment is preferred instead of creating abstract requirements to functions and performances
  - Describe “what” and not “how to”
  - «Smart» functional requirements cause delays and cost increases
Why do not everybody use set-based design:

– Many requirement specifications are extremely structured
  • The client believes strongly that a high number of detailed requirements ensure quality
  • The reality is opposite!
– It is (more?) difficult to document (prove) progress
  • To use resources on alternatives seems expensive
  • Assessment of progress takes place at milestones/integrating events
    – The controllers/auditors prefer to count and measure
– Management and control is transferred from «management» to «chief engineers» and experts
  • These must be trusted
– Difficult to keep focus over time – a culture change is needed
Our experience

Knowledge-based development:
- Reduced manning levels in projects
- Reduced duration
- Reduced number of late changes
- Improved risk management
- More optimum solutions
- Many solutions available for the next project
- The time schedule holds

..as for a wedding

Thanks!