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Ship energy efficiency in simulations and energy system analysis

Modelling and Optimization of Ship Energy Systems
October 23 - 25, 2017. EPFL Sion, Switzerland

Invited speaker
Assoc. Prof. Kari Tammi, Aalto University
Jari Vepsäläinen, Klaus Kivekäs, Juuso Autiosalo, Guangrong Zou

2015: Le Bisse de Clavau
2004: L'Aiguillette d'Argentière
2000: Le Mont Blanc du Tacul

Content

Background

Previous examples

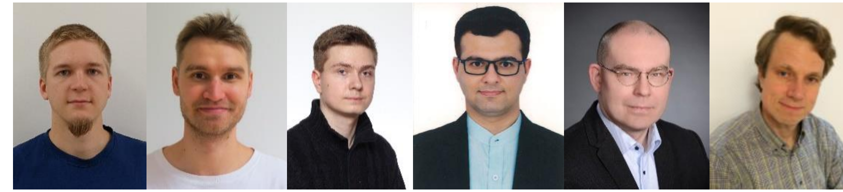
- **HT water control**
- **Power turbine usage**
- **Shaft generator usage**
- **Power demand estimation**

Current work on uncertainty in power system design

- **Cycle uncertainty**
- **Robust design**
- **Digital twin**

Future outlook

Background & team



Kari Tammi, Aalto University 2015-

Earlier Research Professor at VTT: electric machines, energy efficiency, electric vehicles, dynamics & control

At CERN 1997-2000 (LHC/CMS)

Teaching: Mechatronic machine design (5 cr), Vehicle mechatronics (5 cr), Design of electric vehicle systems at IIT Guwahati, India 2016

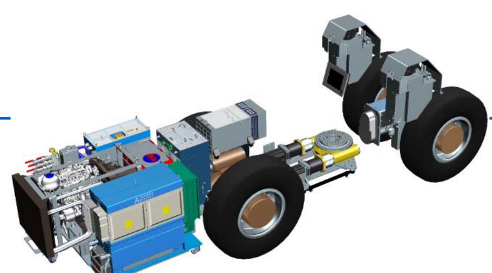
Panu Sainio. Chief Engineer, expertise: vehicle technology, hybridization, electric powertrain

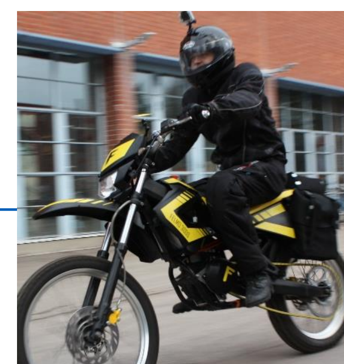
Shashank Arora. Post-doc, expertise: batteries, mechanical modelling

Klaus Kivekäs. Electric powertrain optimization with statistical methods

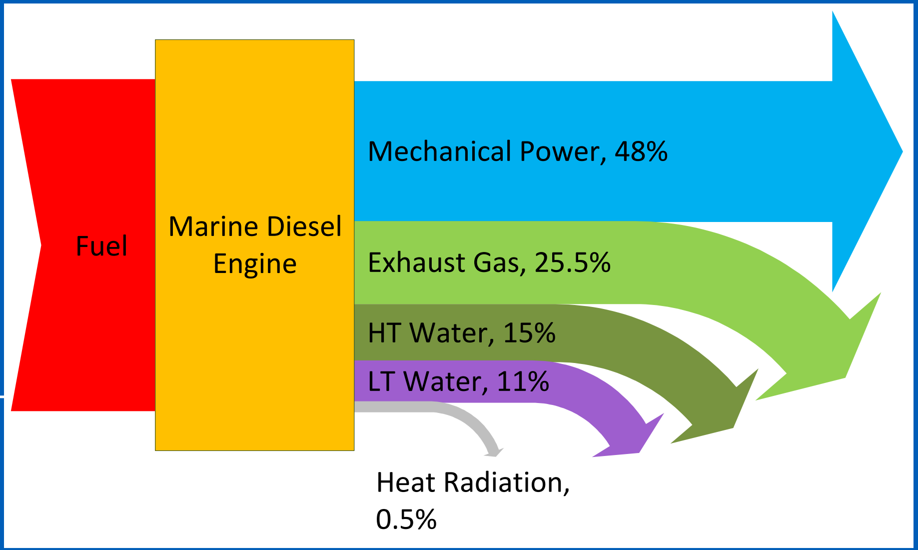
Jari Vepsäläinen. Multi-objective robust design of electric powertrain

Juuso Autiosalo. Digital twin for industrial products





Ship Energy Flow Modelling



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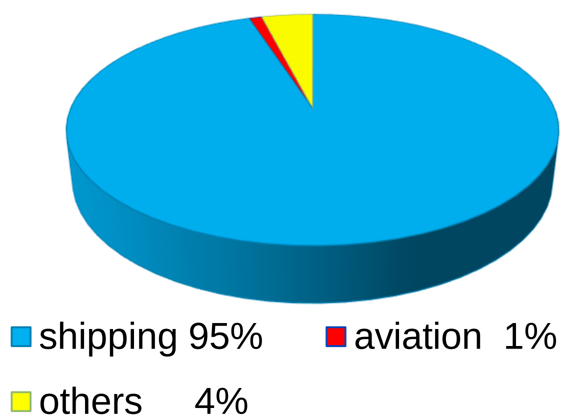
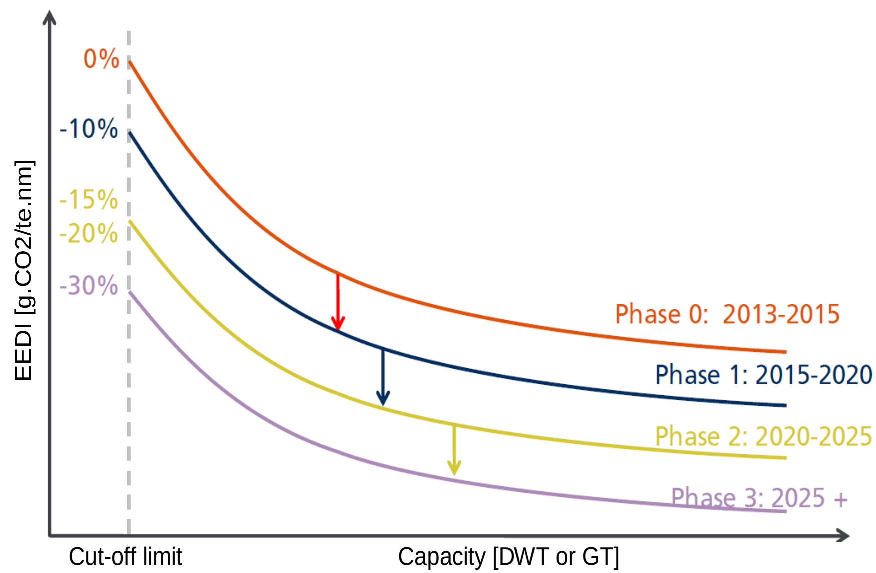
Motivation – Why Ship Energy Efficiency?!

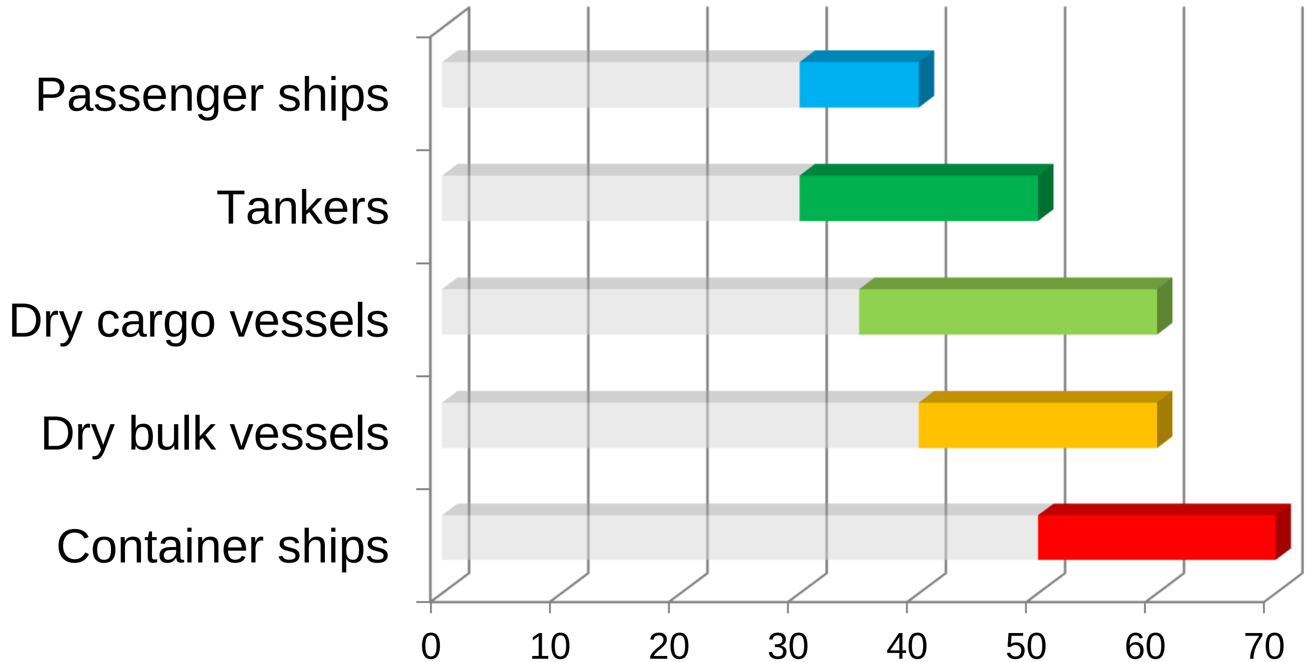
- 95% of worldwide transport of goods by ships
- Increasingly high fuel cost
- Accumulatively strict IMO rules → GREEN SHIPPING!





(Source: Lloyd's Register, (2012), Implementing the Energy Efficiency Design Index)

Fuel costs as a percentage of total operational costs for different ship types



→ Fuel cost for container ships is the highest among all the other ship types

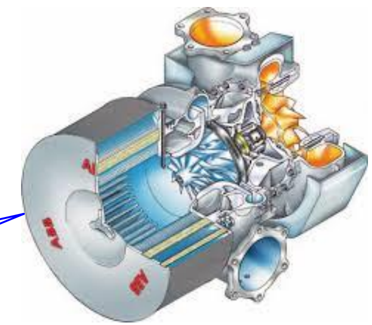
→ Many are struggling to balance their financial sheets

Motivation – How to Improve Ship Energy Efficiency?!

Slow steaming

Energy management

Better planning



Novel technology

Challenge →

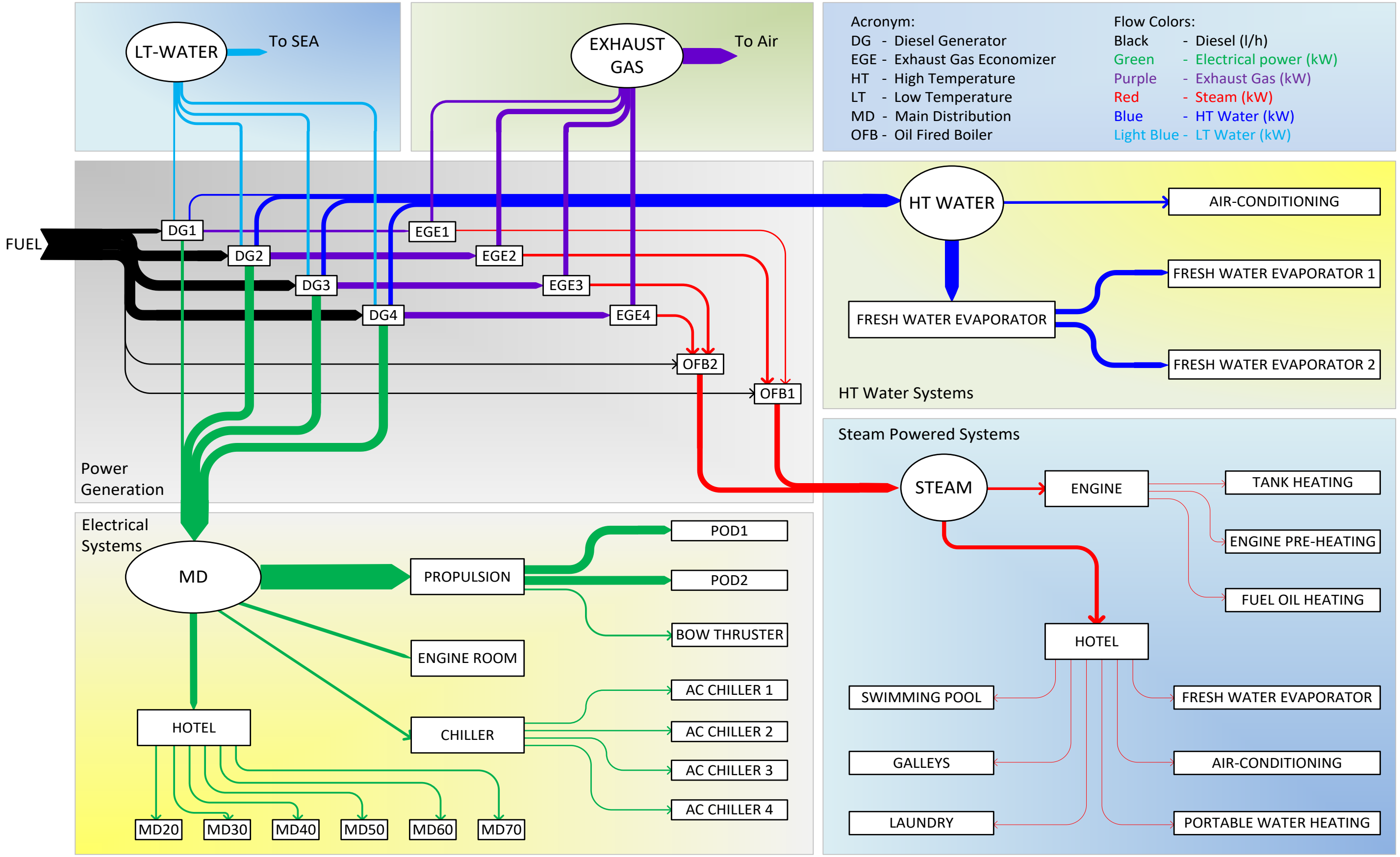
How to evaluate the overall effectiveness of each solution?

How to estimate the Return On Investment of each solution?

Multi-Domain Energy Flow Simulation in Brief

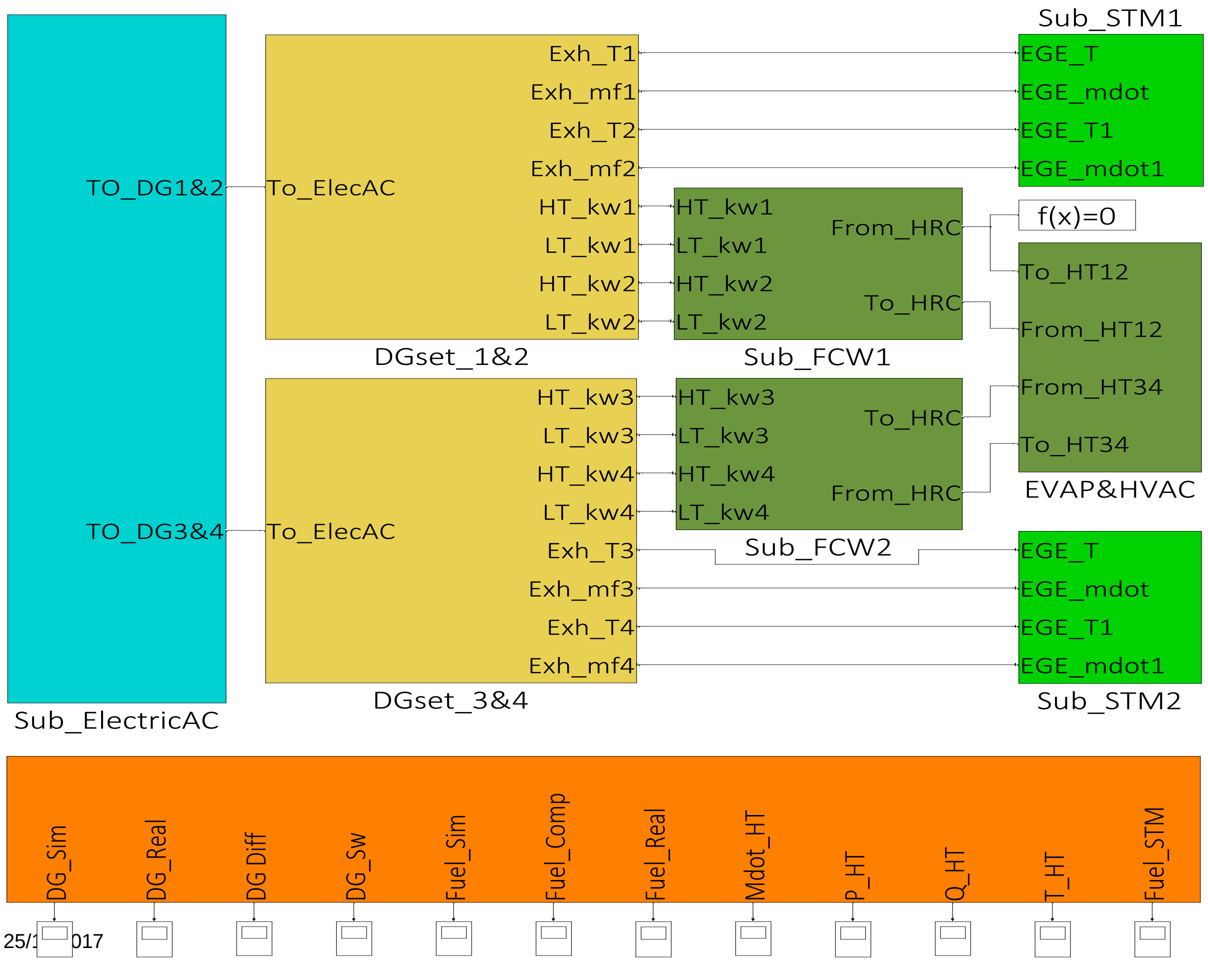
- Started in 2009
- Aim at a general tool for ship power plant simulation
  - To find globally optimal ways to improve ship overall energy efficiency
  - To be modelled at a system level, ONLY main sub-systems included
- Simulator modelling environment → Matlab/Simulink/Simscape
  - Different physical interactions are modelled in DOMAINS in Simscape
    - Available: Mechanical, Electrical, Thermal, pneumatic
    - Self-developed: Electrical AC, Thermalfluid, Steam
  - Component libraries for each domain using Simscape language

Multi-Domain Energy Flow Simulation – Example



- ✓ Helpful to thoroughly understand the energy distribution and consumption
- ✓ Potential to utilize the simulation method in different types of ships

Ship Energy Flow Simulator



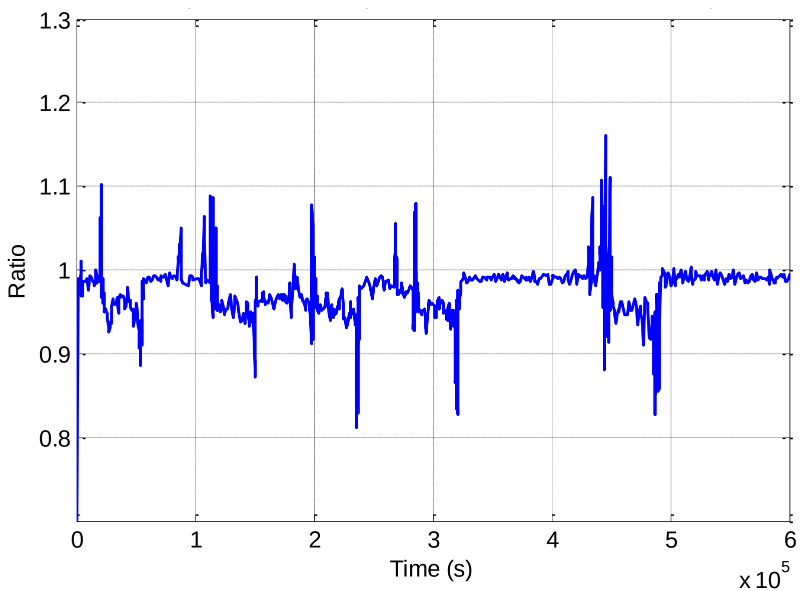
❑ Sub systems

- Electrical AC
- 4 DG sets
- HT/LT FWC
- STEAM
- Data I/O & processing, result display

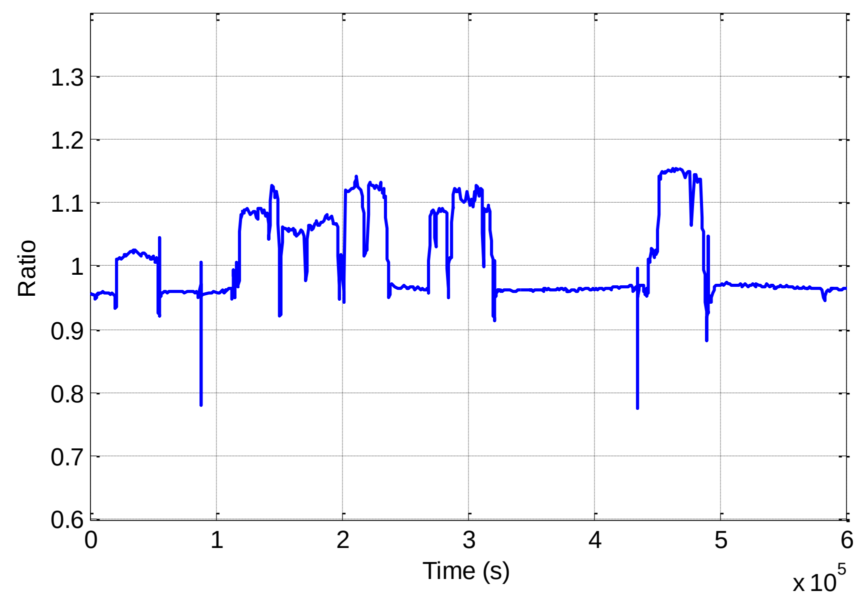
Model validation results

$$ratio = \frac{Simulation\ results}{measured\ data}$$

- DG power output
  → mostly within [0.95 1]



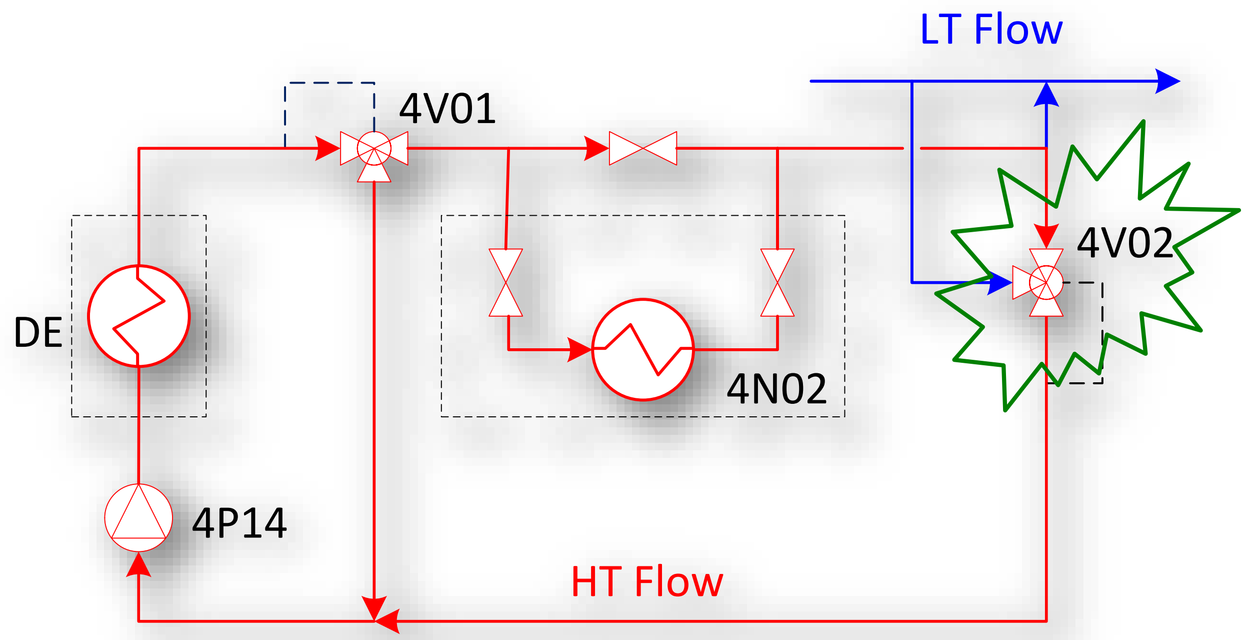
- Ship fuel consumption
  → mostly within [0.95 1.15]



➢ The energy flow simulator can accurately represent the energy flow distribution in the case ship.

HT water control example

- To test and verify different energy saving technologies and ideas



➢ QUESTION: Can we harvest a part of the wasted heat energy by tuning the set-point of valve 4V02?

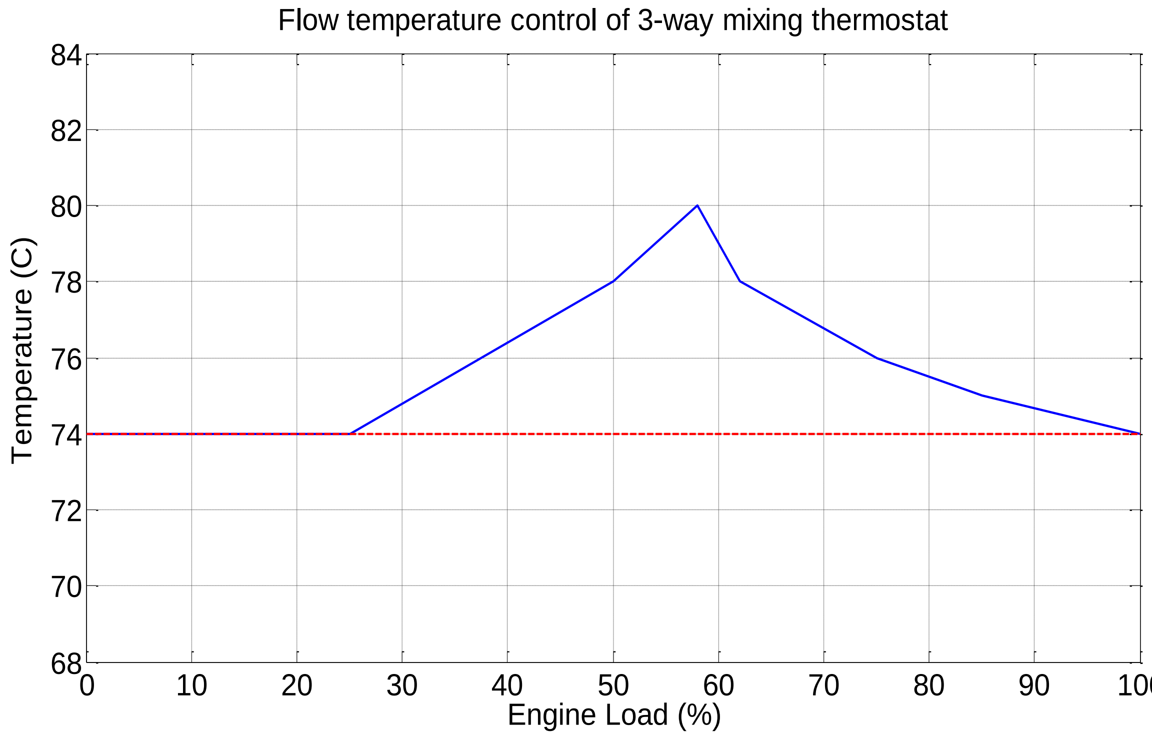
HT water control example

- To specify the set-point of valve 4V02 as a function of engine load

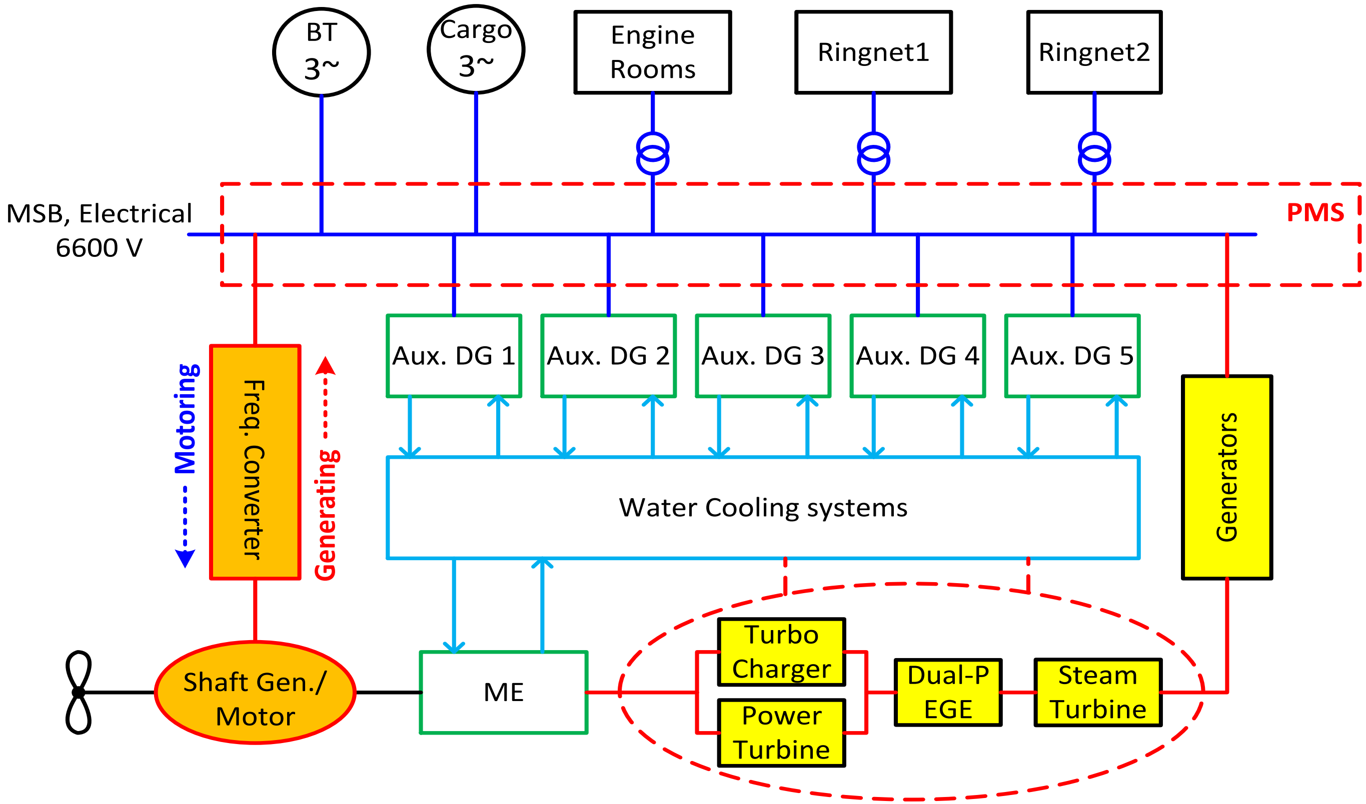
- To Check:
  - Working efficiency
  - WHR
  - Working safety

– Constant set point

– Variable set point

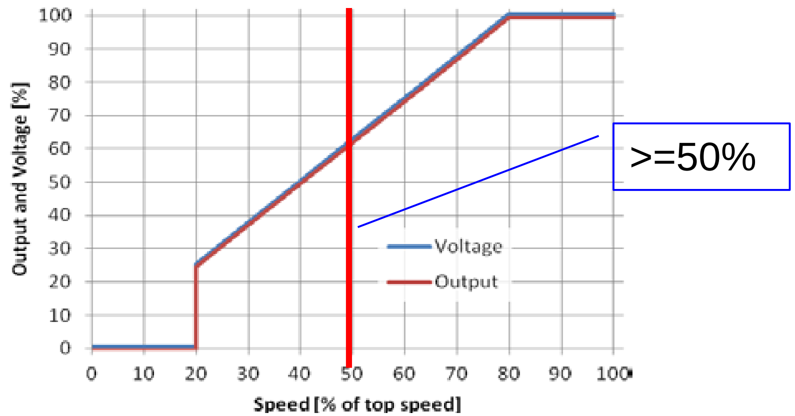


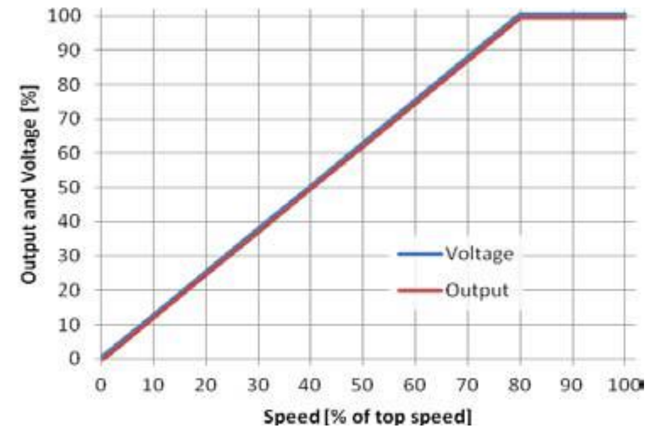
Power and steam turbine usage



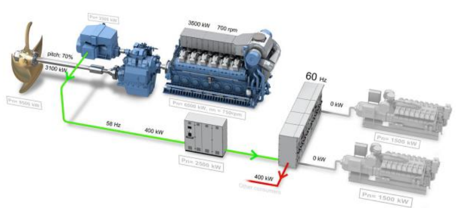
- Shaft generator system (SG)
- Waste heat recovery system (WHR)

Shaft generator usage

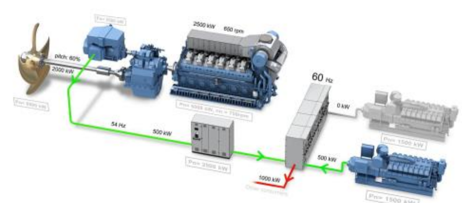




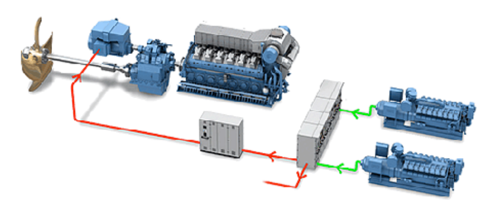
- Generator mode



- Parallel generation



- Motor/booster mode



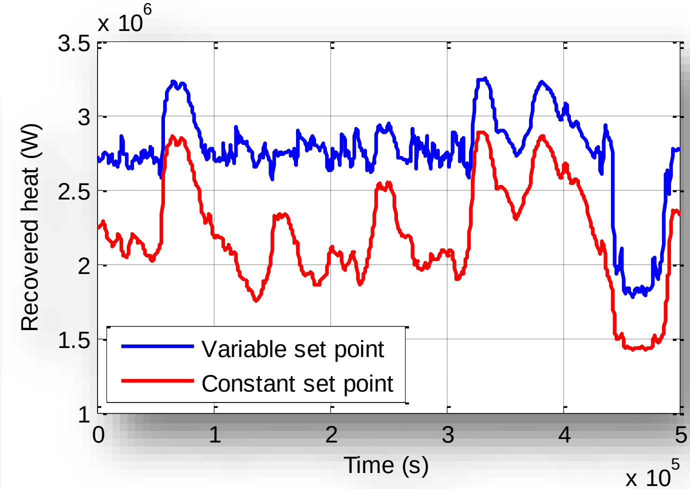
(Source: Rolls-Royce, Hybrid shaft generator propulsion system upgrade)

✓ Harvest energy from ME shaft to generate electricity, less fuel consumption

✓ More flexible energy utilization to achieve higher overall energy efficiency

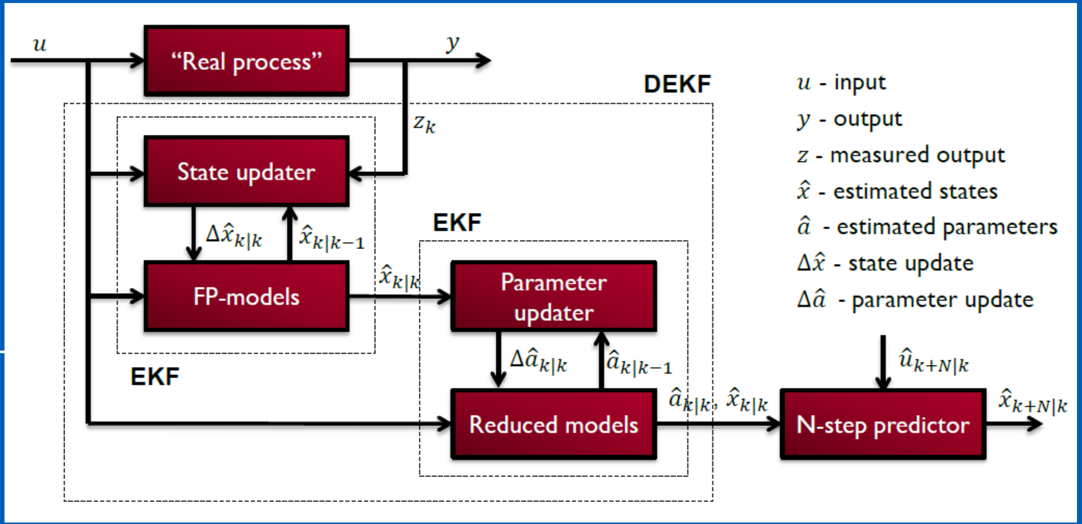
Results

- Different energy saving solutions evaluated under operation cycles recoded on-board
- **Improved HT water temperature control** → ROI 1 year, annual fuel savings 50 kUSD (HT/LT 3-way valve), [1]
  - In collaboration with ABB & Deltamarin
- **Power turbine in waste heat recovery** → ROI 2 years, annual fuel savings 2 M€, [2-3]
  - In collaboration with ABB



1. Zou G., Elg M., Kinnunen A., Kovanen P., Tammi K. & Tervo K. *Modeling ship energy flow with multi-domain simulation*. CIMAC.2013
2. Zou G., Kinnunen A., Tervo K., Orivuori J., Vänskä K. & Tammi K. *Evaluate Ship Energy Saving Scenarios Using Multi-Domain Energy Flow Simulation*. COMPIT.2014
3. Solution developed was installed in 14 new container ships. *ABB to provide waste heat recovery systems for 14 container ships*. World Maritime News. Nov 15, 2013 http://worldmaritimenews.com/archives/97685/abb-to-provide-waste-heat-recovery-systems-for-14-container-ships/

How to Predict Ship energy Flows?



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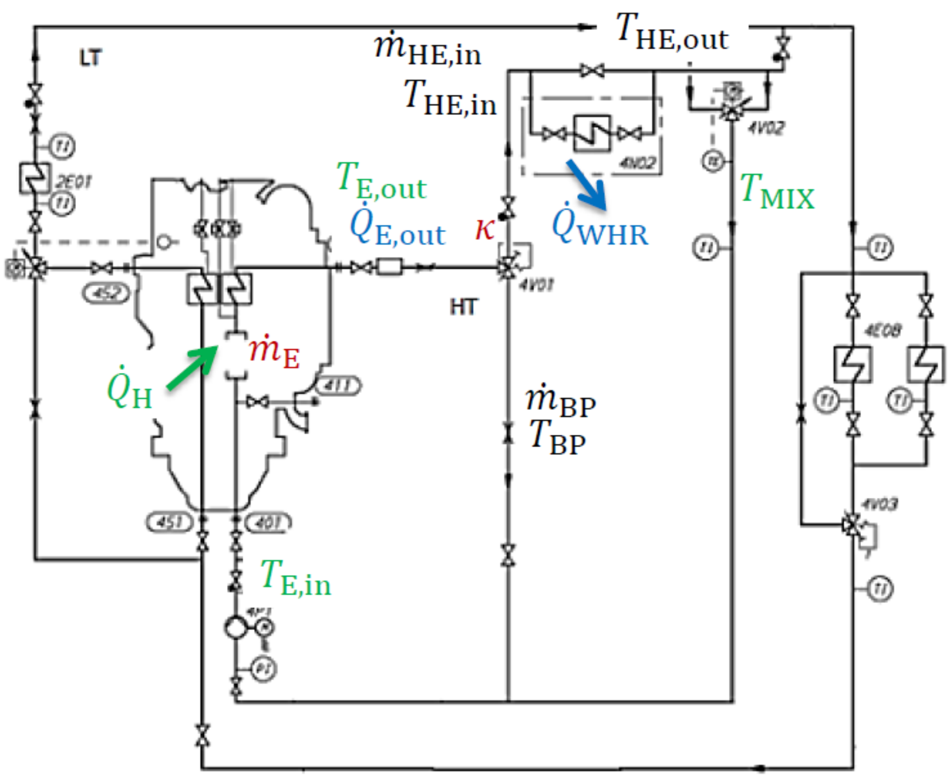
Energy flow prediction

- How to estimate energy flows within ship based on incomplete measurement information?
- How to predict / forecast the energy flows 6-32 hours ahead as accurately as possible?
- How to operate and control ship and ship systems as energy efficiently as possible?

Marine engine cooling water circuit

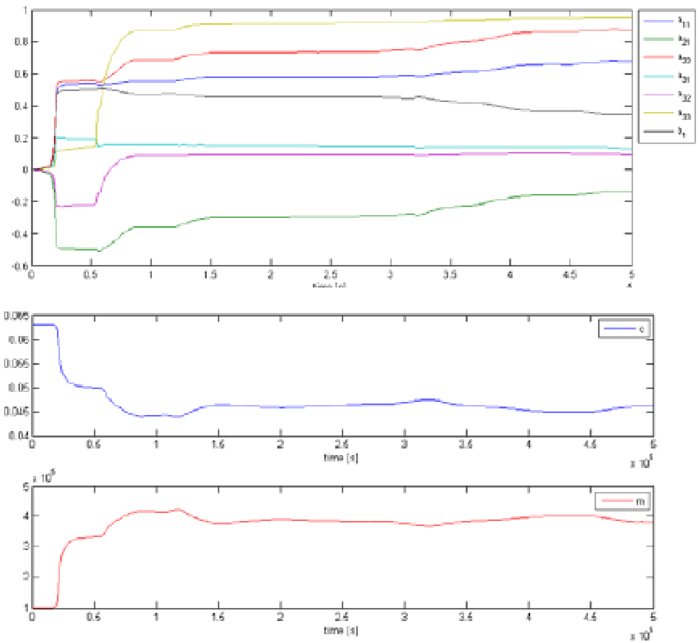
- **Measured signals**
- **Observed signals**
- **Signals to predict**



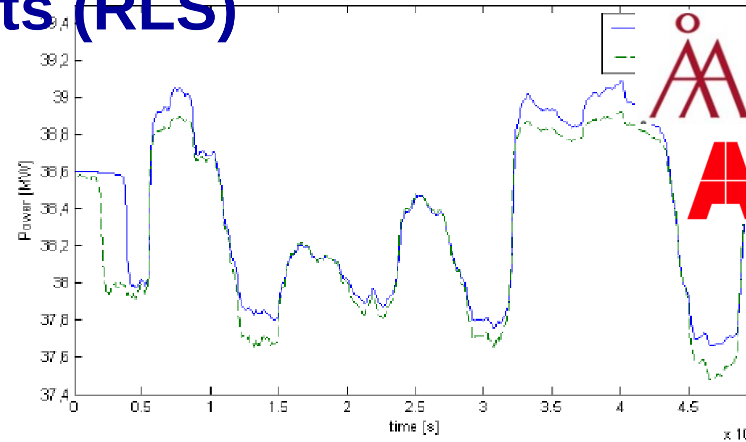
T	–	temperature
$\dot{m}$	–	mass flow
$\dot{Q}$	–	heat
κ	–	thermostat coefficient
<u>Indices</u>		
in	–	inlet
out	–	outlet
E	–	engine
BP	–	bypass
HE	–	heat exchanger
MIX	–	after mixer
WHR	–	waste heat recovery
H	–	heat from load

Signal estimation results (RLS)

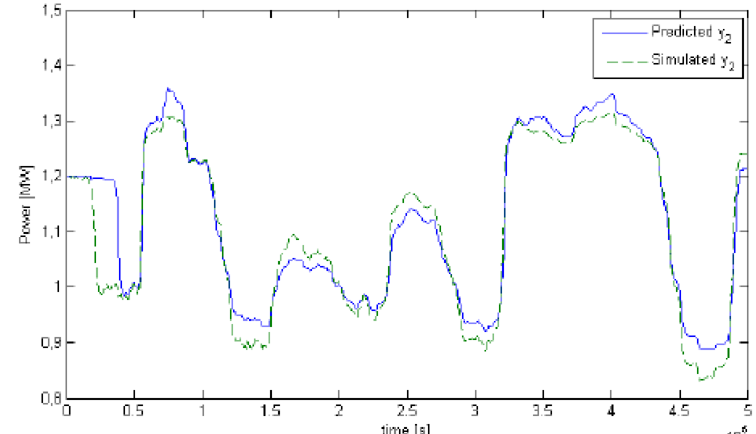
- The "low variation" load profile has been used
- A constant set point for T_{mix} has been used
- Details are presented in the attached, updated report



Estimated parameters



Estimated $\dot{Q}_{\mathrm{E,out}}$



Estimated $\dot{Q}_{\mathrm{WHR}}$

Uncertainty in machinery design Cases electric vehicles

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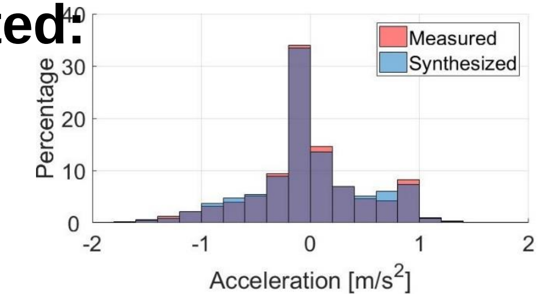
Driving cycle and passenger load uncertainty - approach

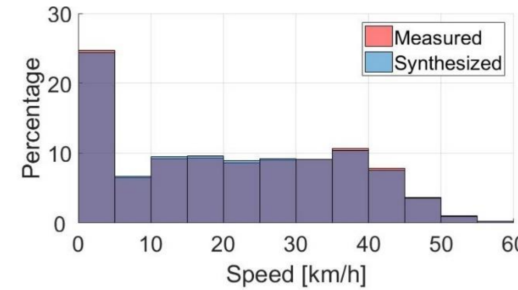
- **How much do the variations in the driving cycle and passenger load on a single bus route affect the energy consumption?**
- **Create a method to generate varying synthetic cycles and passenger flows and then run them with a simulation model.**
- **Case example: Line 11 in Espoo, battery electric bus**

- **Note: “driving cycle” substantially more complicated in ships due to high auxiliary loads**

Driving cycle and passenger load uncertainty - methods

- Divide route into segments between bus stops
- Create new cycles by randomly choosing respective segments from measured cycles
- Segments need to be connected
- The bus stops at which the vehicle stops are also randomized
- Cycle synthesis validated:

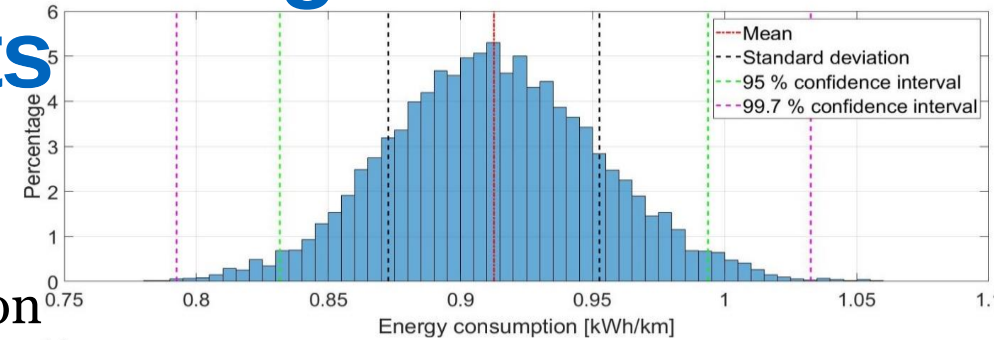


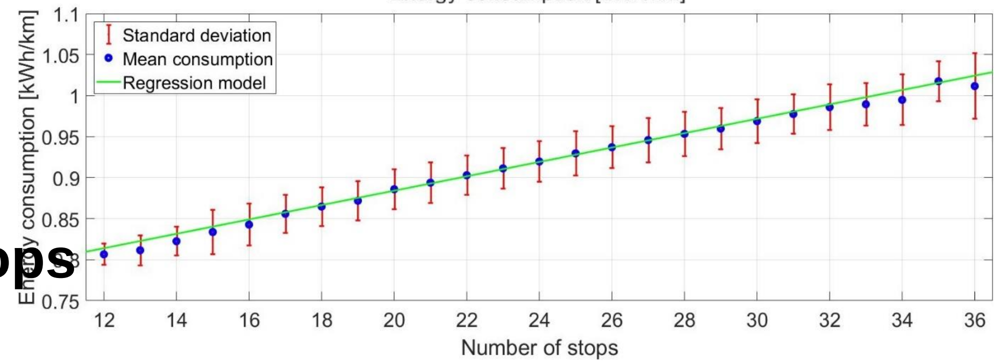


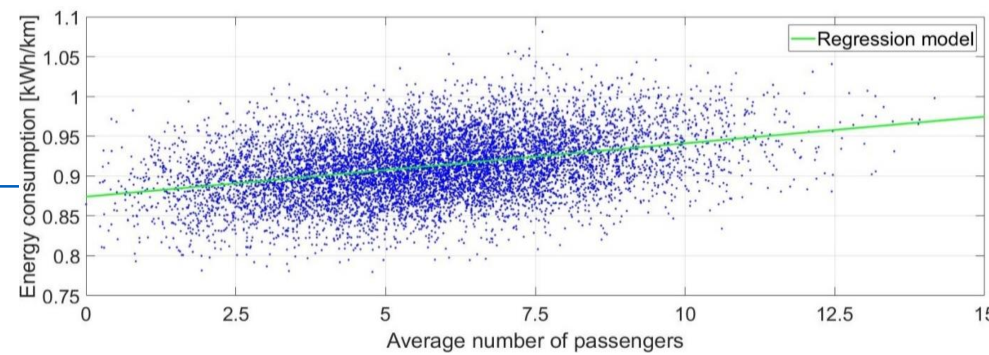
- Passenger flow is sampled from a multivariate distribution

Driving cycle and passenger load uncertainty - results

- **Energy consumption distribution acquired**
  - Resembles normal distribution
  - Mean: 0.913 kWh/km,
    Range: 0.301 kWh/km
- **Consumption correlates strongly with number of stops**
  - Pearson coefficient: 0.778
- **Lesser correlation with passenger load**







Robust Design – Approach (1/2)

- ***Noise factors*** cause unwanted variation in vehicle performance
- ***Robust design*** = make the system insensitive to these variations
- **Identify** ***noise factors*** and their range of values
- **Study** ***control factors*** that reduce the effect of noise factor variation

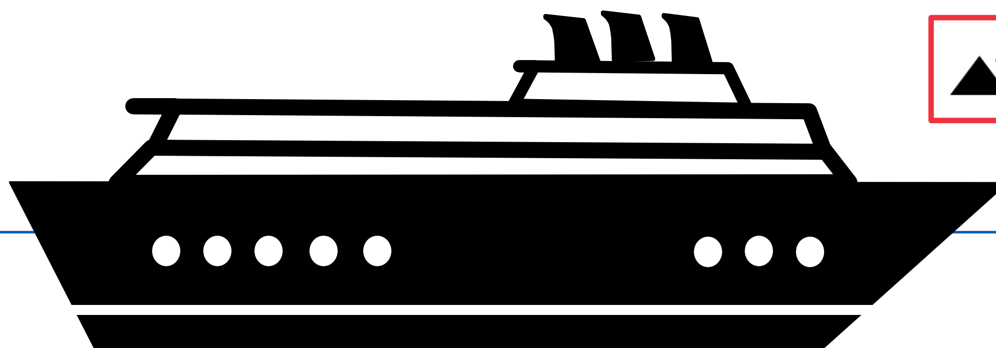
Payload

User Behaviour

Operating Temperature

Age & Wear

Waves & Storms

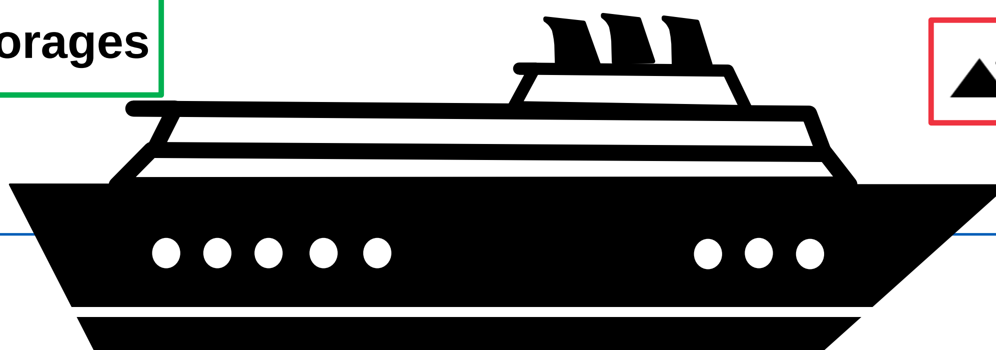


Robust Design – Approach (2/2)

- **Robustly optimize *control factors*** to guarantee long lasting quality design, without unnecessary oversizing of components

- Payload
- User Behavior
- Temperature
- Age & Wear
- Waves & Storms

- + + Energy Generation & Control
- + Energy Storages
- Propulsion



Robust Design – Methods

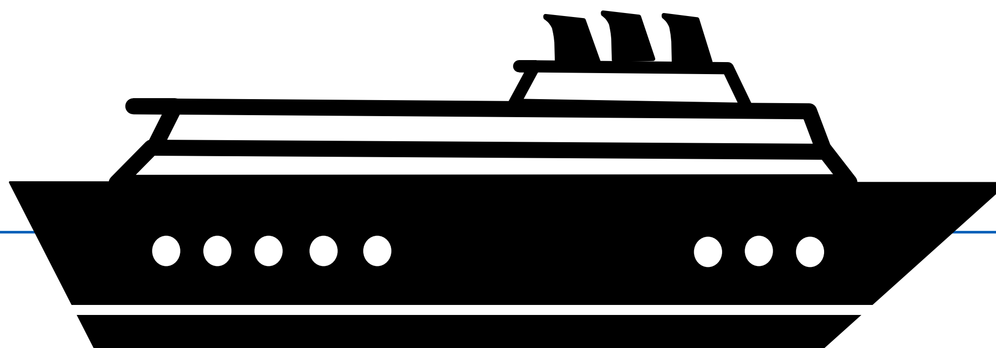
Solution: Surrogate analytical model (PCE)

Challenge: Complex dynamic model

Sensitivity analysis: Impact of Noise Factors

Noise Factors

Control Factors

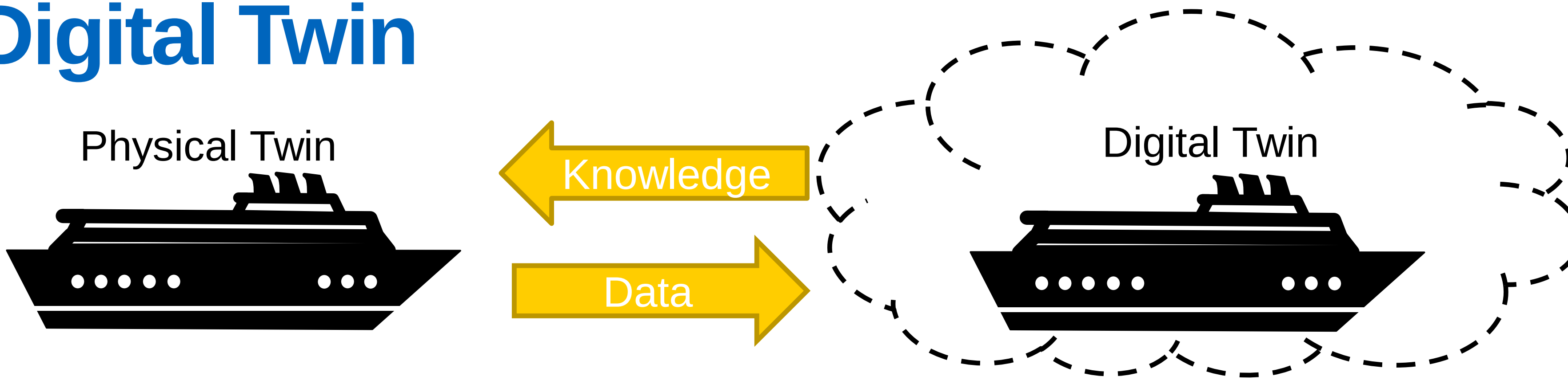


Robust Design – Results
Case: Electric City Bus

The consumption varied from 0.4 to 2.3 kWh/km in the selected route

- **Key noise factors**
  1. Ambient temperature
  2. Rolling resistance
  3. Mission
  4. Driver aggressiveness
  5. Traffic
  6. Payload
  7. Headwind

Digital Twin



1. **Can be inspected with all senses on location**
2. **Obeys laws of physics**
3. **Doesn't have intelligence**
4. **Is constantly changing**

1. **Can be inspected through a user interface from anywhere around the world**
2. **Laws of physics must be simulated**
3. **Can have artificial intelligence that can be used to control physical twin**
4. **Must be updated to match the physical twin**

IoT & Digital Twin, Approach

Ship energy systems are constantly producing vast amount of data. This data could be utilized better with enhanced connectivity and data management

Currently, there is no standardized way of transferring and displaying data. Standardizing work is necessary, and good standards can only be achieved through experience

Functional demonstrators will crucial for creating the future standards.

IoT & Digital Twin, Benefits

Benefits of Digital Twin come from multiple factors:

1. **Deeper knowledge of the energy process state**
2. **Centralized data interface**
3. **Deductions from comparing large populations with e.g with artificial intelligence**
4. **Truly integrating connected products to each other with standardized data formats**

→ Energy system optimisation

→ Operation optimisation

→ Fleet management

Future outlook

Technologies (to be) studied

IoT: automation systems provide with various measurements

Computer power enables on-line control and e.g.

- **Uncertainty and sensitivity in design**
- **Tracking simulator approaches**

Emerging technologies:

- **Electrification (hybridization), DC grid, variable AC**
- **Energy storages, electric and thermal**
- **Waste Heat Recovery (ORC, connection to energy storages)**
- **Absorption chillers**
- **Power turbines and multi-stage turbo charging**

SET final publication in VTT Technology series
http://www.vtt.fi/inf/pdf/technology/2017/T306.pdf.