Mathematical Optimization Approach in Economic and Optimal Scheduling of Energy Management System in a Hybrid Ferry

DAMEN

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POLITECNICO MILANO

IPESE
INDUSTRIAL PROCESS AND ENERGY SYSTEMS ENGINEERING

MOSES Workshop - October 2017

Review

Introduction

Strategy

Navid Mohammadzadeh
Francesco Baldi

Case Study

Results

Master Thesis

Simulation and Control of Hybrid Ferry
Defined By Damen Shipyard
Gorinchem, Netherland

1

7

2

6

3

5

4

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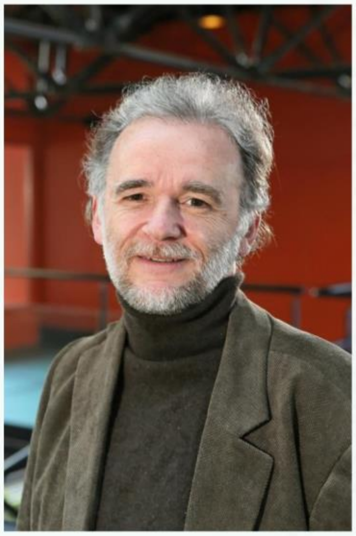

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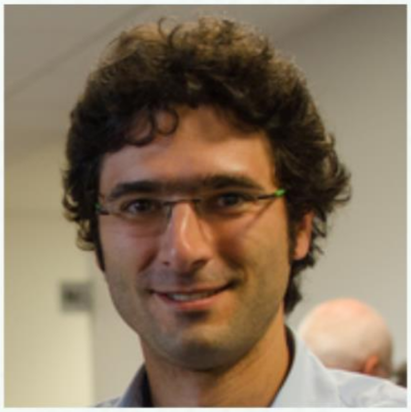

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INTERNATIONAL
MARITIME
ORGANIZATION

Why Hybridization?

Problem?

EMS/PMS

Solution

Power Plant Configuration

Gannt Chart

Problem?

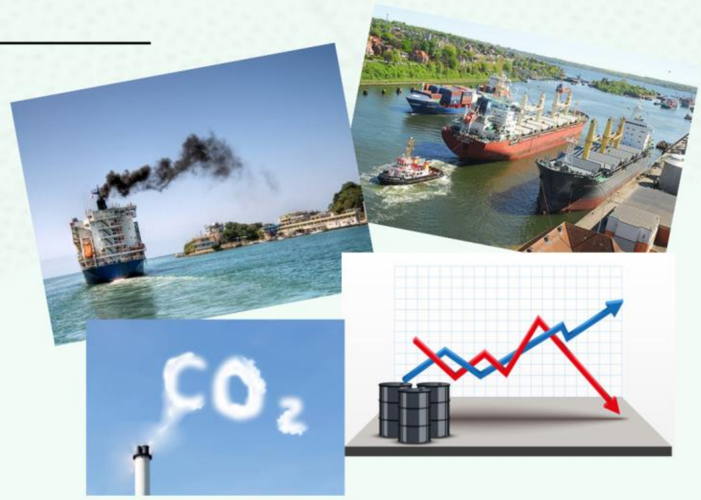
- Important Share in the World Trade Transportation

- Fluctuation of the Fuel Price

- Tough Environmental Regulations by International Maritime Organization

- Significant contribution to global greenhouse gas emission

**CO2 Emission increases between 50%-250% by 2050. [IMO]



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Problem?

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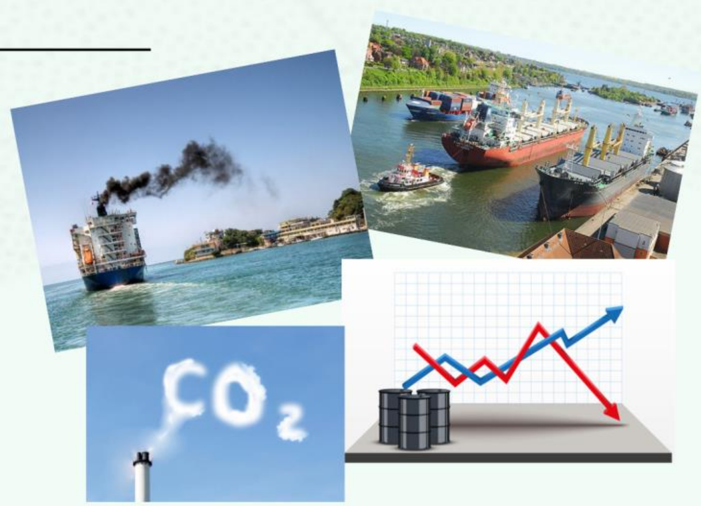

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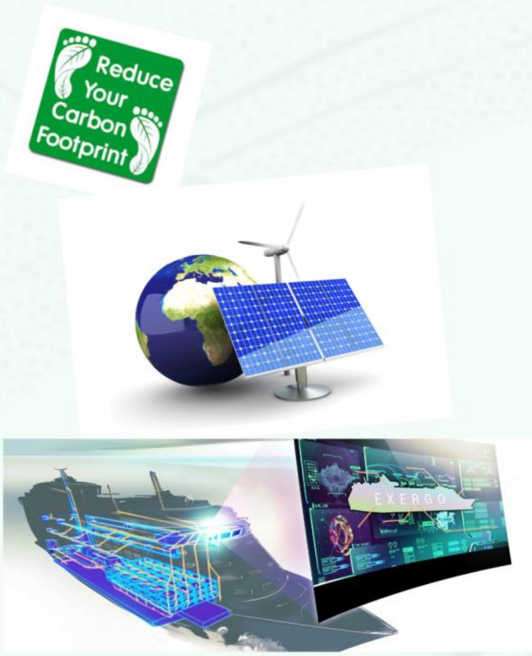

Solution

- Advanced, Intelligent and Eco-friendlier Technologies

- Hybridization

- REDUCE the Fossil Fuel Dependency (Alternative Fuels)

- OPTIMAL Energy Management System**

BUT… How?

I have a proposal …

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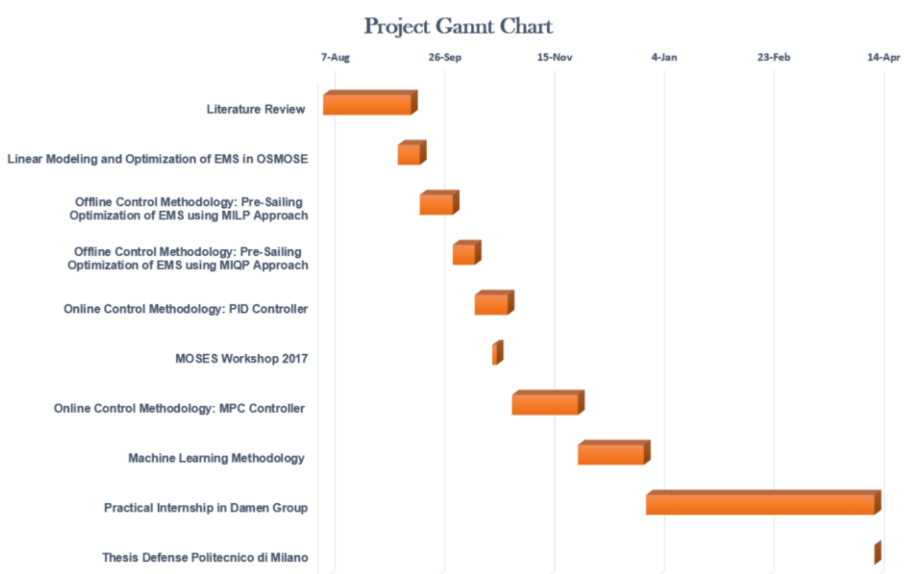
What I propose …



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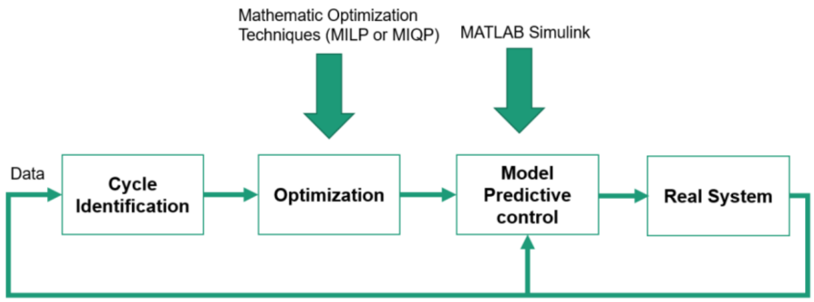
Simpler?



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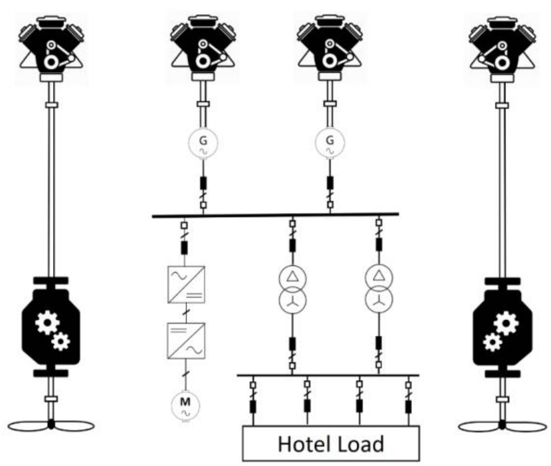
Power Plant Configurations: Mechanical Propulsion System



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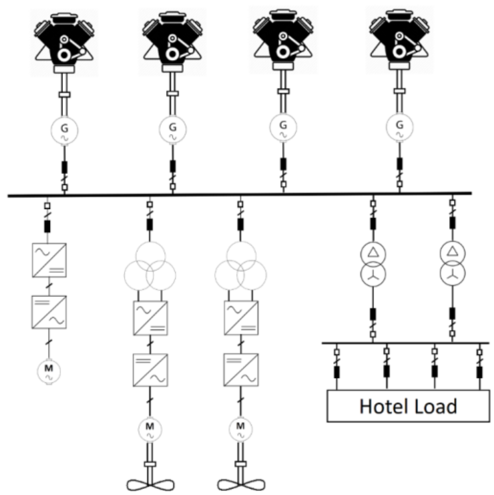
Power Plant Configurations: Electrical Propulsion System



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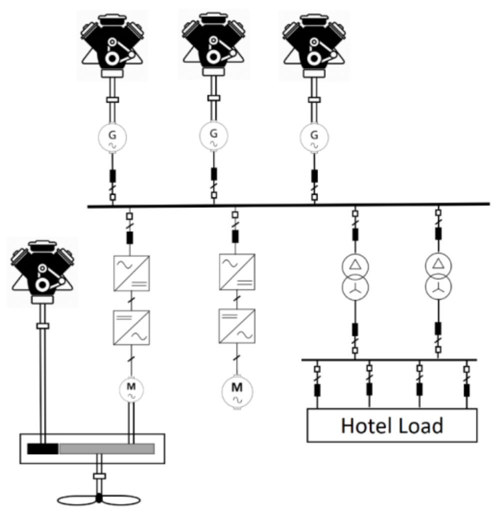
Power Plant Configurations: Hybrid Propulsion System



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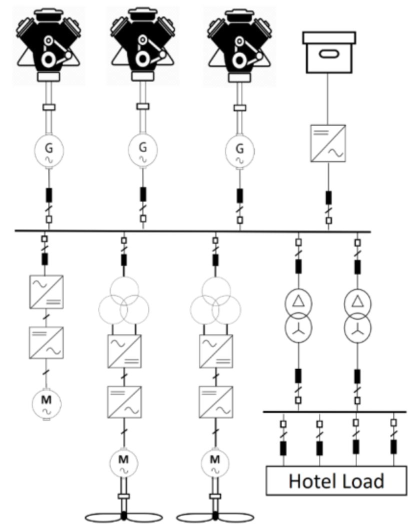
Power Plant Configurations: Hybrid Power Supply



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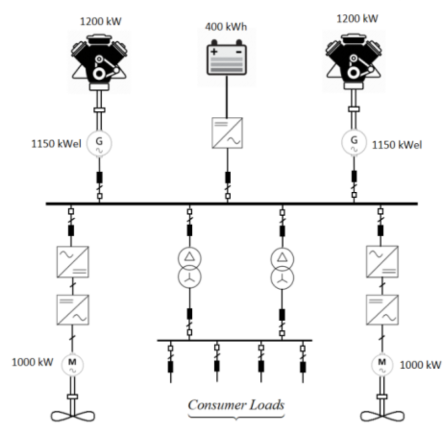
Case Study Configuration



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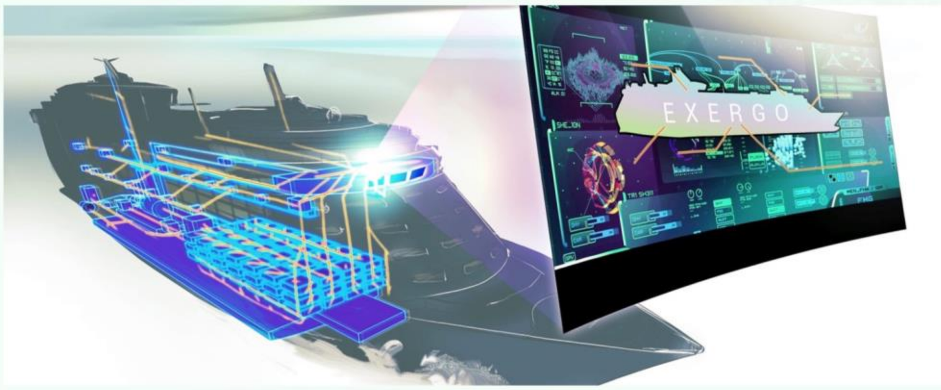
EMS: Energy Management System
PMS: Power Management System



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What is their Job?!

Both control the ship's power plant and scheduled load sharing among the power sources to meet the propeller and hotel load demand.

So What is the difference?

PMS works at instantaneous time with stabilizing voltage and frequency

BUT...

EMS considers past, present along with future events.

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What can we IMPROVE by EMS?

Crews can schedule the gensets

Difficult task with a poor decision

Includes a Big ERROR

Does not support
Reduction of Fuel Consumption

Neither Environmental Footprints

Let's focus on EMS...

- EMS as a part of PMS is an **Advanced Decision Support Tool** and a **Scheduling Algorithms** which addresses the **"optimal operational scheduling"** when Energy Storage System wants to synchronize with the other power sources.

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Let's focus on EMS...

Conclusion: We have a powerful decision maker to have an optimal load sharing among the power sources leading to reduction of fuel consumption and emission.

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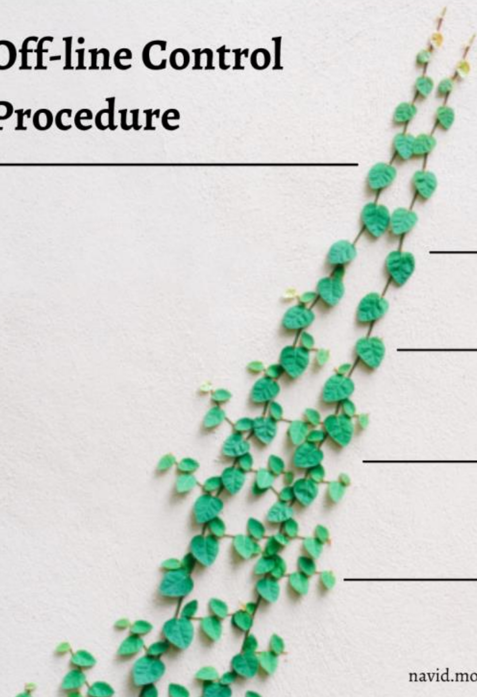
Off-line Control

- Assumption
- Procedure
- Constraints
- Linear vs Quadratic Diesel Enigne Models
- Decision Variables
- Objective Function

Off-line Control Procedure



Analysis the Results

OPTIMIZATION ALGORITHMS (MILP and MIQP)

Defining Objective Function, Decision variables and Weights

Modelling Based on Experimental Data

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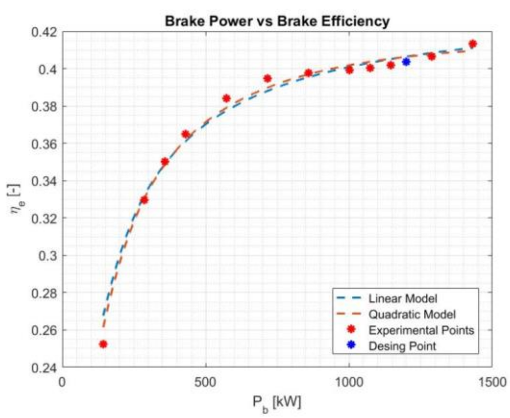
Linear vs Quadratic Diesel Enigne Models



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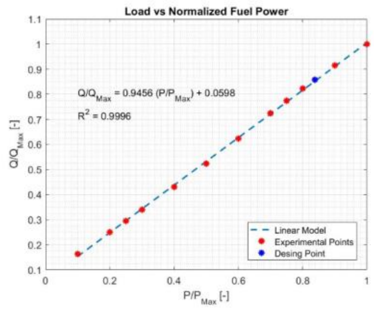
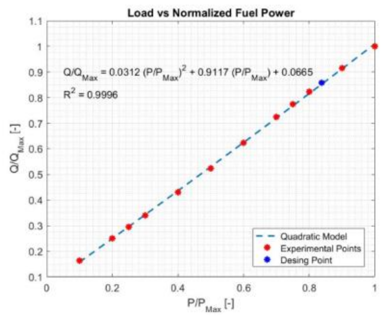
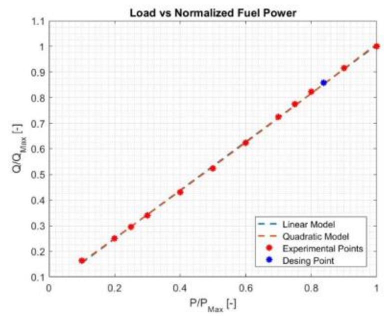
Linear vs Quadratic Diesel Enigne Models



Linear Diesel Engine Model



Quadratic Diesel Engine Model



Comparision of the Two Models

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Objective Function for MILP Optimization

(Linear Model in the Objective Function)

$$\min_{y_i} J(k) = \sum_{i}^{N} \underbrace{\left(a_1 x_i^{(k)} + a_0 y_i^{(k)}\right)}_{\text{Fuel Consumption}} + w_t \cdot \sum_{i}^{N} \underbrace{\left(y_i^{(k)} \cdot \Delta t\right)}_{\text{Operational Time}} + w_s \sum_{i}^{N} \underbrace{\left(\delta_i^{(k)}\right)}_{\text{Starts/Stops}}$$

$$\min_{y_i} J(k) = \sum_{i}^{N} \left(a_1 x_i^{(k)} + (a_0 + w_t \cdot \Delta t) y_i^{(k)}\right) + w_s \sum_{i}^{N} \left(\delta_i^{(k)}\right)$$

k : Time Step Index
i : Engine Index
Wt: Engine Operational Time Weight
Ws: Engine Starts/Stops Weight.

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Objective Function for MIQP Optimization

(Second order polynominal in the objective funtion)

$$\min_{y_i} J(k) = \underbrace{\sum_{i}^{N}\left(a_2\left(x_i^{(k)}\right)^2 + a_1 x_i^{(k)} + a_0 y_i^{(k)}\right)}_{\text{Fuel Consumption}} + w_t \cdot \sum_{i}^{N}\underbrace{\left(y_i^{(k)}\cdot\Delta t\right)}_{\text{Operational Time}} + w_s \sum_{i}^{N}\underbrace{\left(\delta_i^{(k)}\right)}_{\text{Starts/Stops}}$$

$$\min_{y_i} J(k) = \sum_{i}^{N}\left(a_2\left(x_i^{(k)}\right)^2 + a_1 x_i^{(k)} + (a_0 + w_t \cdot \Delta t) y_i^{(k)}\right) + w_s \sum_{i}^{N}\left(\delta_i^{(k)}\right)$$

k : Time Step Index
i : Engine Index
Wt: Engine Operational Time Weight
Ws: Engine Starts/Stops Weight.

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Decision variables

14 Decision varibales .* # Time Steps

$f =$	
y_1	On/Off Switching DE1
y_2	On/Off Switching DE2
u_C	Battery Charing Switching
u_D	Battery Discharging Switching
δ_1^{STA}	Number of Starts up for DE1
δ_2^{STA}	Number of Starts for DE2
δ_1^{STP}	Number of Stops for DE1
δ_2^{STP}	Number of Stops for DE2
x_1	Load DE1
x_2	Load DE2
P_{Ch}	Battery Charging Power
P_{DC}	Battery Discharging Power
E_{ESS}^{0}	Initial Battery State of Charge
E_{ESS}	Battery State of Charge

It Is NoT an EaSy PrOblEm!!

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Constraints: Inequality constraints: (Limitation and safety for the System)

1) Engine Load Limitation: $x_{\min} \cdot y_i(k) \le x_i(k) \le x_{Max} \cdot y_i(k)$

2) Generator Load Limitation : $x_i(k) \cdot \eta_{gen} \le x_{Max.Gen} \cdot y_i(k)$

3) Battery Dicharge Power Limitation : $0 \le P_{Ess}^{Dis}(k) \le P_{Max.Ess} \cdot u_D(k)$

4) Battery Charge Power Limitation : $P_{Min.Ess} \cdot u_C(k) \le P_{Ess}^{Ch}(k) \le 0$

5) Battery Charging /Discharging: $u_D(k) + u_C(k) \le 1$

6) Engine Strat/Stop Condition: $\delta_i^{START}(k) + \delta_i^{STOP}(k) \le 1$

7) Engine Load Variation Limitation: $\dfrac{x_i(k+1) - x_i(k)}{t(k+1) - t(k)} \le \dot{x}$

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Constraints: Equality constraints: Talks about the balance equations

1) Power Balance: $\sum_{i=1}^{n} P_{\max} \cdot x_i(k) \cdot \eta_{gen} + \dfrac{P_{Ess}^{Ch}(k)}{\eta_{ch}} + P_{Ess}^{Dis}(k) \cdot \eta_{Dis} = \dfrac{P_{\text{Propellers}}}{\eta_{inv} \cdot \eta_{EM}} + P_{\text{Hotel}}$

2) Battery Energy Balance: $E_{Ess}(k-1) - E_{Ess}(k) = \left(P_{Ess}^{Ch}(k) + P_{Ess}^{Dis}(k)\right) \cdot \Delta t$

3) Initial and Final Battery Energy: $E_{Ess}(t=0) = E_{Ess}(t = t_f)$

4) Starts/Stop: $y_i(k) - y_i(k-1) = \delta_i^{START}(k) - \delta_i^{STOP}(k)$

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Assumptions

Assumption		Description
$P_d = 1200$	$[kW]$	Design Power
$P_{Max.Generator} = 1150$	$[kWel]$	Maximum Generator Power
$P_{Max.ElectricMotor} = 1000$	$[kW]$	Maximum Electric Motor Power
$E_{ESS.Max} = 400$	$[kWh]$	Battery Capacity
$P_{ESS.Max} = 400$	$[kW]$	Maximum Discharge Power of the Battery
$P_{ESS.Min} = -400$	$[kW]$	Maximum Charge Power of the Battery
$\dot{x}_{DE} = 0.416$	$[1/\text{sec}]$	Maximum Diesel Generator load rate
$SOC_{Max} = 1$		Maximum State of Charge of the Battery
$SOC_{\min} = 0.3$		Minimum State of Charge of the Battery
$\eta_{Generator} = 0.99$		Generator Efficiency
$\eta_{ElectricMotor} = 0.96$		Electric Motor Efficiency
$\eta_{Charging} = 0.85$		Charging Efficiency
$\eta_{Dischargin} = 0.98$		Discharging Efficiency
$\eta_{inverter} = 0.92$		Inverter Efficiency (DC-AC)
$\eta_{Rectifier} = 0.96$		Rectifier Efficiency (AC-DC)

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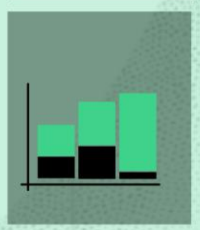
Case Study

Compare the two state of arts:

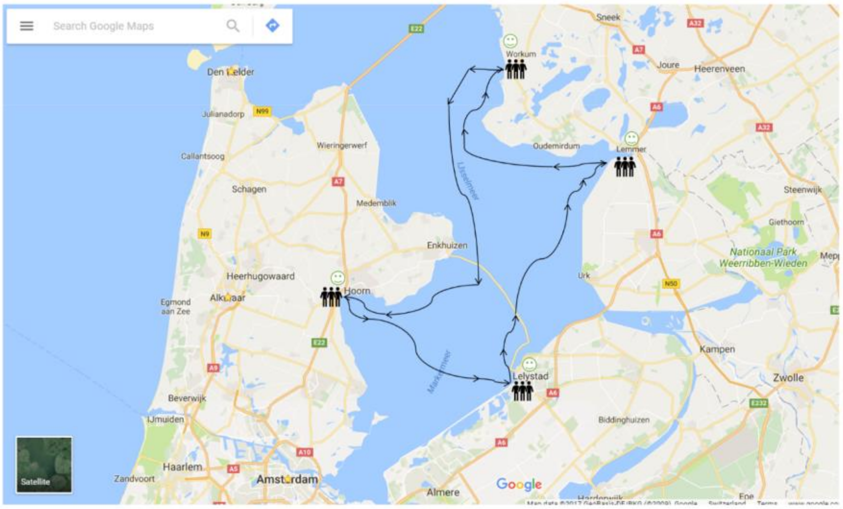
Hybrid Ferry

Electric Ferry



Operational Profile

Considered Operational Profile (17 TimeSteps)



It is not a real Operational Profile.

14 * 17 = 238 DECISION VARIABLES

Do not worry! We are Engineers and we have COMPUTERS! :)

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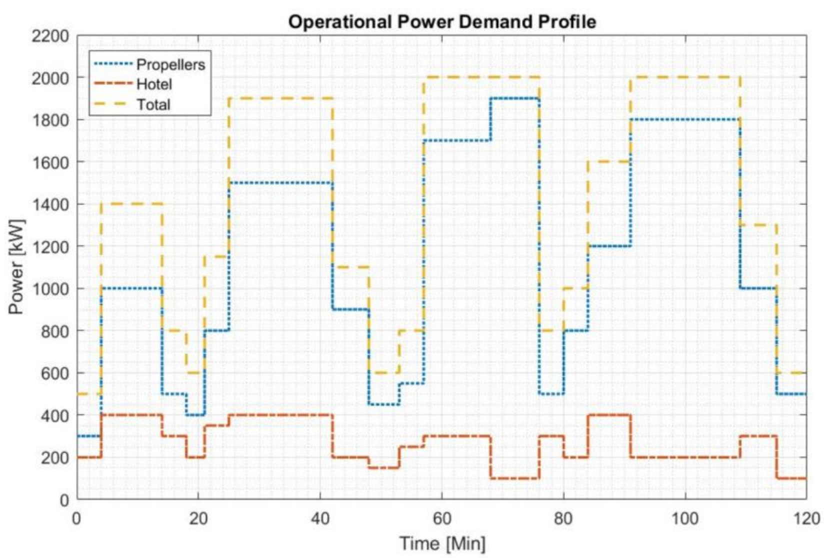
Operational Power Demand



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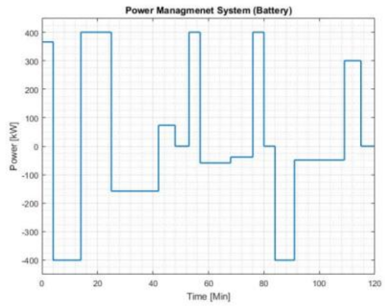
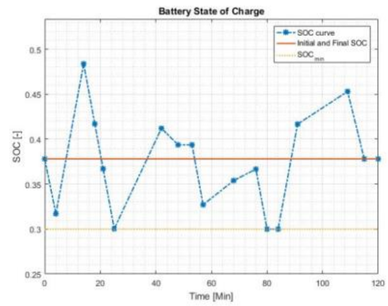
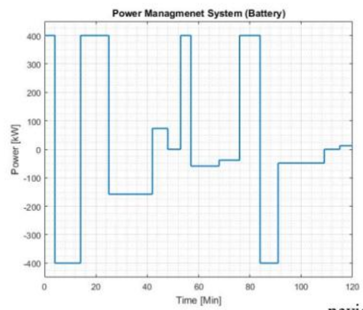
MILP vs MIQP: Results come from EMS with Wt = 0.01 and Ws = 0.12

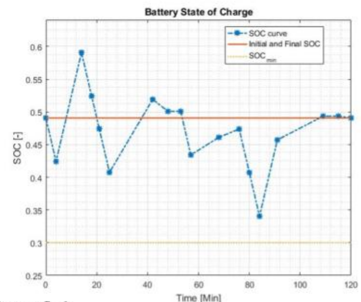
MILP





MIQP





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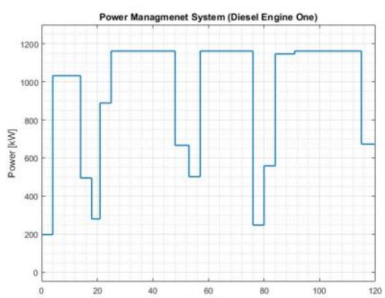
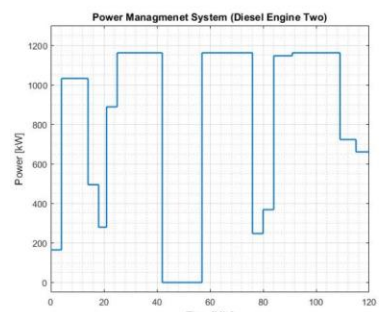
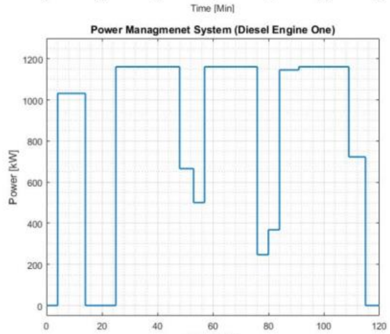
MILP vs MILQP results come from EMS with Wt = 0.01 and Ws = 0.12

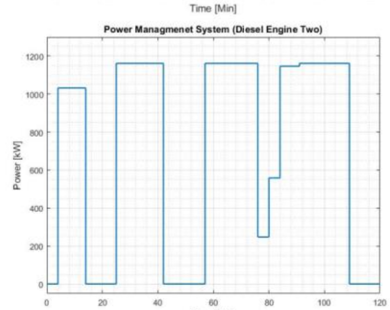
MILP





MIQP





Fuel Consumption and Calculation time for Ws= 0.12 and Wt = 0.01 with MILP and MIQP Optimization

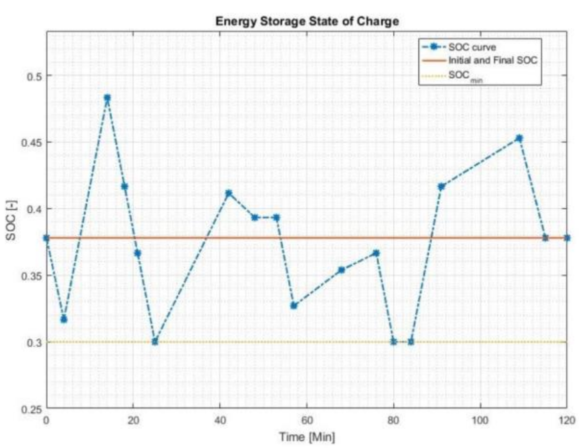
MIQP: 39.81 kTons/Year
Calculation Time = 141.45 sec.

MILP: 39.94 kTons/Year
Calculation Time = 0.1138 sec.

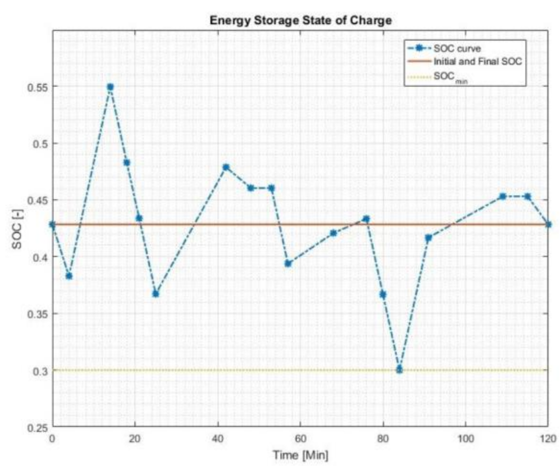
Effect of Starts/Stops on State of Charge of the Battery:

Offline Control --> MILP Optimization

Ws = 0



Ws = 0.15



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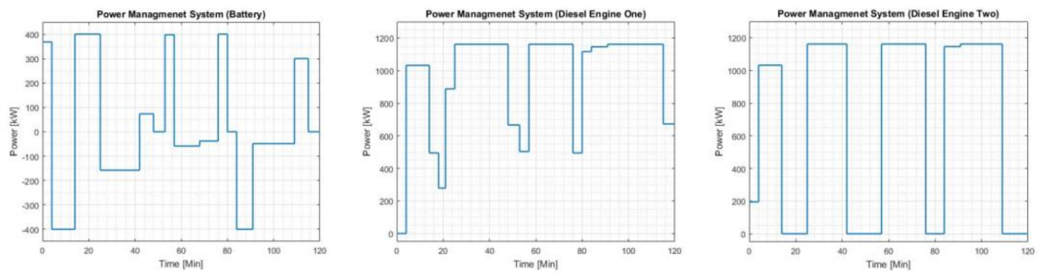
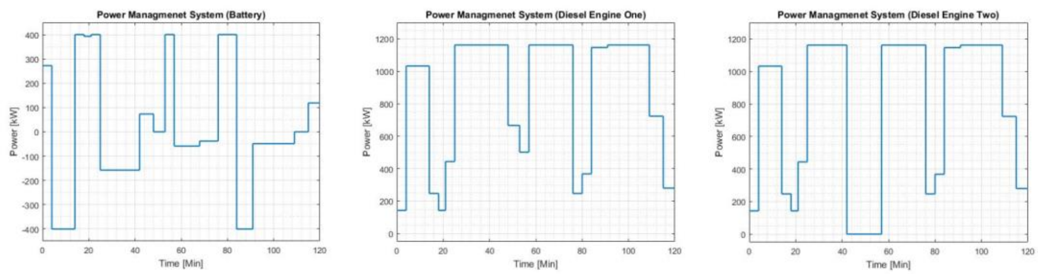
Effect of Starts/Stops on PMS

Ws = 0



Ws = 0.15



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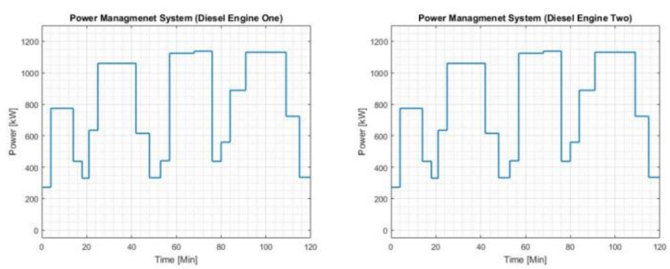
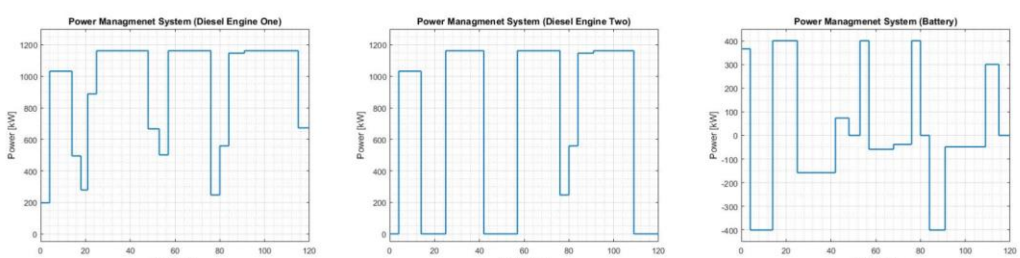
Diesel Engine Load in Electric Vs Hybrid Ferry: Ws = 0.12

Electric Ferry



Hybrid Ferry



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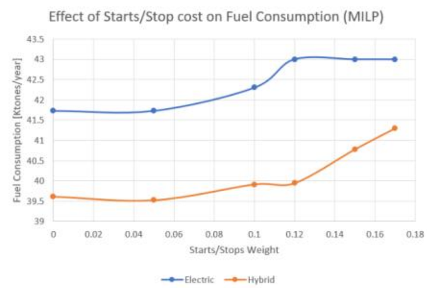
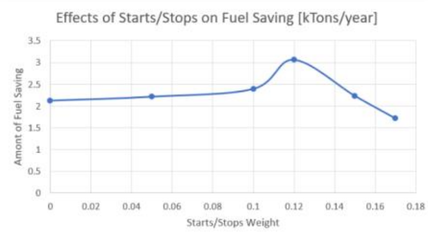
Effect of Starts/Stops on Fuel Constumption

Ws	Fuel Consumption [kTons/year]	Total Number of Starts/Stops	Objective Function Value
Electric Ferry (Wt = 0.01)(MILP)			
0	**41.73**	8	18.2
0.05	41.73	8	18.76
0.1	42.3	4	19.24
0.12	43	0	19.26
0.15	43	0	19.26
0.17	**43**	0	19.26
Hybrid Ferry (Wt=0.01)(MILP)			
0	**39.61**	10	16.79
0.05	39.52	8	17.46
0.1	39.91	6	18.08
0.12	39.94	6	18.18
0.15	40.77	2	18.34
0.17	**41.29**	0	18.39
Differents Between Electric and Hybrid			
0	2.12	-2	
0.05	2.21	0	
0.1	2.39	-2	
0.12	**3.06**	-6	
0.15	2.23	-2	
0.17	1.71	0	
Average	**2.29**		





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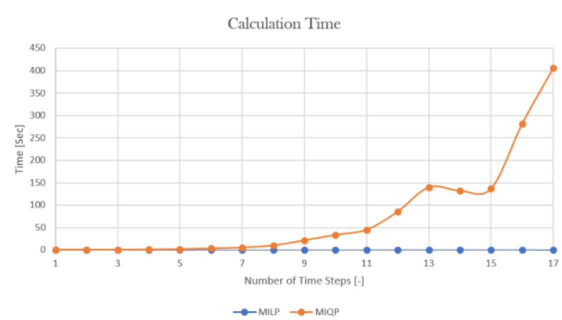
MILP vs MIQP

Ws = 0.12 and Wt = 0.01						
Time steps	Calculation Time			Fuel Consumption		
	MILP	MIQP	MIQP - MILP	MILP	MIQP	MIQP - MILP
1	0.024	0.608	0.583	1.06	1.06	0
2	0.035	0.571	0.536	3.97	3.97	0
3	0.050	0.529	0.479	5.54	5.06	-0.47
4	0.020	0.980	0.960	6.03	6.04	0
5	0.023	1.631	1.608	8.29	8.30	0.01
6	0.024	3.313	3.289	11.88	11.88	0
7	0.021	5.450	5.429	13.85	13.85	0
8	0.025	9.949	9.925	15.09	15.09	0
9	0.029	21.344	21.315	16.70	16.71	0
10	0.032	33.396	33.364	20.89	20.88	-0.01
11	0.035	45.130	45.094	25.01	25.01	0
12	0.037	85.453	85.417	26.83	26.81	-0.03
13	0.039	139.722	139.683	28.43	28.42	-0.01
14	0.040	131.770	131.730	32.13	32.11	-0.02
15	0.041	136.996	136.954	36.06	36.06	0
16	0.045	281.688	281.643	38.76	38.76	0
17	0.076	405.998	405.921	39.94	39.82	-0.12



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Now Lets Move to Online Real Time Control

PID Online controller of my project is not finished ...

BUT

Up to now, It shows me the robustness but I will investigate the optimality.
I expect with the controller we have low fuel consumption close to the reference fuel consumption calculated by the Energy Managment System.

If your have suggestion, do not hesitate tellling me to improve my master project. :)

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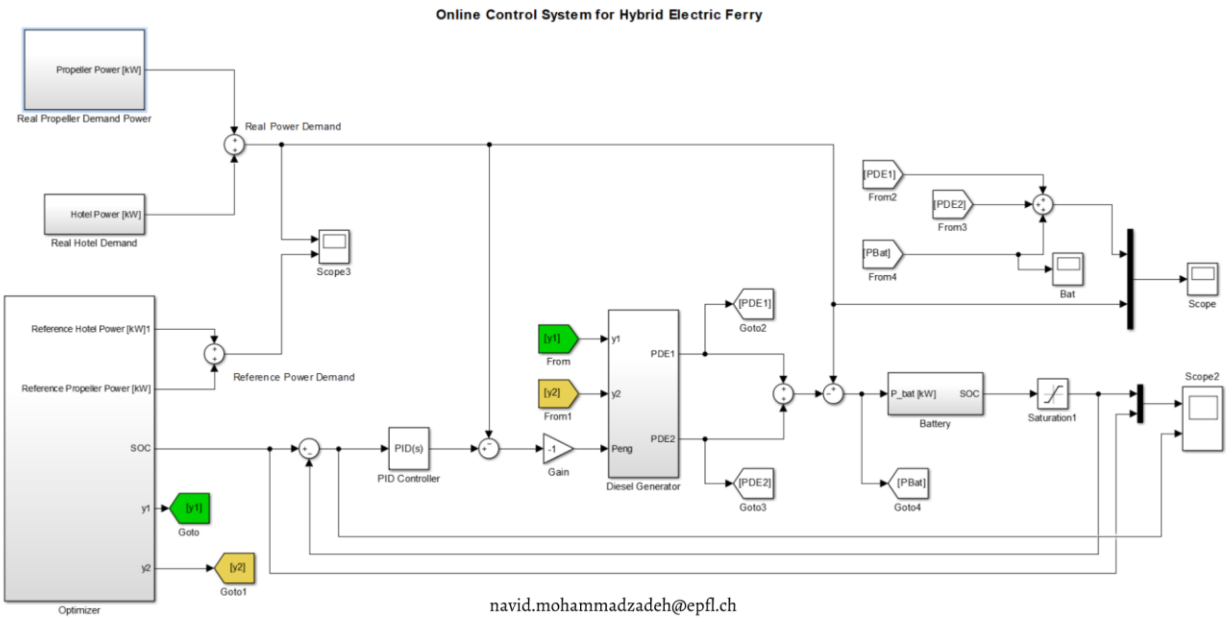
Online Control Methodology: (Proportional-Integral-Derivative Control)



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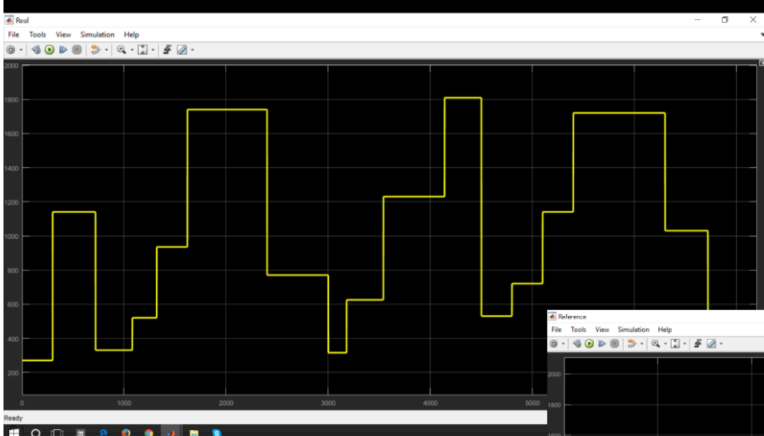

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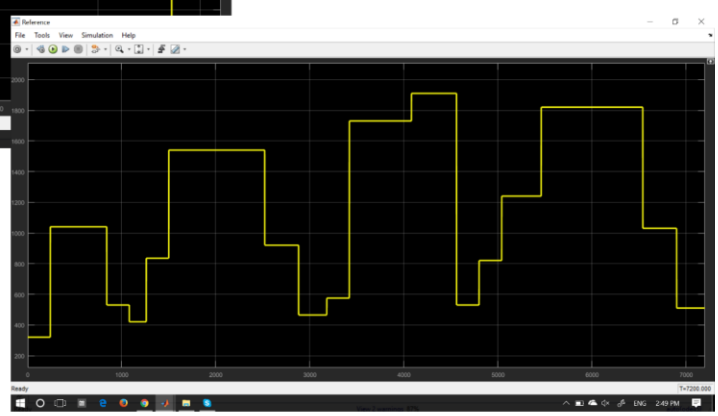


SOC
File Tools View Simulation Help
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0.4
0.3
0.2
0.1
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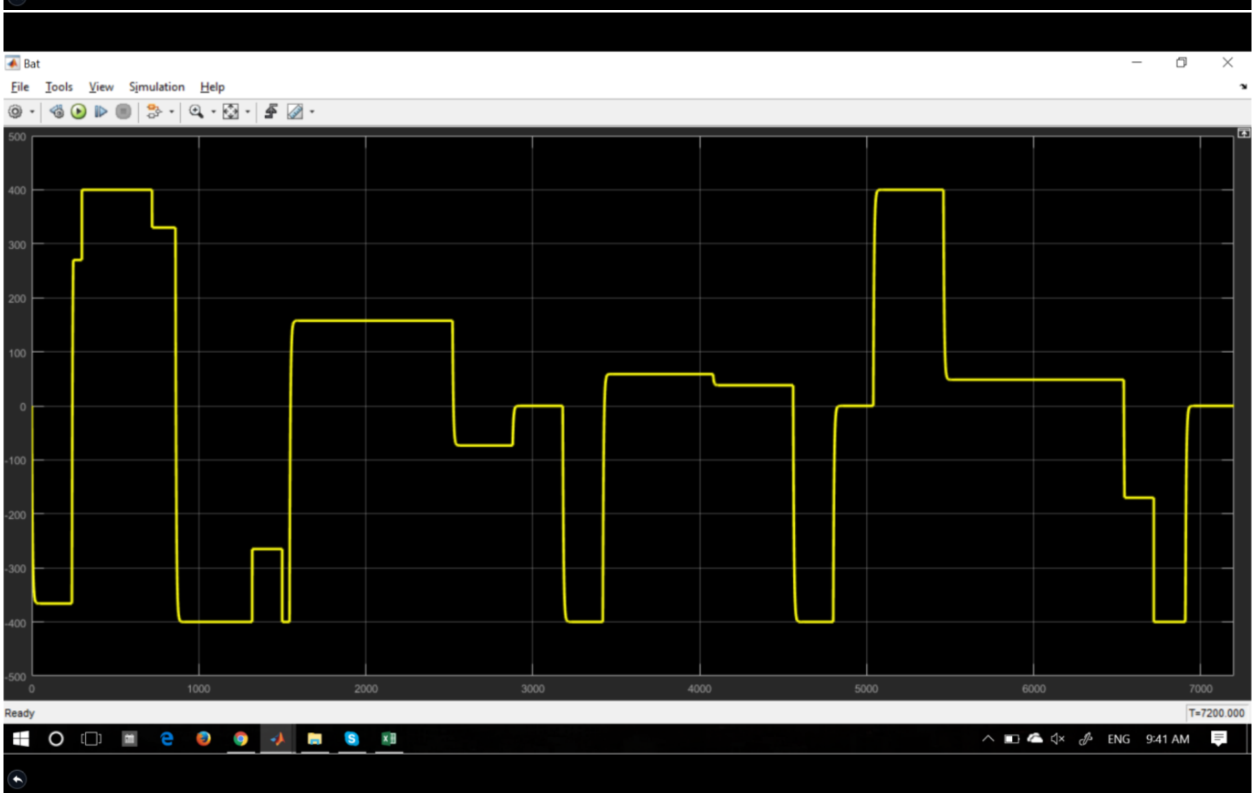
Frozen
T=7200.000
ENG 9:34 AM


Bat
File Tools View Simulation Help
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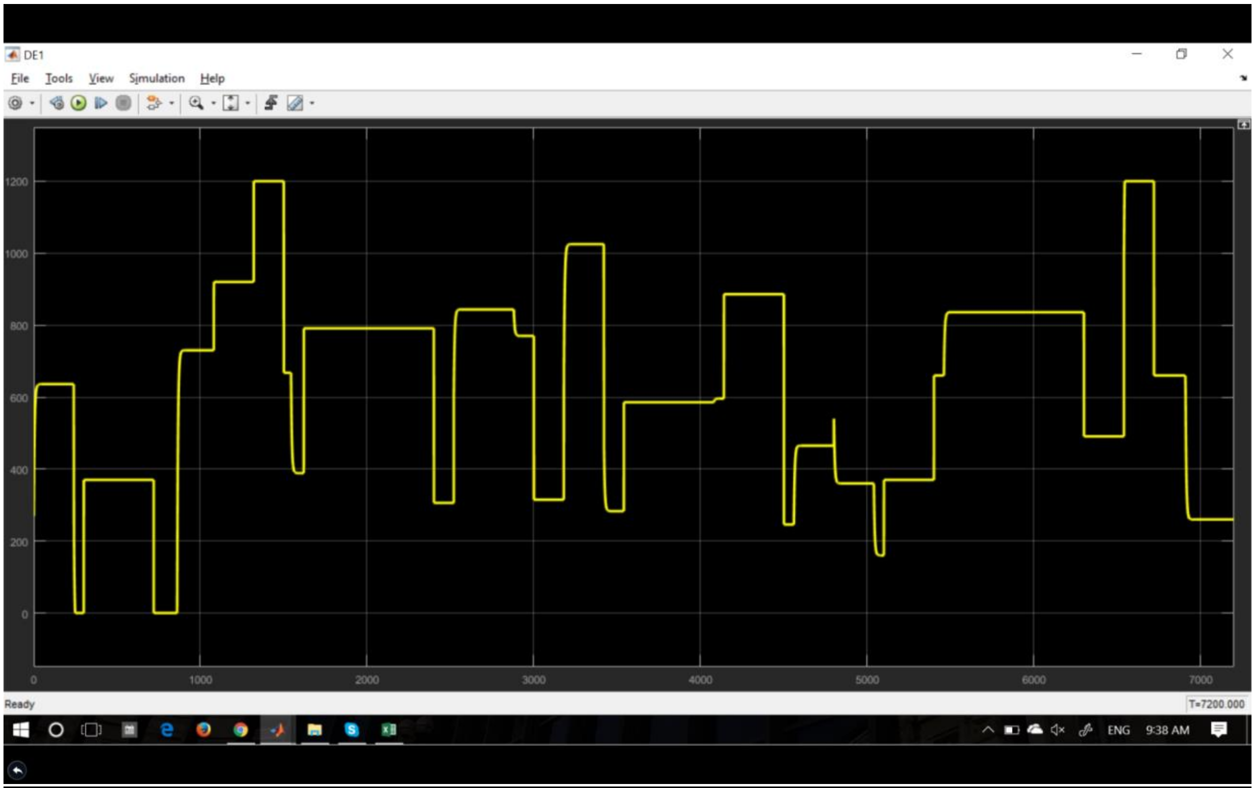
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5000
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Ready
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ENG 9:38 AM


DE2
File Tools View Simulation Help
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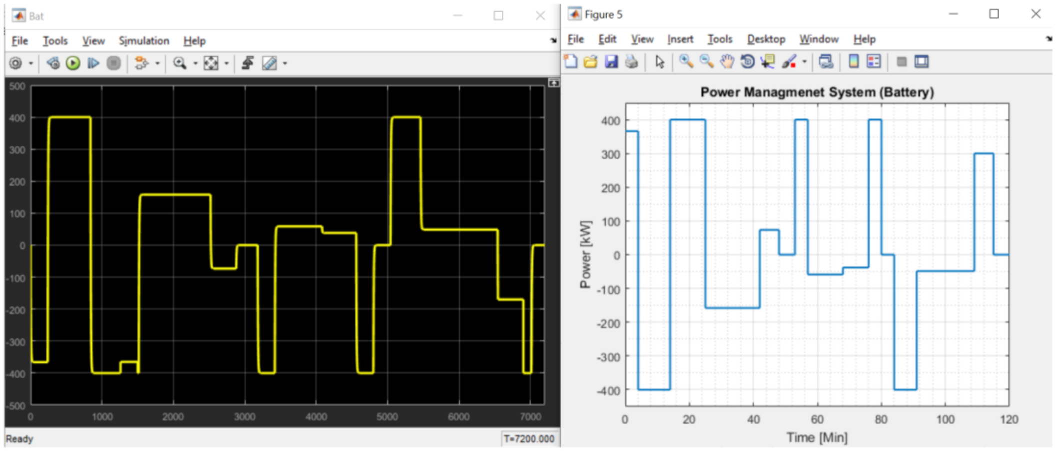
Current challenge and possible comment on...



Because of outputs comes from EMS is switching conditions of Engine instead of loads... Let me know your idea about, Please!

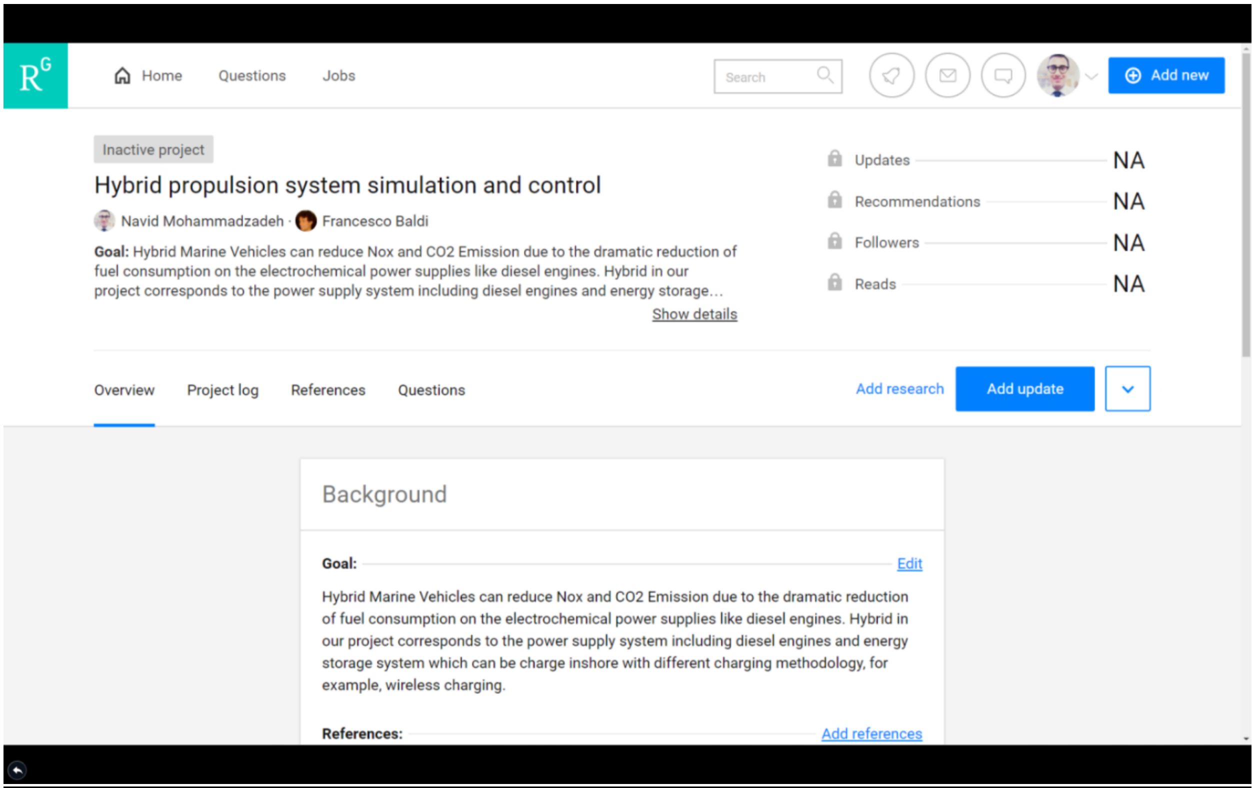
What do we have to next...?

- Application of Model Predictive Control
Why?
If we can use the simpler controller, why CoMpLeX?!

- Application of Machine Learning in the Cycle Identification ... (Learning in the case of changing the roat.)

- Consider the lifetime Assesement of the battery

- Considering Free onshore Charging (with wireless charging with Inductive Power Transer (IPT))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Hybrid propulsion system simulation and control
Navid Mohammadzadeh · Francesco Baldi
Goal: Hybrid Marine Vehicles can reduce Nox and CO2 Emission due to the dramatic reduction of fuel consumption on the electrochemical power supplies like diesel engines. Hybrid in our project corresponds to the power supply system including diesel engines and energy storage…
Show details
Updates NA
Recommendations NA
Followers NA
Reads NA
Overview
Project log
References
Questions
Add research
Add update
Background
Goal:
Edit
Hybrid Marine Vehicles can reduce Nox and CO2 Emission due to the dramatic reduction of fuel consumption on the electrochemical power supplies like diesel engines. Hybrid in our project corresponds to the power supply system including diesel engines and energy storage system which can be charge inshore with different charging methodology, for example, wireless charging.
References:
Add references


Appreciate your consideration
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