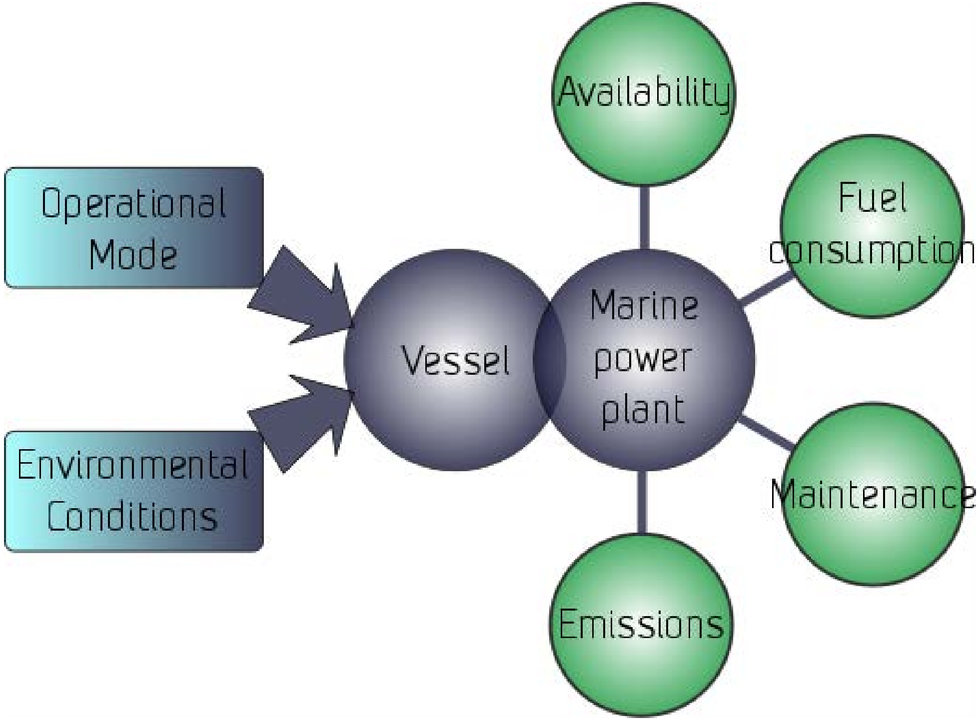
NTNU – Trondheim
Norwegian University of
Science and Technology

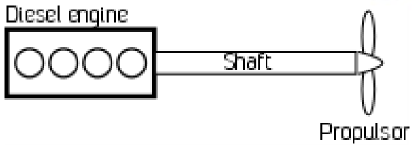
Transient Performance and Emissions of Turbocharged Diesel Engines for a Marine Power Plant

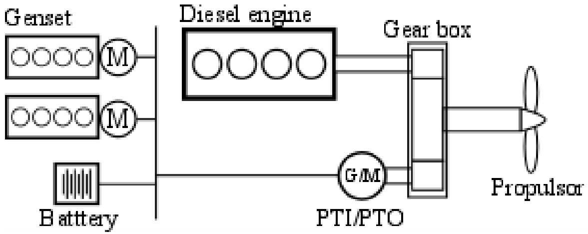
Numerical Simulation and Experimental Investigation

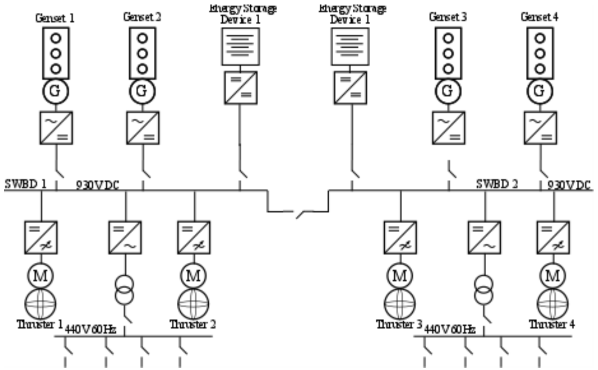
Introduction

Marine Power / Propulsion Plant



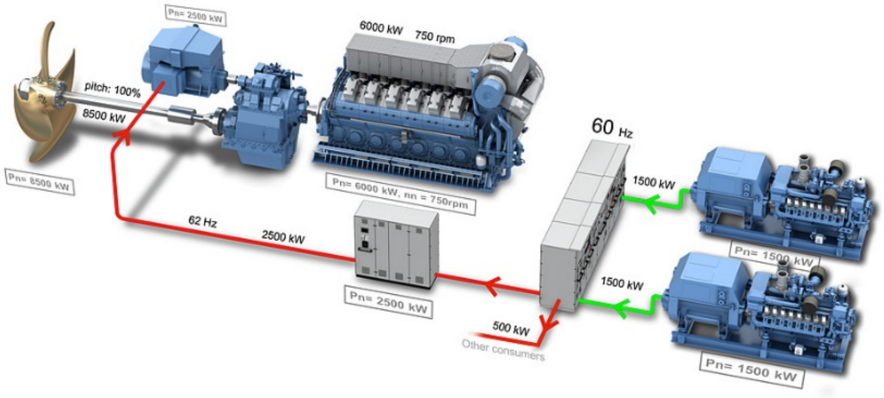






Industry and Research Trend

- Hybrid Power System
- System integration
- Simulation based design and analysis



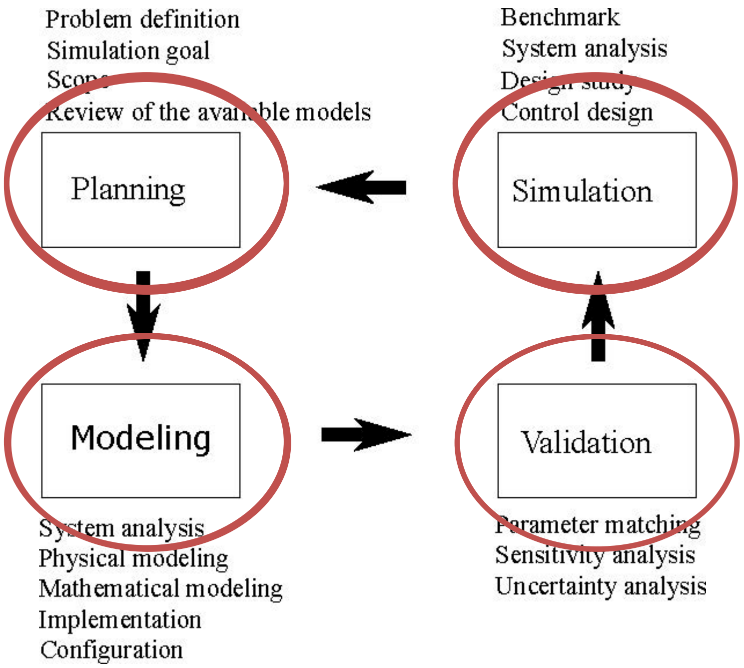
Research Questions

How can one build a mathematical model of a turbocharged diesel engine for various contexts of marine propulsion or power systems?

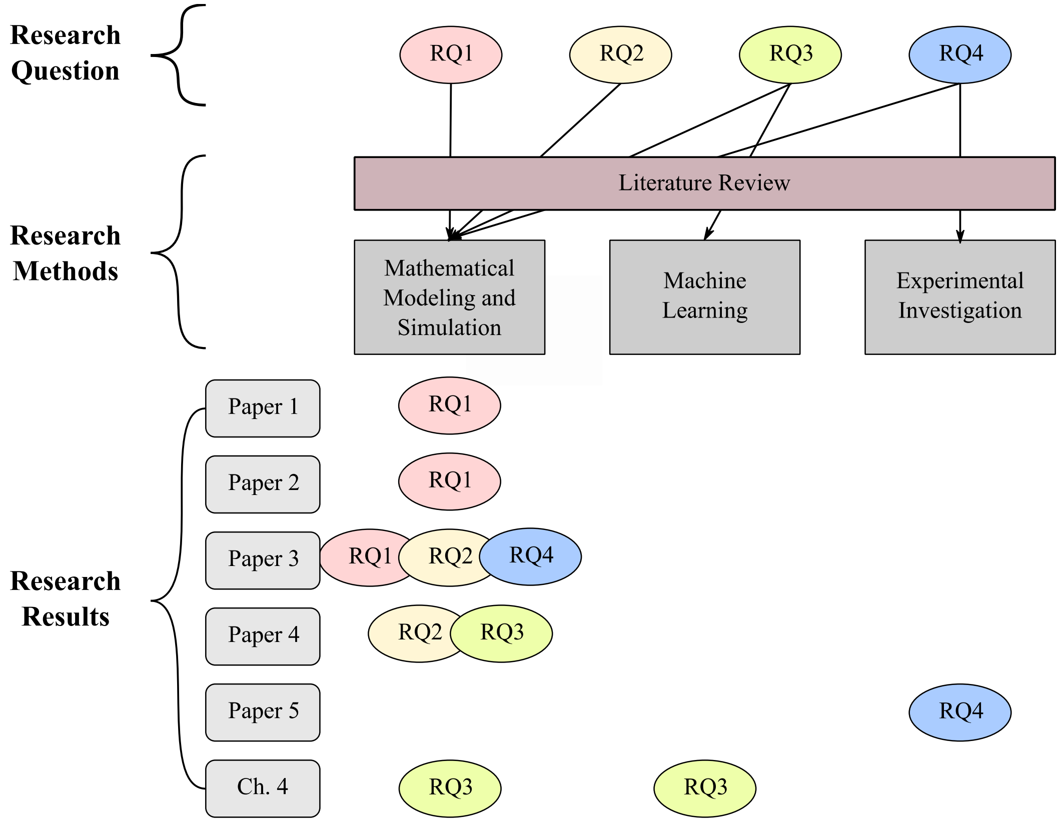
[illegible] loads on the marine diesel engine in terms of efficiency and emissions?

[illegible] for different contexts [illegible] propulsion and power plant simulations?

[illegible] information of the system response?



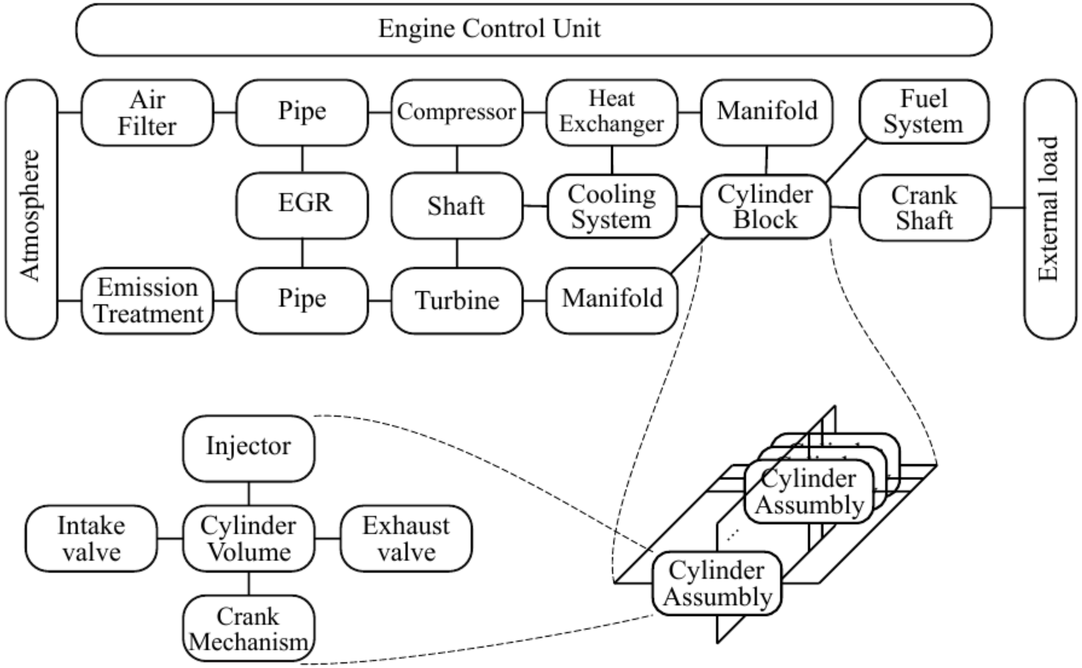
Research Methods and Results



Modeling Framework for a Turbocharged Diesel Engine

Hierachical Structure of System Models

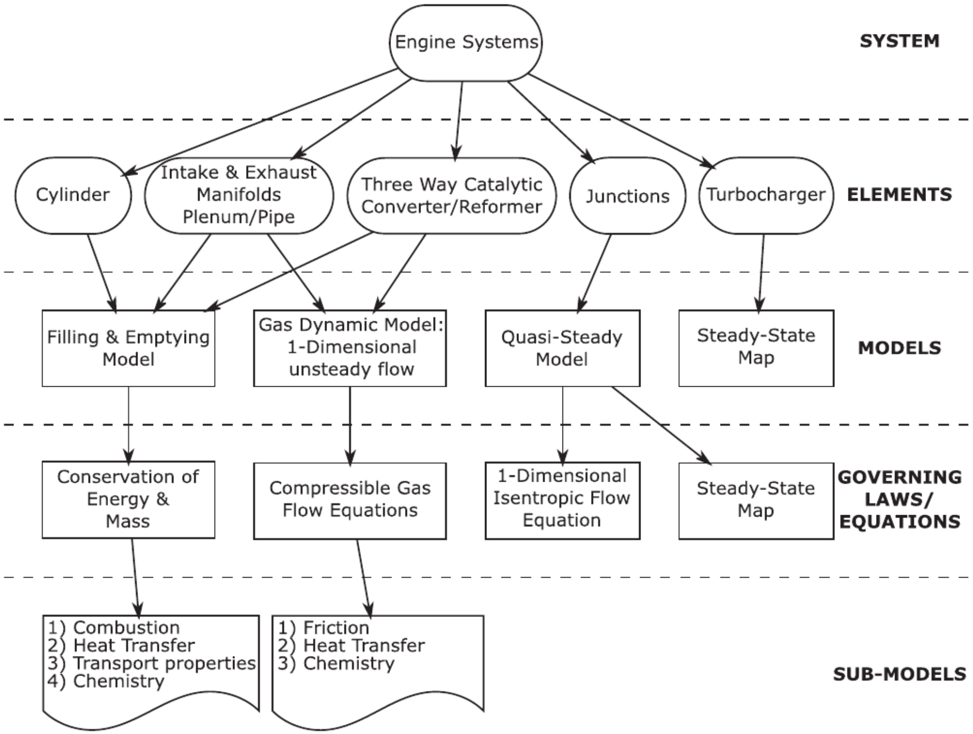
- Technical composition

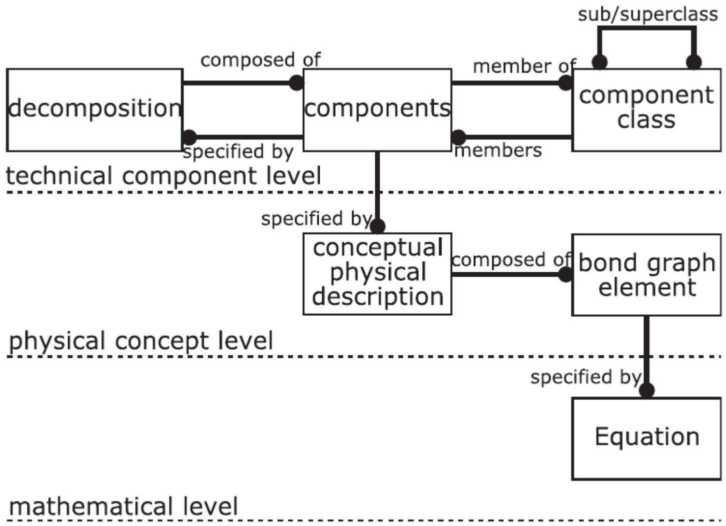


Model Library

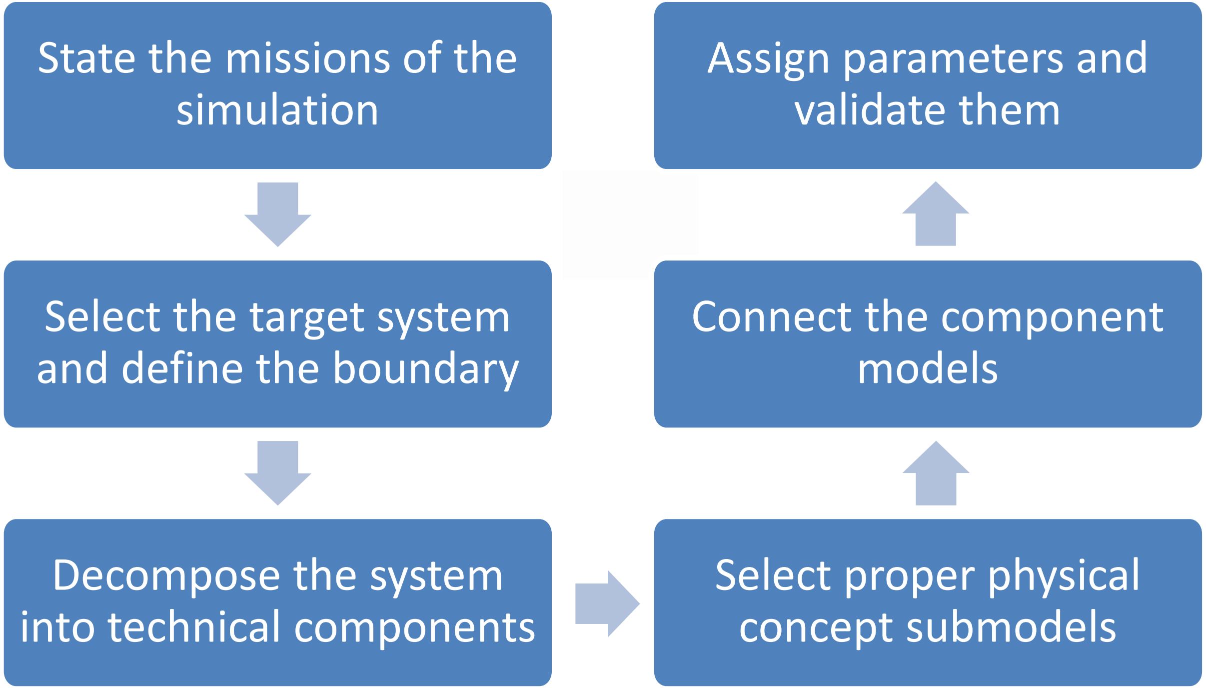
Hierachical Structure of System Models

- Level of Abstraction





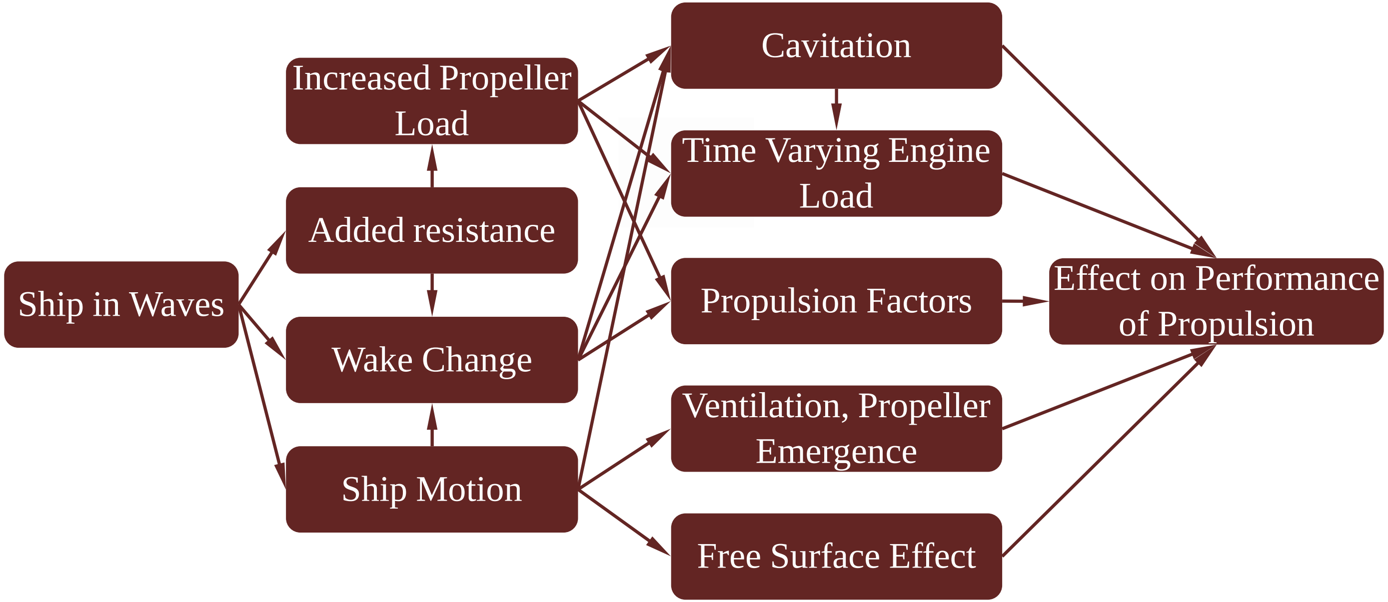
Procedure for building a system model from the model library



Diesel Engine Models for Propulsion System Simulation in Waves

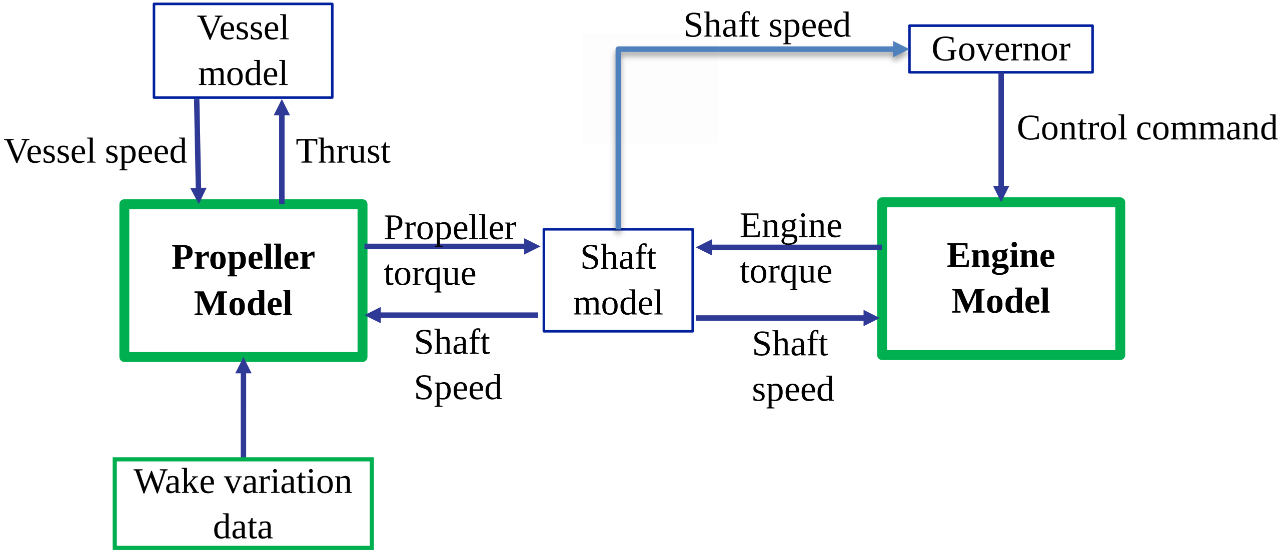
Motivation – Propulsion in Waves

- Propulsion in Waves

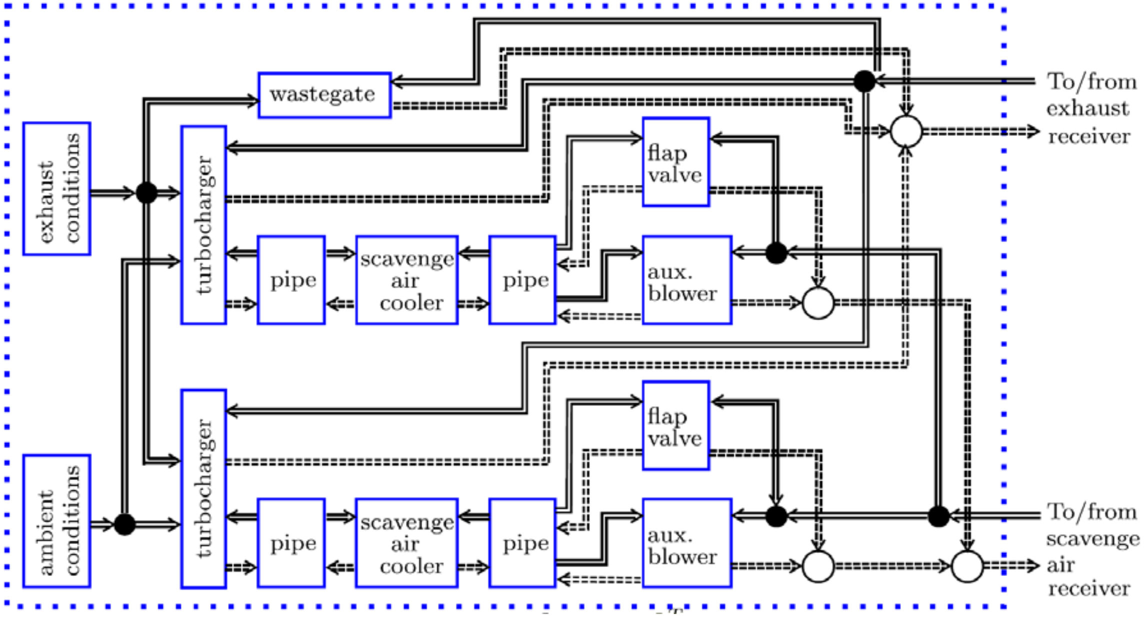


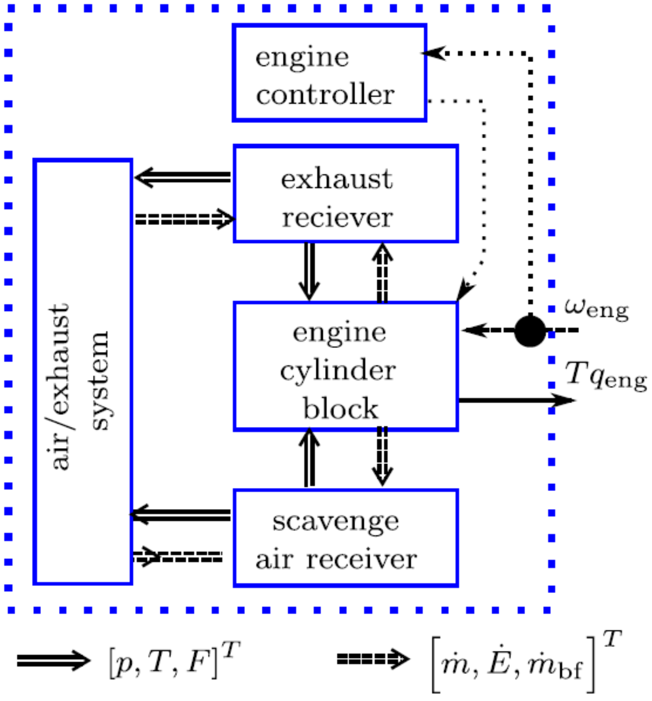
Coupled Engine Propeller Model

- Develop a hull-propeller-diesel engine simulator
- Understand the system dynamics in propulsion in waves
- Compare the transient fuel consumption with the steady-state mapping value



Engine Model Structure





Engine Model

- Modeling framework

Components		Process	Submodel
Engine Cylinder	Control volume	Thermodynamic states	0D single zone
		Heat transfer	Convection only
	Scavenge port	Mass flow	Isentropic comp. flow
	Exhaust valve	Valve lift	A look up table
		Mass flow	Isentropic comp. flow
	Crank mechanism	Transformation	Kinematics only
	Gas exchange	Scavenging	Empirical model (S-shape model by Sher)

Case Vessel – KVLCC2

CFD and experimental wake data available for the KVLCC2 hull in three different wavelengths i.e. λ/L = 0.6, 1.1 and 1.6

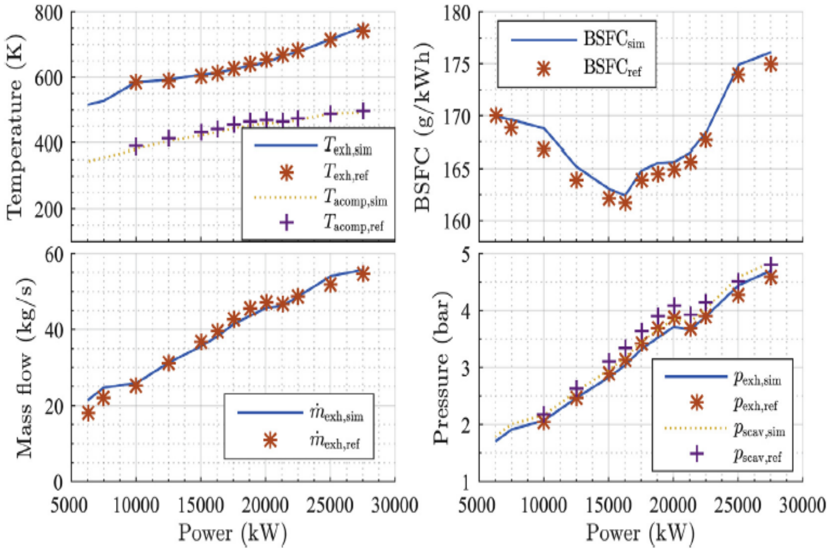
Ship Particulars	
Lbp (m)	320.0
Lwl (m)	325.5
Bwl (m)	58.0
Depth (m)	30.0
Draft (m)	20.8
∇ (m^3)	312622
C_B	0.8098
V (kts)	15.5

Propeller Particulars	
D (m)	9.86
No of blades	4
Hub diameter (m)	1.53
Rotational speed (RPM)	95
A_e / A_0	0.431
(P/D)mean	0.47
Skew (°)	21.15
Rake (°)	0

Engine Particulars	
Model	Wartsila 8RT-flex68D
Bore (mm)	680
Rated MCR (kW)	25,040
Speed at rated power (RPM)	95
Stroke (mm)	2720
Mean Effective Pressure (bar)	20
Number of cylinders	8
Turbocharger	2 x ABB A175-L35

Validation of the model

- Steady-state



Main parameters for adjustment

- Valve timing, injection timing
- Turbine, compressor map

- Transient – no data to fit
  - Sensitivity analysis

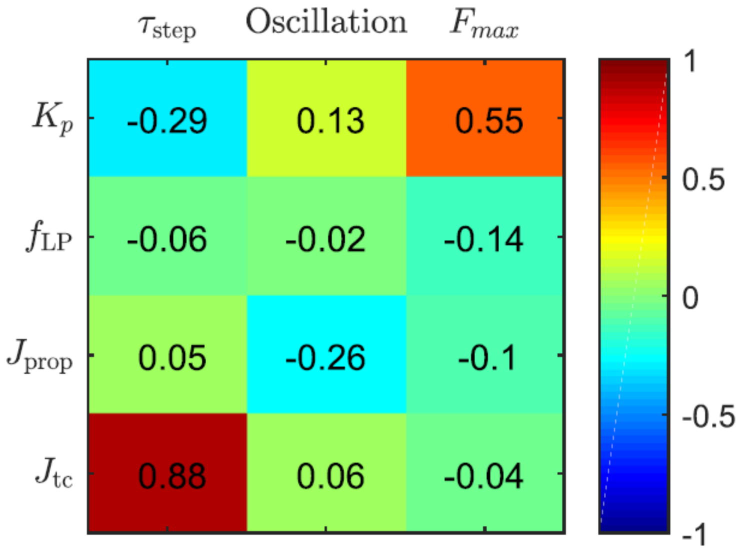
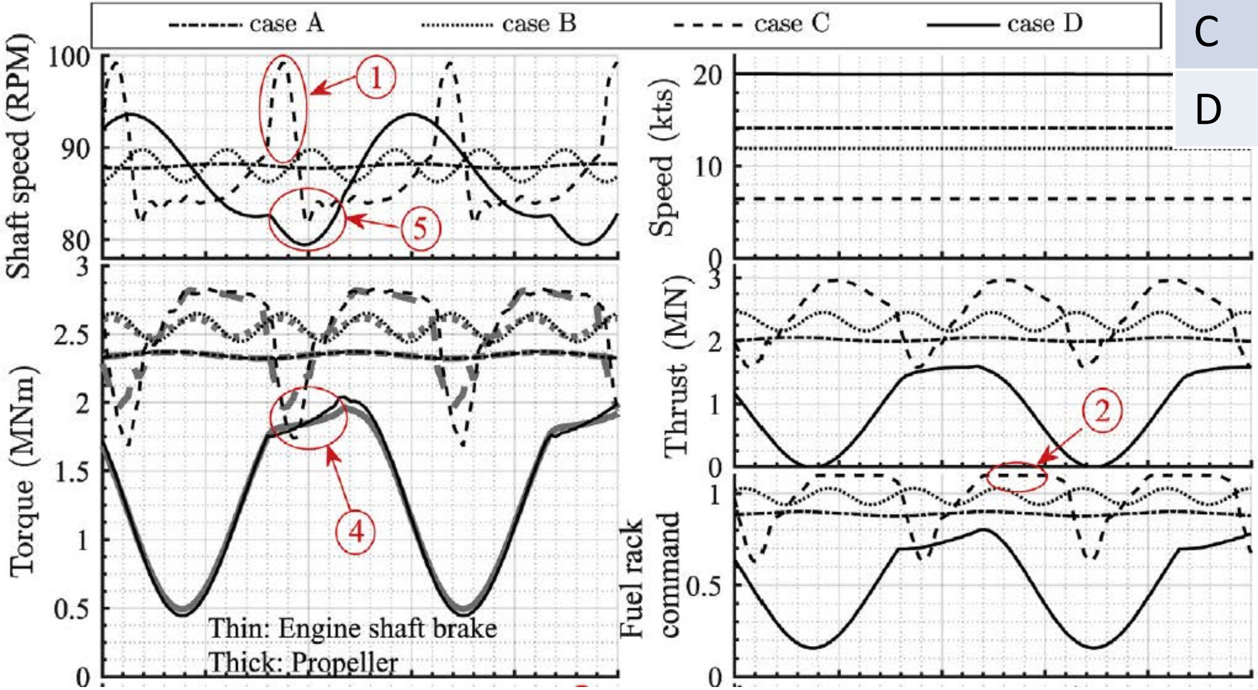


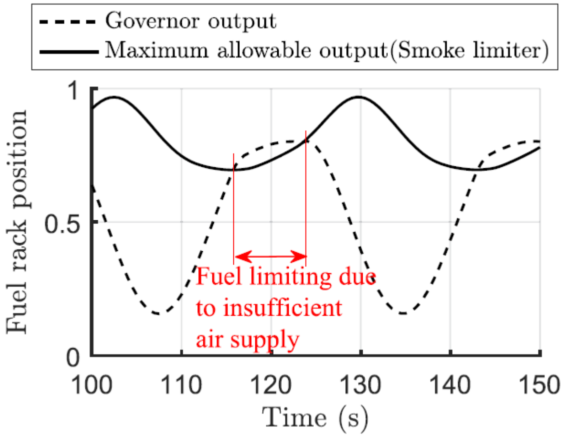
Fig. 20. Correlation matrix for the step response analysis.

Simulation Results

Case	H (m)	λ (m)	χ (°)
A	3	512	90
B	3	192	180
C	5	512	180
D	5	192	0

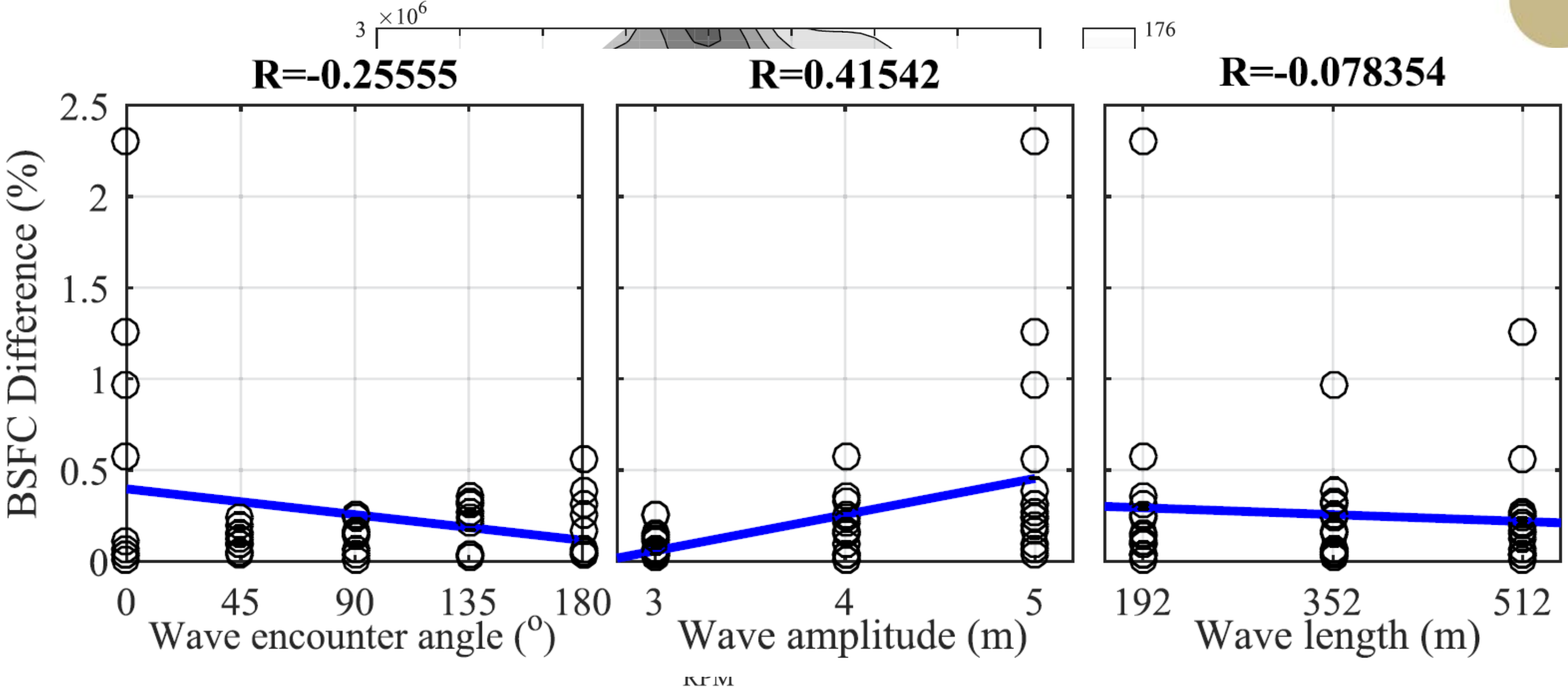
- System dynamics





Simulation Results

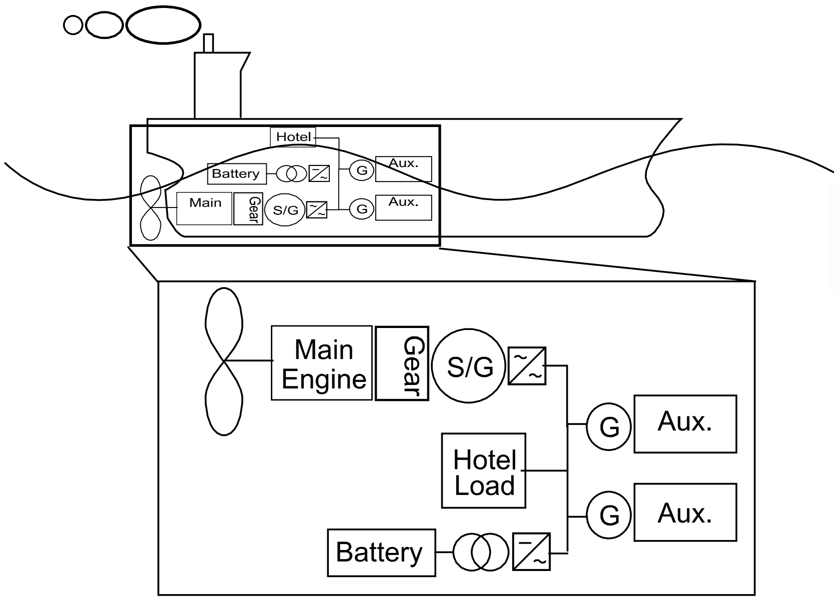
- Transient simulation vs. steady state mapping

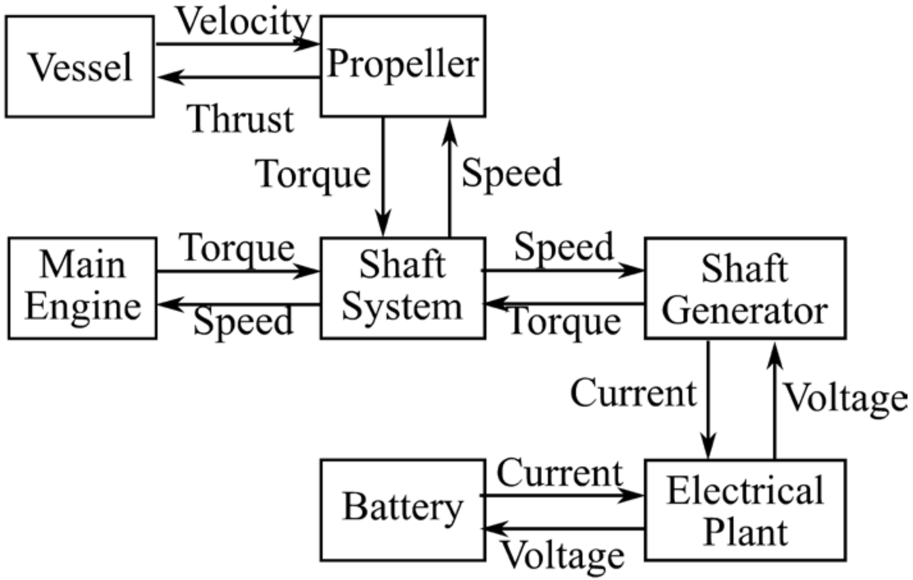


Findings

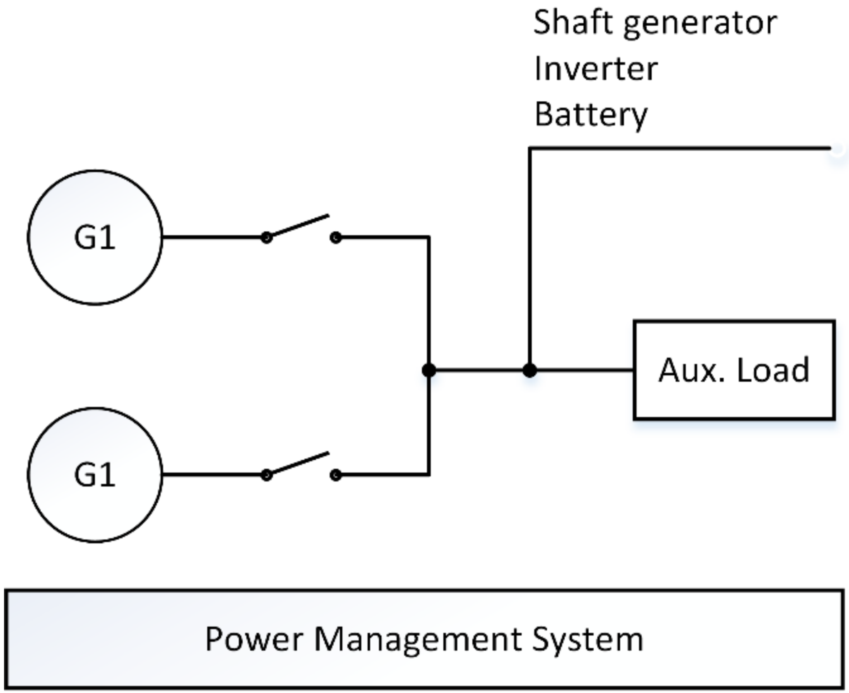
- The simulator demonstrated the complex interactions between a hull, a propeller, a diesel engine and a control system.
- For transient response of the diesel engine with a governor and a smoke limiter, inertia of a turbocharger rotor plays important role as well as the control parameters.
- Steady-state mapping of the specific fuel consumption shows small deviations from the transient simulation with 0D model (fixed combustion profile).

Hybrid Propulsion System for Deep-sea Shipping



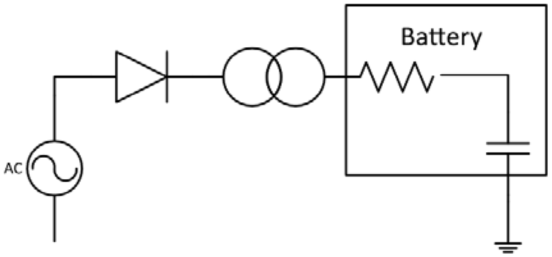


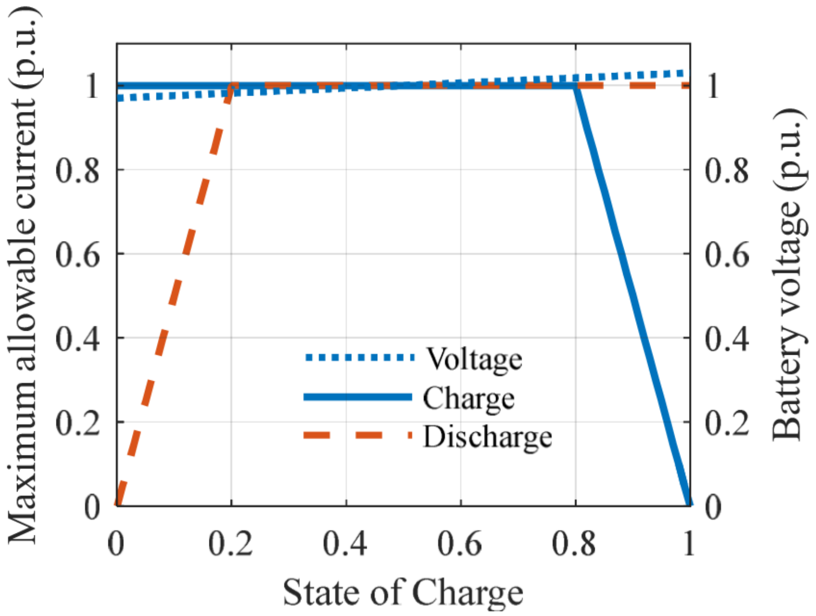
Electrical Plants



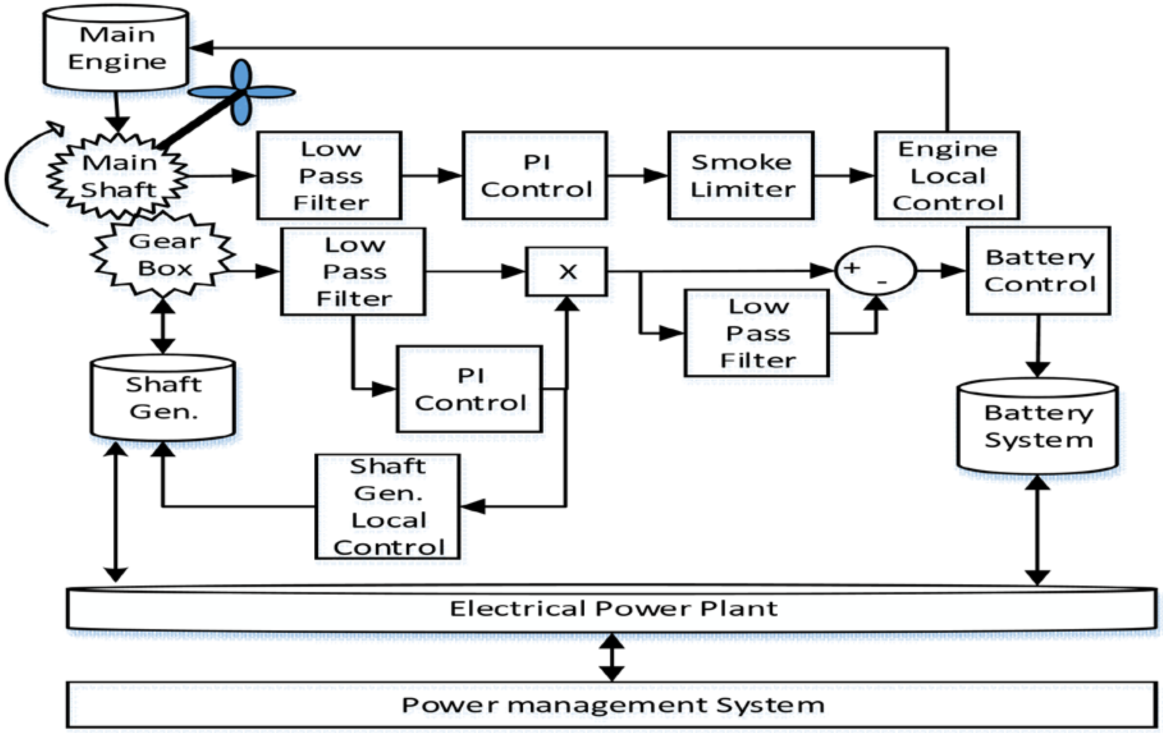
- Reference to Tom Arne Pedersen, “Bond graph modeling of marine power systems”, 2009
- Transient three-phase voltage, current and frequency simulation using dq-frame modeling and transformation

Battery model





Control System



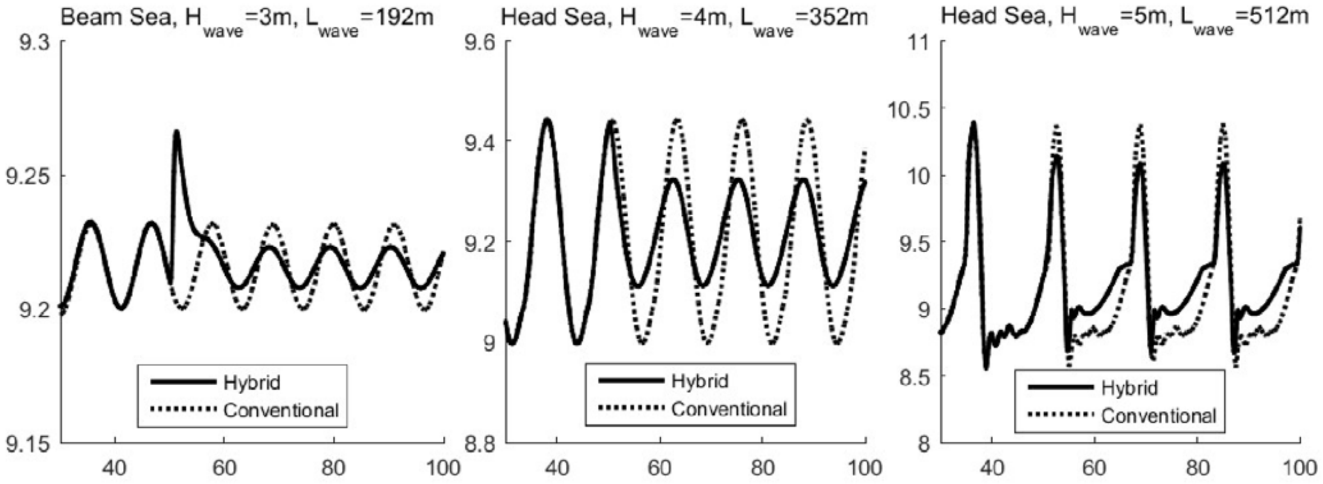
Result

- Reduction in amplitude of shaft speed and engine power fluctuation

		Shaft speed	Engine power
Reduction Ratio	Mean	2.20	2.00
	Maximum	2.85	2.62
	Minimum	1.30	1.06
	Standard deviation	0.36	0.45
Correlation coefficient to	χ_{wave}	-0.35	-0.46
	H_{wave}	-0.24	-0.46
	L_{wave}	0.24	0.13

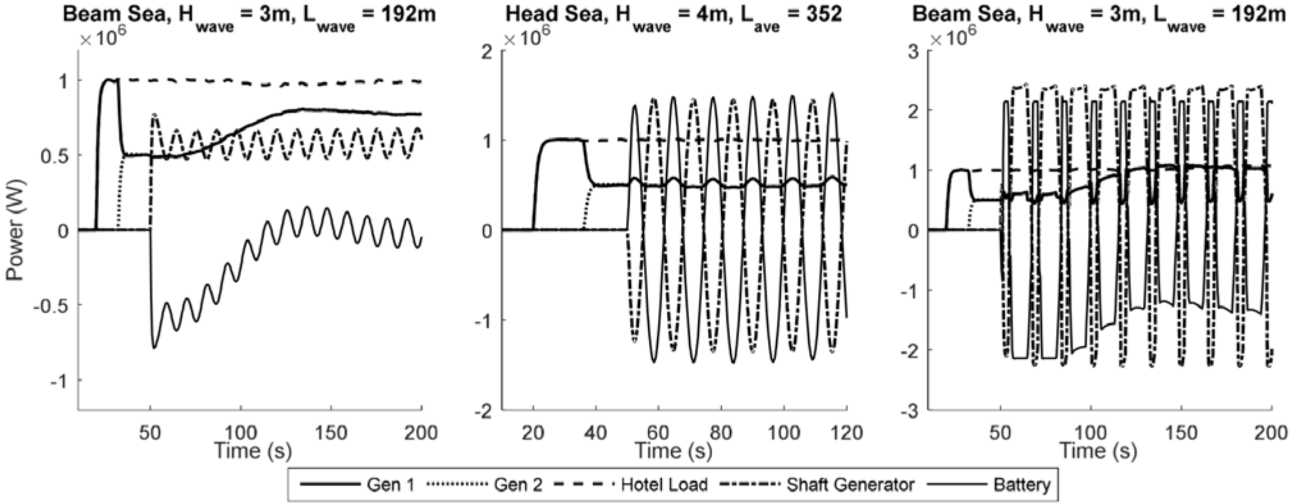
Result

- Time series simulation of the propulsion shaft speed



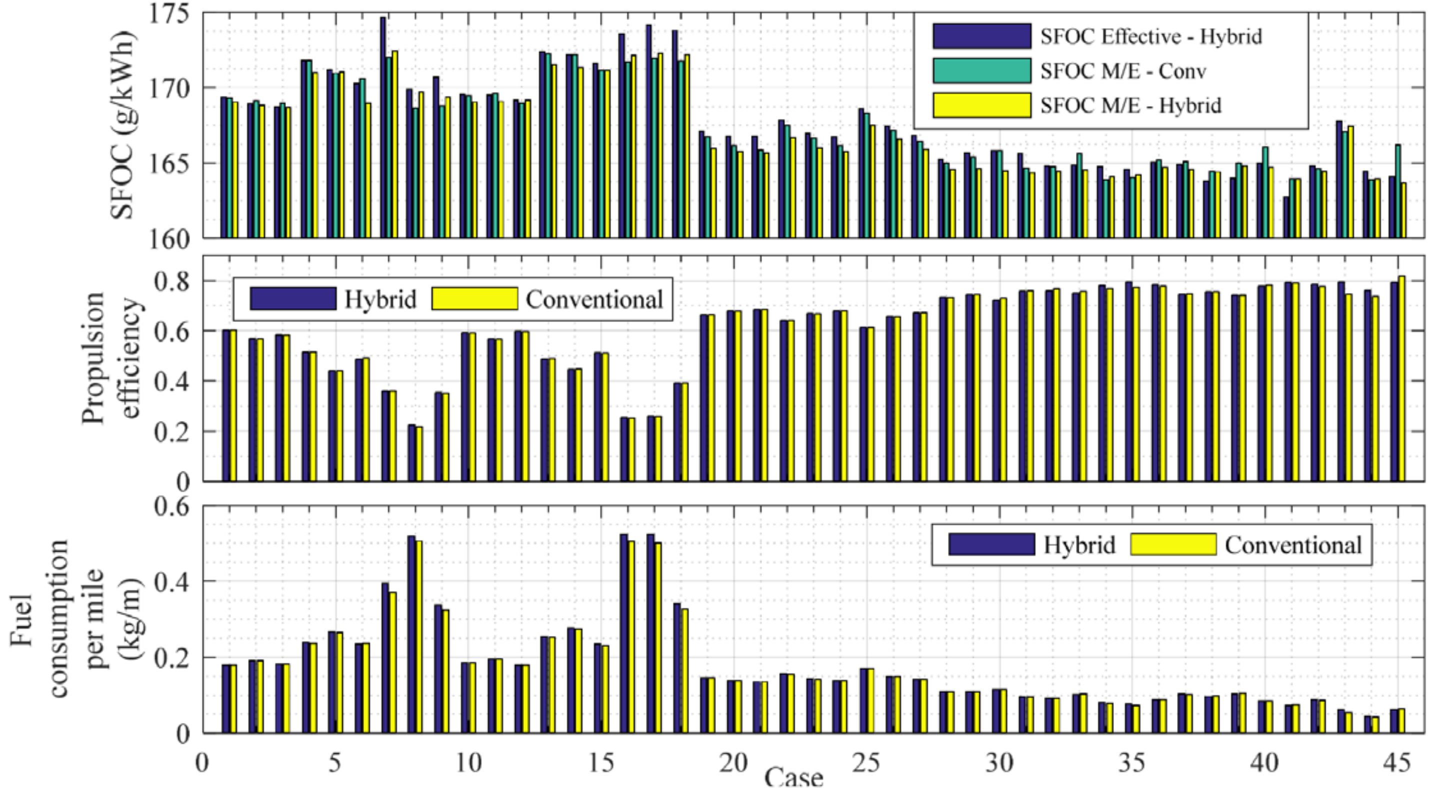
Result

- Time series simulation of the electrical power balance



Result

- Average Efficiency



Findings

- The simulation shows the possibility for reducing speed variation even for the mechanical propulsion using the existing installation by adding the battery system.

- The hybrid propulsion system utilized for peak-shaving in the extreme sea cases showed an equivalent level of efficiency.

- Optimization of the power plant including the main engine and the electrical power plant has potentials to improve the efficiency.

- Improvement for the battery control should be incorporated in the design of the power plant.

Experimental Investigation of the transient emissions

When is transient load dominant in the marine operation?

- Transit in waves
- DP operation in the extreme sea
- Active heave compensation in drilling or crane operation

} Cyclic load

- Crane operation => Step load

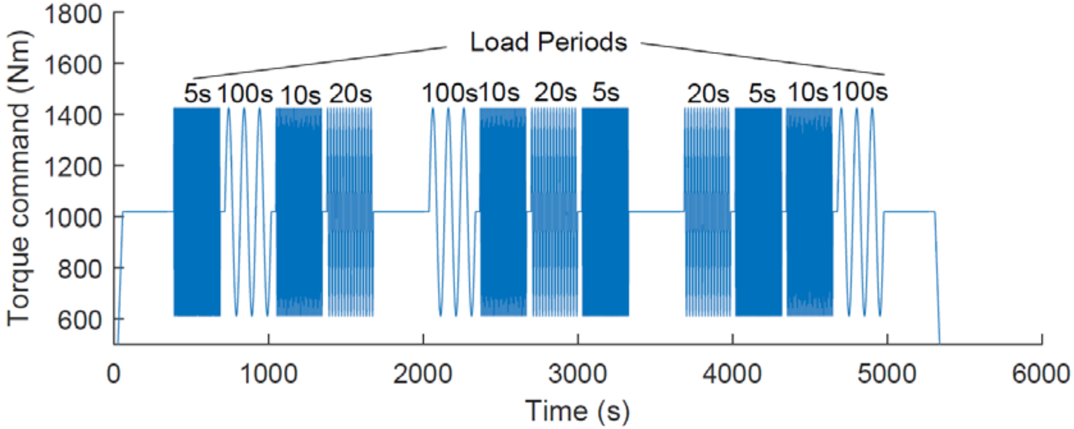
Research question

- Is there an effect of a cyclic transient load on the average fuel consumption and average NOx emission?

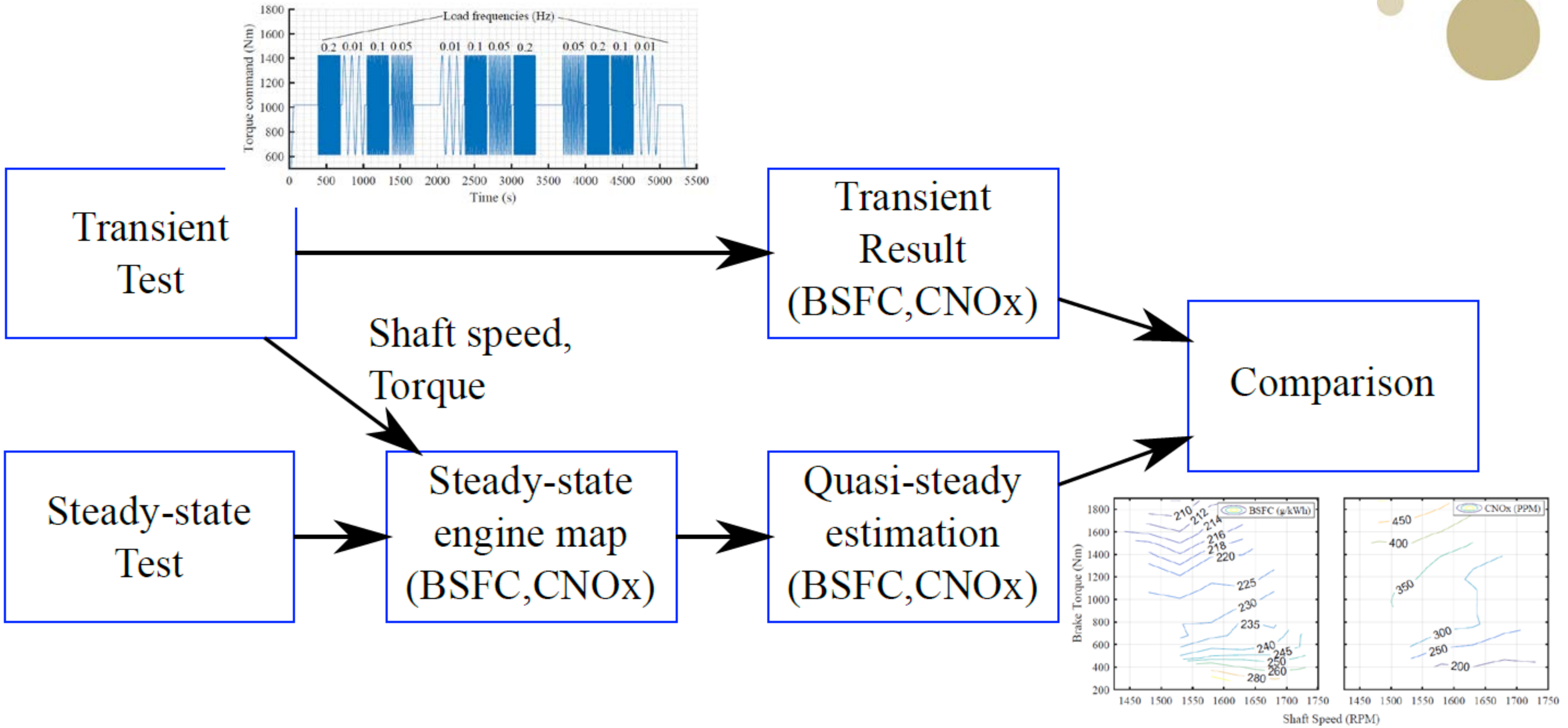
- If so, can we quantify the influence?

Methodology

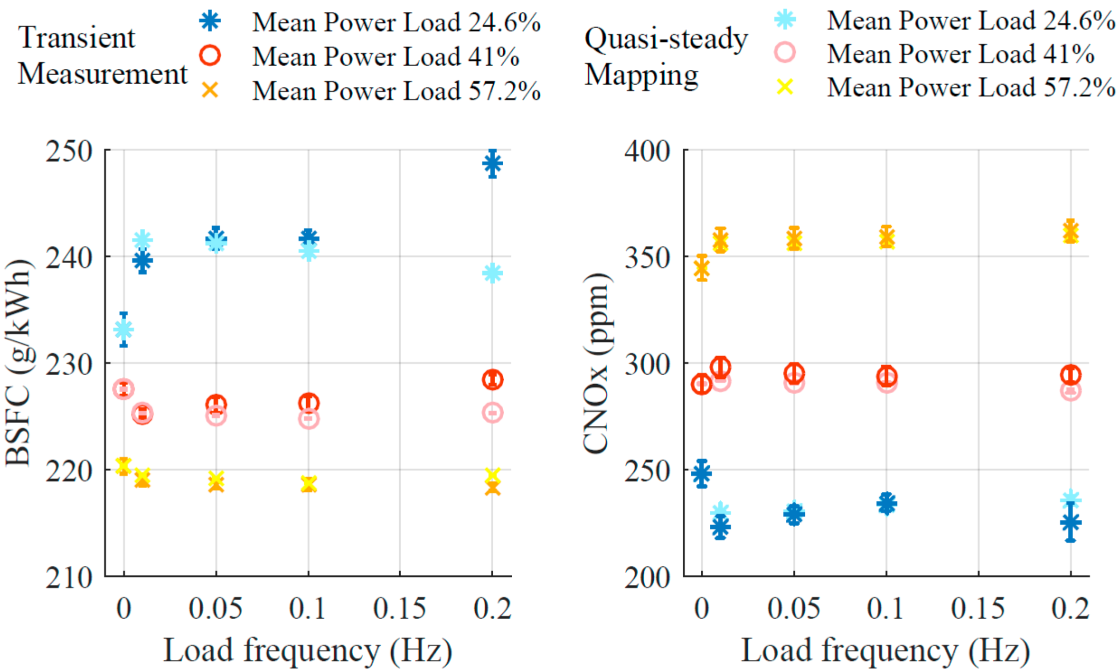
- Definition of the test case of transient load
  - Shaft speed(RPM): 1600
  - Load torque, combination of following
    - Period(s) : 5, 10, 20, 100
    - Amplitude(Nm): 407Nm
    - Mean Torque(Nm): 611, 1019, 1420



Methodology

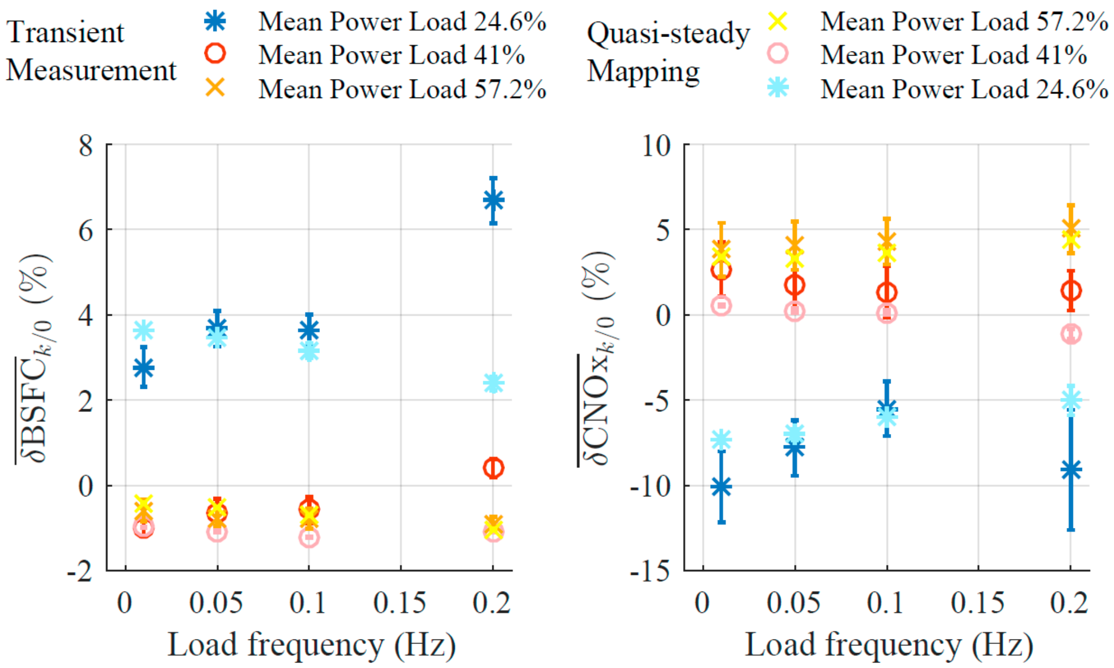


Result



Transient Measurement
Mean Power Load 24.6%
Mean Power Load 41%
Mean Power Load 57.2%
Quasi-steady Mapping
Mean Power Load 24.6%
Mean Power Load 41%
Mean Power Load 57.2%
BSFC (g/kWh)
250
240
230
220
210
0
0.05
0.1
0.15
0.2
Load frequency (Hz)
CNOx (ppm)
400
350
300
250
200
0
0.05
0.1
0.15
0.2
Load frequency (Hz)

Result


Transient Measurement
Mean Power Load 24.6%
Mean Power Load 41%
Mean Power Load 57.2%
Quasi-steady Mapping
Mean Power Load 57.2%
Mean Power Load 41%
Mean Power Load 24.6%
$\overline{\delta \mathrm{BSFC}_{k/0}}$ (%)
8
6
4
2
0
-2
0
0.05
0.1
0.15
0.2
Load frequency (Hz)
$\overline{\delta \mathrm{CNOx}_{k/0}}$ (%)
10
5
0
-5
-10
-15
0
0.05
0.1
0.15
0.2
Load frequency (Hz)

Findings

- The effect of the cyclic transient load is found to be dependent on the average load level and becomes more visible as the load level is lowered.
- The quasi-steady mapping method provides an estimation of fuel consumption with a good accuracy, even without transient correction, for most cases.
- The effect of load smoothing for cyclic loads depends on the shape of the steady-state fuel consumption rate around the operating point.

Use of Machine Learning Tools for Model Identification and model reduction

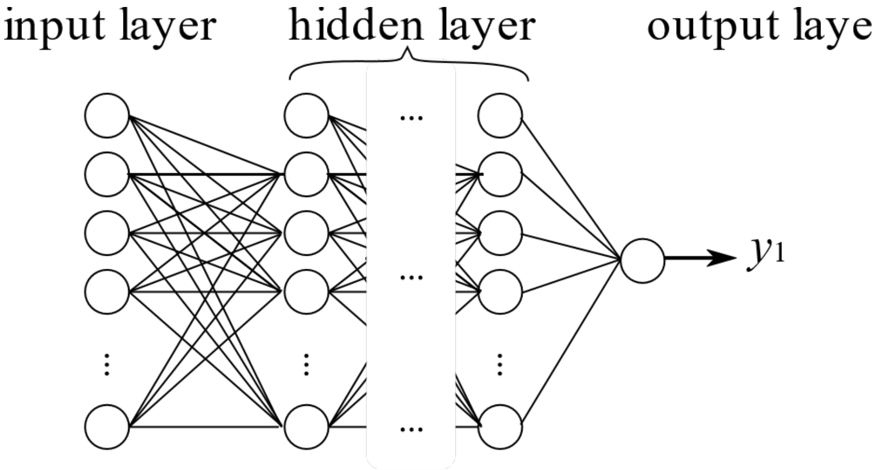
Motivation

- Model identification
  - Highly non-linear relation between the time-varying parameters and the operating conditions
  - Compact representation of the dataset

- Model reduction
  - Replacement of the high fidelity model with the data-driven empirical model

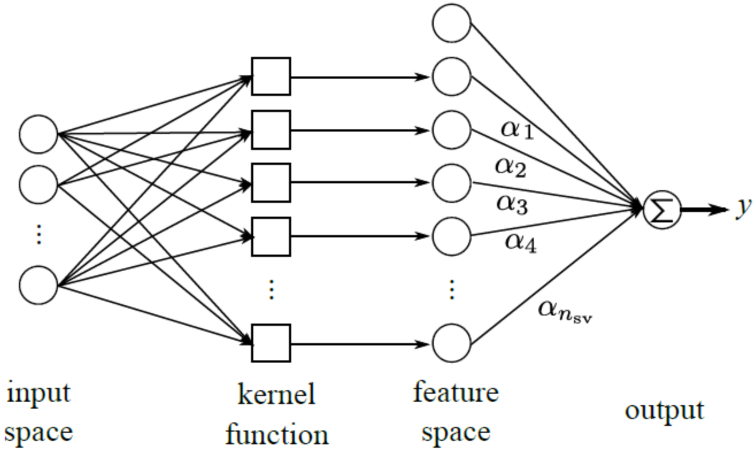
ANN and SVM

- ANN



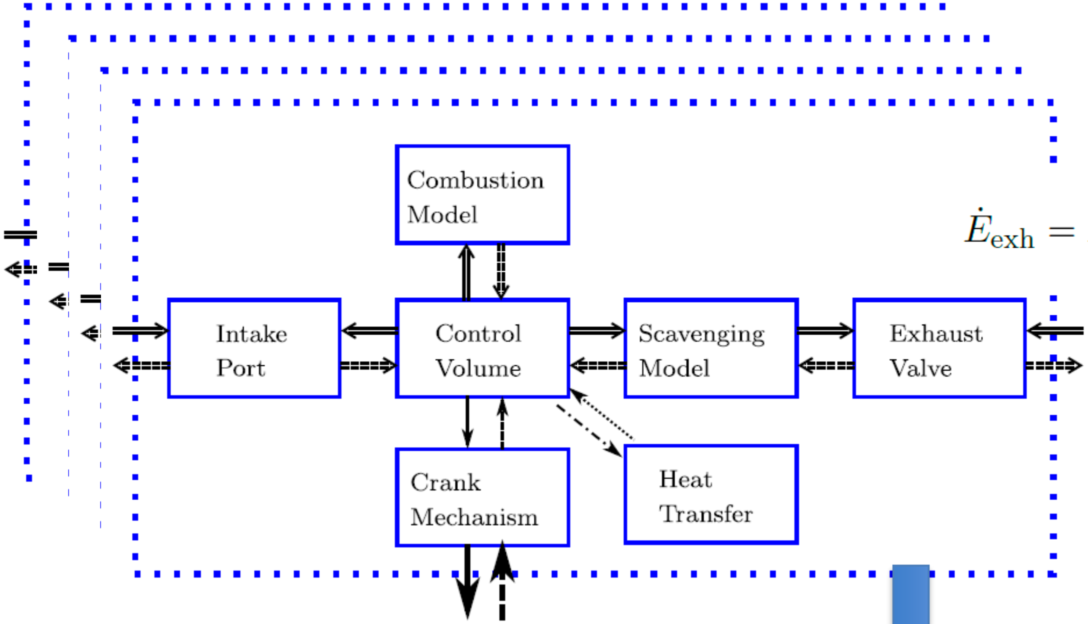
$$x_{k,j} = g\left(\sum_{i=1}^{n} w_i \cdot x_{i,j-1} + b\right)$$

- SVM



$$y = \sum_{i=1}^{n_{SV}} \alpha_i \phi\left(\mathbf{x}, \mathbf{x}'\right) - \rho$$

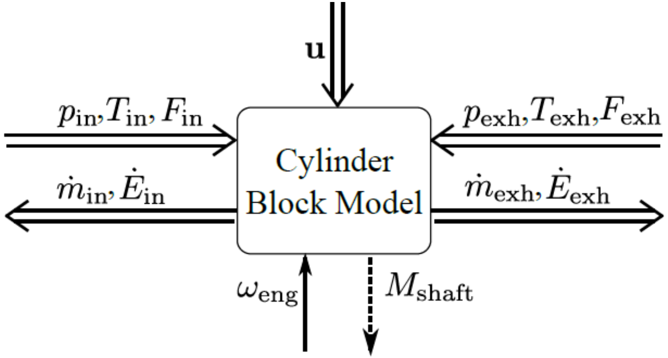
Surrogate modeling of the cylinder block



$$M(\mathrm{Nm}) = \frac{3.6\mathrm{e}6 \cdot m_{\mathrm{f,inj}}(\mathrm{g})}{2\pi n_{\mathrm{R}} \cdot \mathrm{bsfc}(\mathrm{g/kWh})}$$

$$\dot{E}_{\mathrm{exh}} = \dot{E}_{\mathrm{in}} + \frac{N \cdot m_{\mathrm{f,inj}}}{n_{\mathrm{R}}}\left(q_{\mathrm{LHV}} - \frac{1}{\mathrm{bsfc}}\right) + P_f - \dot{Q}_{\mathrm{HT}}$$

$$\dot{m}_a = \begin{cases} \frac{1}{2}\rho_{a,0} V_{\mathrm{d}} N \eta_v, & \text{four stroke} \\ \rho_{a,0} V_{\mathrm{d}} N \Lambda, & \text{two stroke} \end{cases}$$



Process

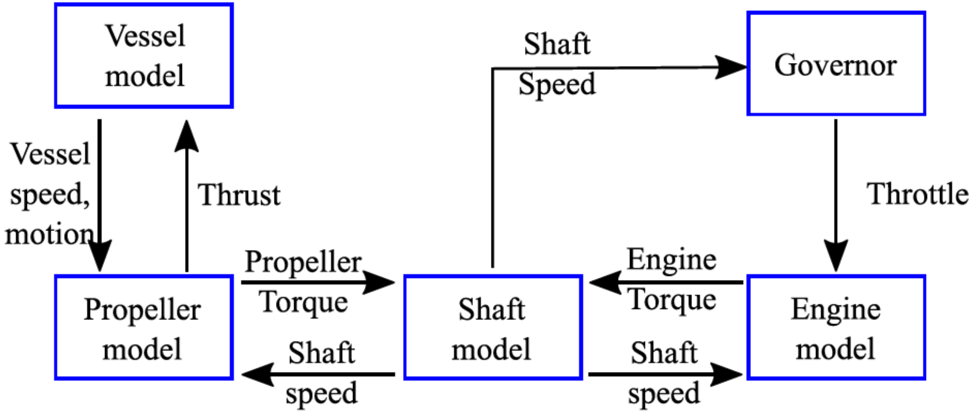
Generation of the training datasets from simulation

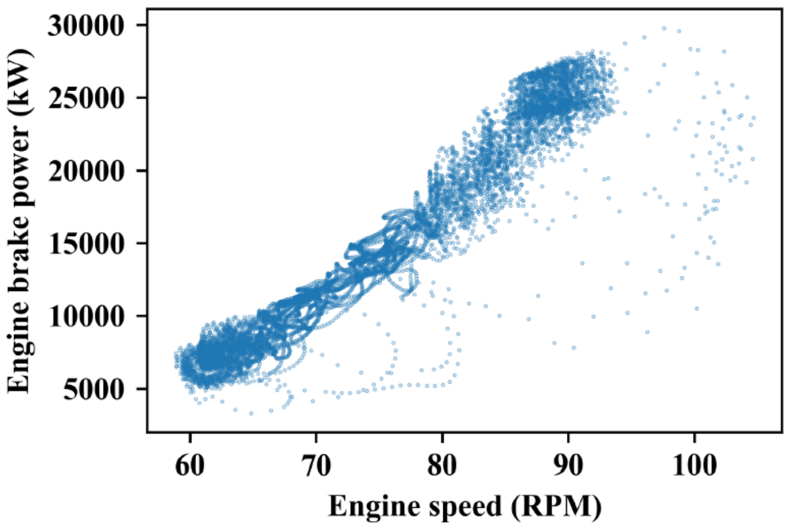
Training ANN and SVM models

Validation

Generation of the training datasets

- Propulsion in irregular waves





Input – Output Data Screening

Input

ω_{eng}	engine shaft speed
T_{scav}	scavenge air temperature
T_{exh}	exhaust gas receiver temperature
ω_{tc}	turbocharger speed
φ_{SOI}	start of injection
u_{EVC}	exhaust valve closing command
p_{scav}	scavenge air pressure
p_{exh}	exhaust gas receiver pressure
F_{exh}	exhaust gas fuel-air equivalence ratio
u_{gov}	fuel command from the governor
u_{EVO}	exhaust valve opening command

Output

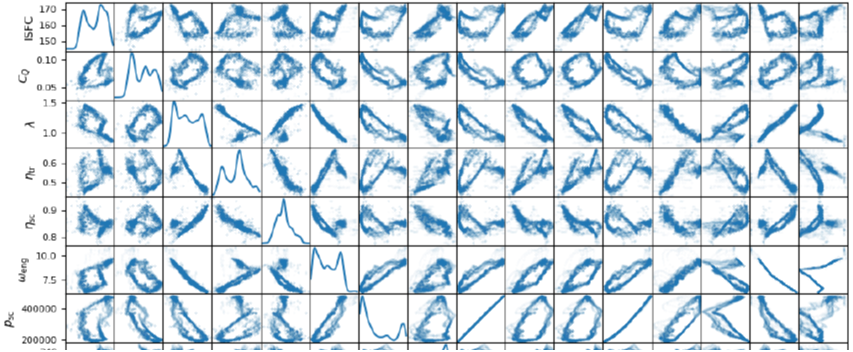
ISFC	Indicated specific fuel consumption
C_Q	Heat loss factor
Λ	Delivery ratio

$$\mathrm{ISFC[g/kWh]} = \frac{m_{\mathrm{f,cyc}}}{\int_{t_{\mathrm{BDC,n}}}^{t_{\mathrm{BDC,n+1}}} P_{\mathrm{cyl}} dt} \cdot 3.6e9$$

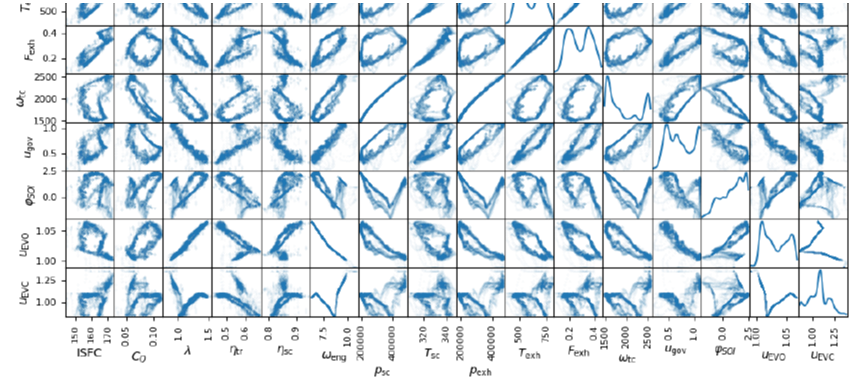
$$\Lambda = \frac{\int_{t_{\mathrm{IPO}}}^{t_{\mathrm{IPC}}} \dot{m}_{\mathrm{in}} dt}{\rho_{\mathrm{scav}} \cdot V_d}$$

$$C_Q = \frac{\int_{t_{\mathrm{BDC,n}}}^{t_{\mathrm{BDC,n+1}}} \dot{Q} dt}{m_{\mathrm{f,cyc}} \cdot q_{\mathrm{LHV}}}$$

Input – Output Data Screening



$$[\mathrm{ISFC}, C_Q, \Lambda]^T = \Phi\left(\omega_{\mathrm{eng}}, p_{\mathrm{scav}}, T_{\mathrm{exh}}, u_{\mathrm{gov}}, \varphi_{\mathrm{SOI}}, u_{\mathrm{EVC}}\right)$$



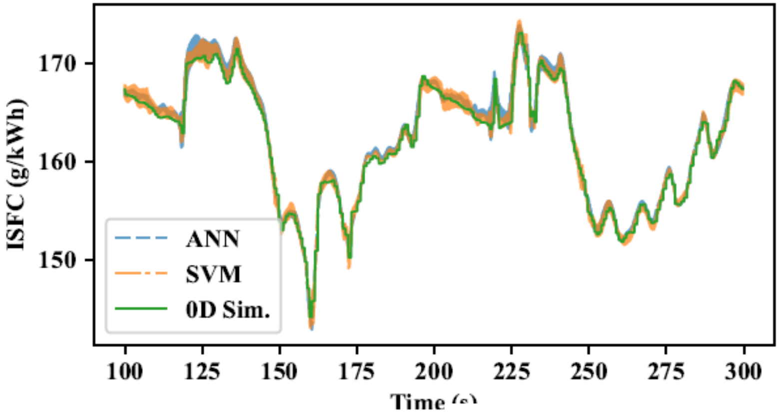
Training results

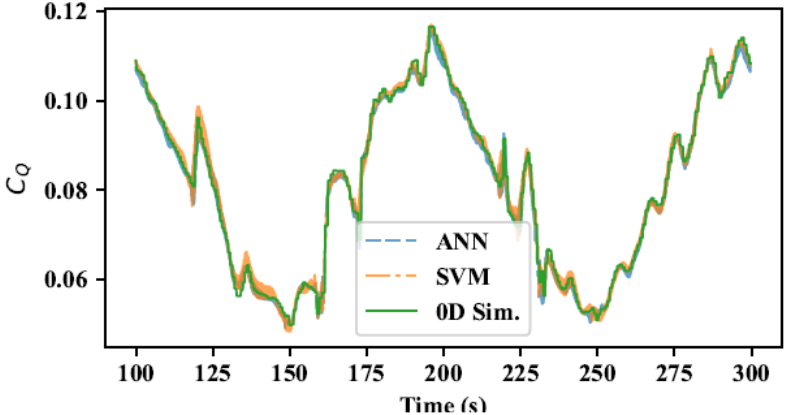
- Cross validation results (25%)

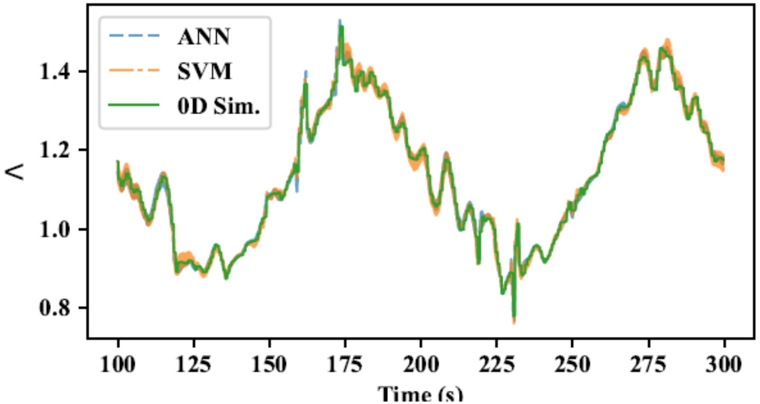
		ISFC (g/kWh)	C_Q	Λ	η_{tr}	η_{sc}
ANN	MAPE	0.26	1.14	0.61	0.66	0.25
	SAPE	0.23	1.22	0.74	0.84	0.33
SVM	MAPE	0.16	1.97	0.58	0.44	0.27
	SAPE	0.20	2.70	1.38	0.74	0.67

Verification

- Simulation in the open-loop

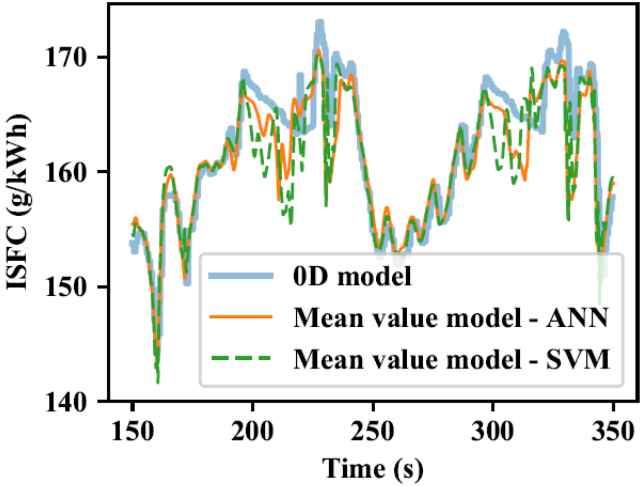


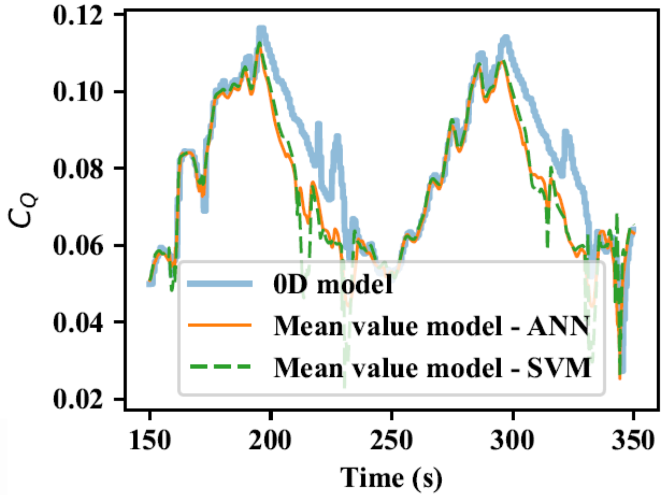


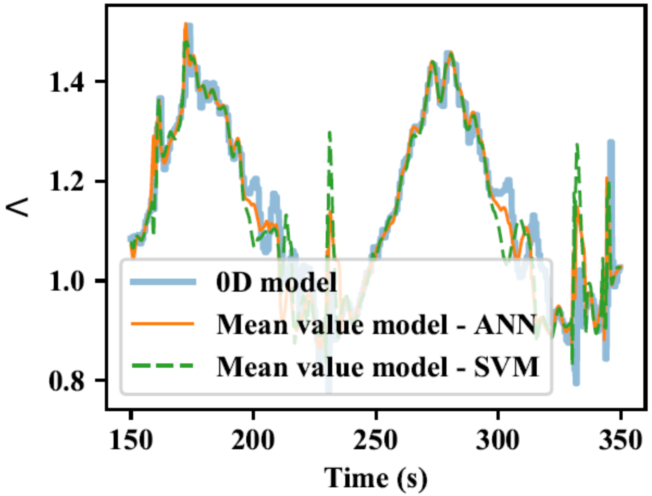


Verification

- Simulation in the closed-loop





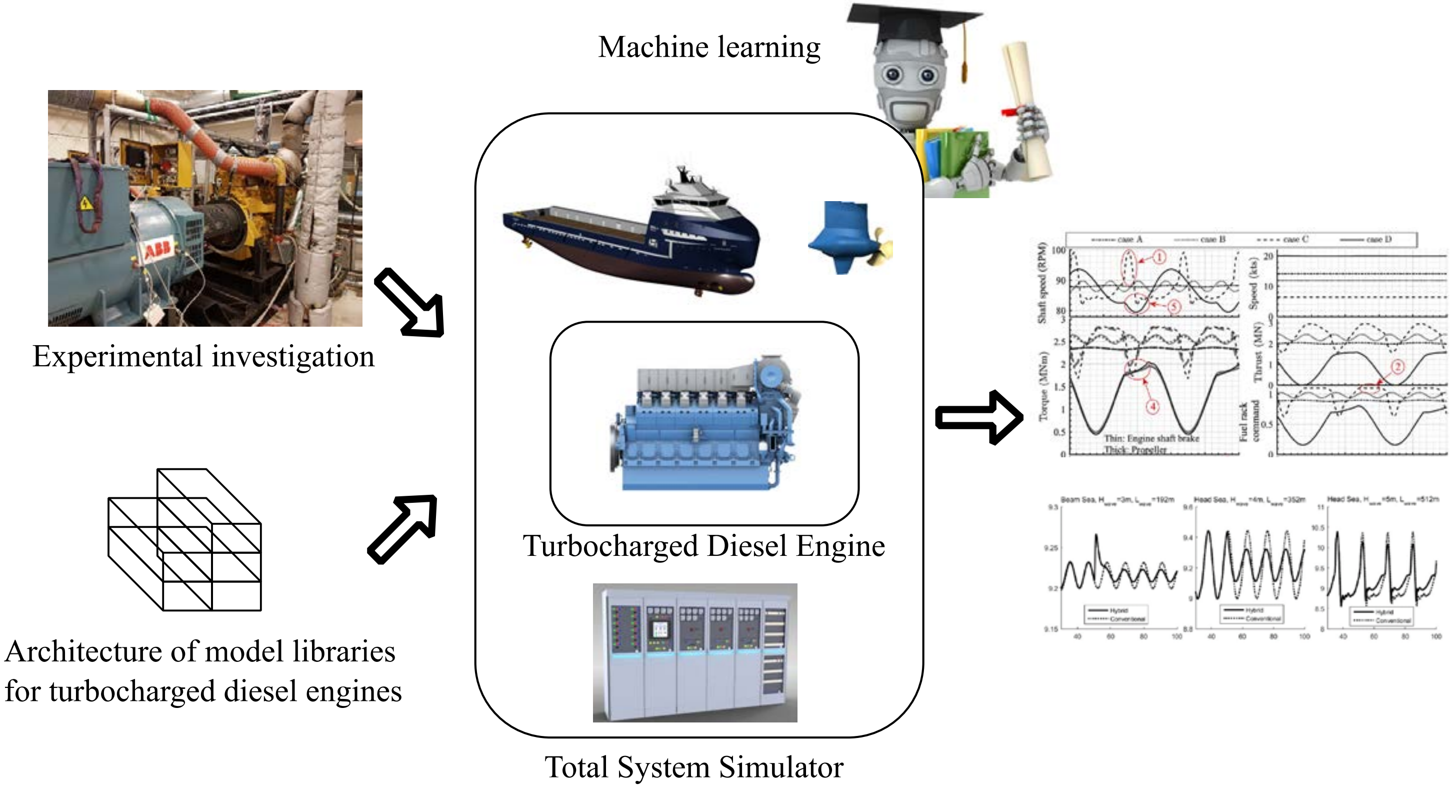


Findings

- ANN and SVM models showed good performance for prediction of the key parameters for mean value cylinder process model
- Generating training data by the total system simulator should have both high variance and correlation to the physical laws. Then, it becomes an effective method to avoid the curse of dimensionality
- Model reduction comes with unavoidable loss of fidelity. The effect of such loss should be evalueated on the system level.

Conclusion

- Main contribution of the thesis



Conclusion

- Further works
  - Development of transient NOx model for real-time simulation and validation
  - Development of gas engine model
  - Validation of the total system simulator by a full-scale test
  - Experimental investigation of transient effect under cyclic load for different type of engines

Thank you for your attention!