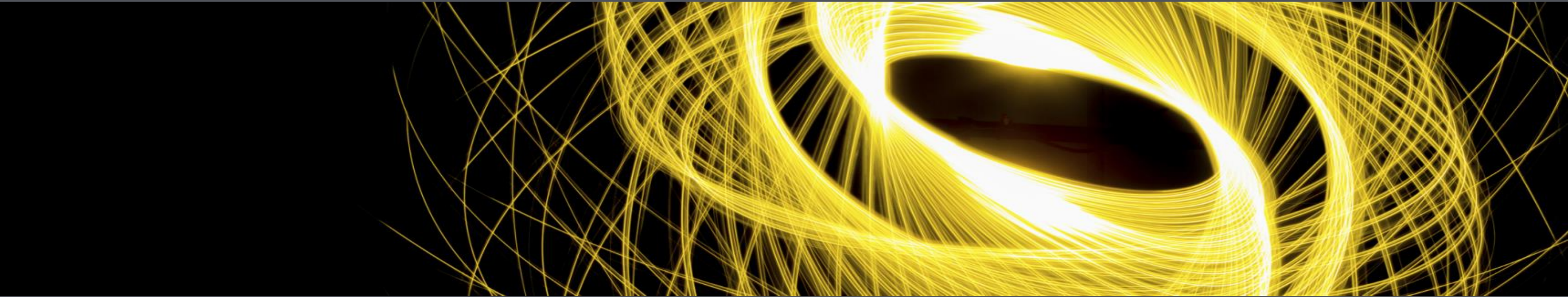
University of Reading

OPTIMAL ENERGY CONTROLLERS OF ENERGY STORAGE SYSTEMS BASED ON LOAD FORECASTING FOR RTG CRANE NETWORKS



By : Feras Alasali

Dr. Stephen Haben

Prof. William Holderbaum

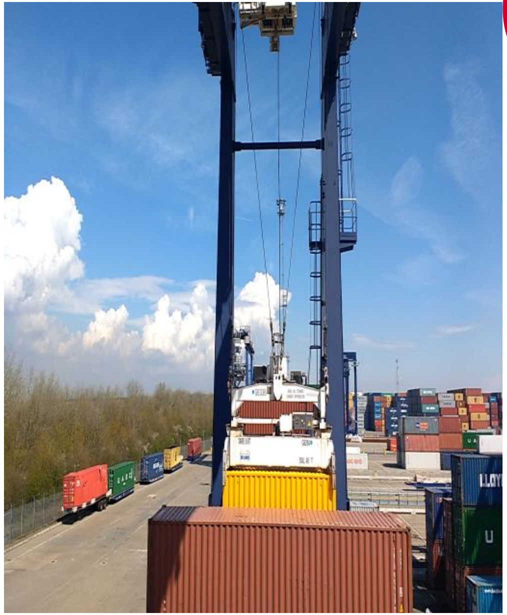
TABLE OF CONTENTS

University of Reading

PROBLEM STATEMENT

University of Reading

Electrified RTG Crane



As electrical loads increase across the RTG crane network due to the electrification of the cranes, port operators will be forced to reinforce the network to meet this increased demand and support the distribution network. In addition, there is a lack of understanding of the port network and the RTG crane energy demand behaviour.

ESS as a potential significant solution to enable LV networks to become more energy efficient. However, there is a gap in how we can maximise the potential benefits of using an ESS in a LV network of RTG cranes.

This project studies how an ESS on a network of RTG cranes can be optimally controlled based on load forecasts, in order to reduce the electricity energy costs and achieve the maximum peak demand reduction.

RESEARCH OBJECTIVES

University of Reading

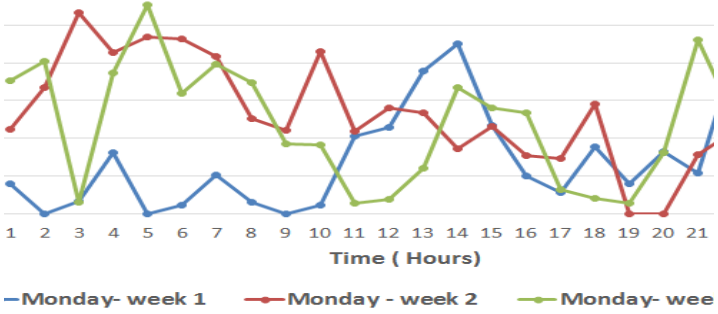
- ✓Analyse the e-RTG crane demand.
- ✓Develop forecast models to generate the half-hourly load profile.
- ✓Design optimal energy control strategies of the ESS based on the load forecasts of the RTG cranes network.
- ✓Analyse the storage device performance in different location scenarios

ANALYSE THE E-RTG CRANE DEMAND

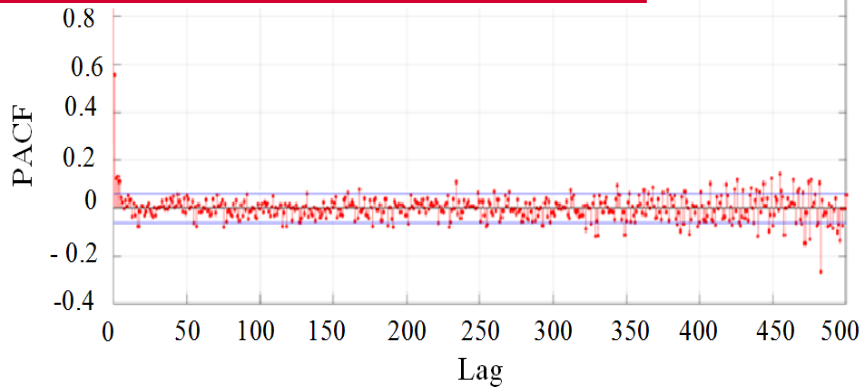
University of Reading

There is no clear trends or seasonality patterns, therefore the RTG crane demand is highly volatile, non-smooth and less predictable behaviour compared to many other low voltage loads such as residential customers.

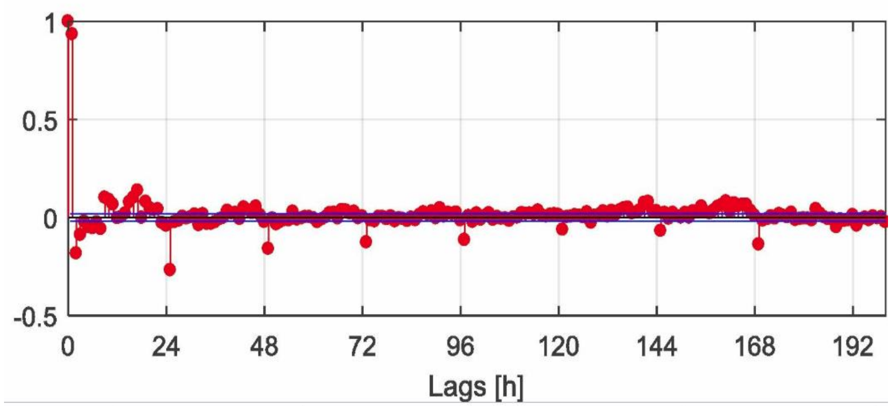
Daily load usage (Monday)



PACF for RTG crane



PACF for L.V network [1]

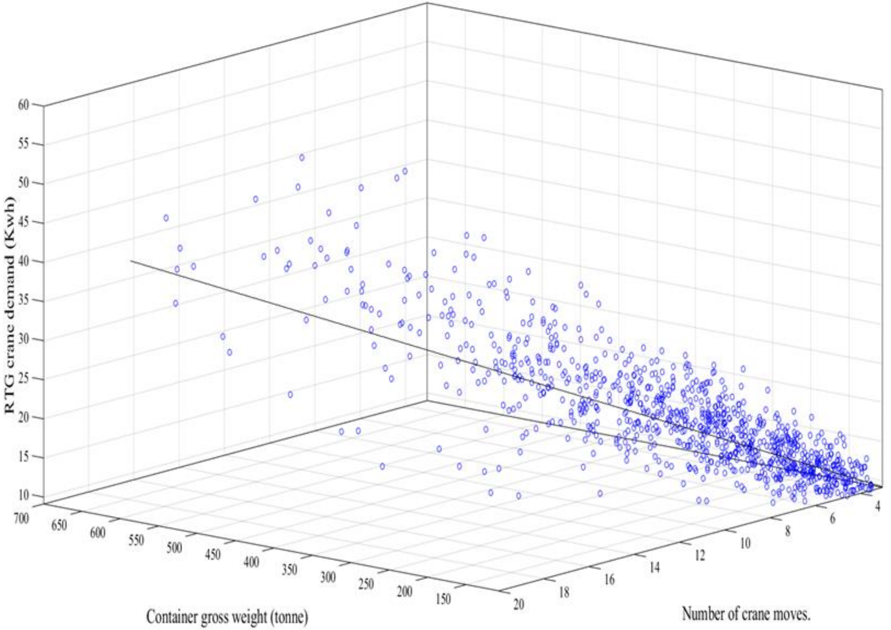


ANALYSE THE E-RTG CRANE DEMAND

University of Reading

- There is correlation between the crane demand and container weight and number of moves but still there high load variation due to the human operator factor.

Moves	Weight (ton)	Time	Demand (kWh)
7	173	11th of Feb (05:00)	30.9
		15th of Feb (17:00)	21.2
4	102	19th of Feb (14:00)	8.3
		4th of March (21:00)	12.4
		21th of March (06:00)	15.2



LOAD FORECASTING MODELS

University of Reading

ARIMA, AR, ARIMAX

<u>**ANN**</u>

- The load forecasting models has been developed and tested based on the following:

1. Estimating the exogenous variables (number of crane moves and container gross weight) .
2. Estimating one of the exogenous variables and assuming the other variable is known in advance.
3. Assuming both exogenous variables are known in advance.
4. Generating the forecast models without the exogenous variables.

❖ In order to estimate both exogenous variables, the joint probability distribution has been used.

Testing period	MAPE (%)							
	Model A	Model B1	Model B2	Model B3	Model B4	Model C1	Model C2	Model C3
Period 1	21.9%	**8.1%**	10.7%	10.8%	31.1%	9.8%	11.9%	12.7%
Period 2	27.8%	**9.1%**	11.4%	12.5%	32.6%	10.6%	10.7%	14.6%
Period 3	19.6%	**7.7%**	8.7%	16.3%	18.1%	9.1%	8.9%	24.1%

Testing period	MAPE (%)						
	Model C4	Model D1	Model D2	Model D3	Model D4	Model E	Model F
Period 1	43.1%	9.8%	9.5%	13.6%	49.1%	36.3%	36.1%
Period 2	31.2%	10.9%	10.9%	13.9%	32.5%	36.9%	36.5%
Period 3	43.5%	9.7%	10.3%	27.8%	42.9%	21.3%	23.8%

- Model A : ANN based on historical load and without exogenous variables information.
- Model B: ANN . Model C :ARIMAX Model D: ARX Model E :AR Model F: ARIMA

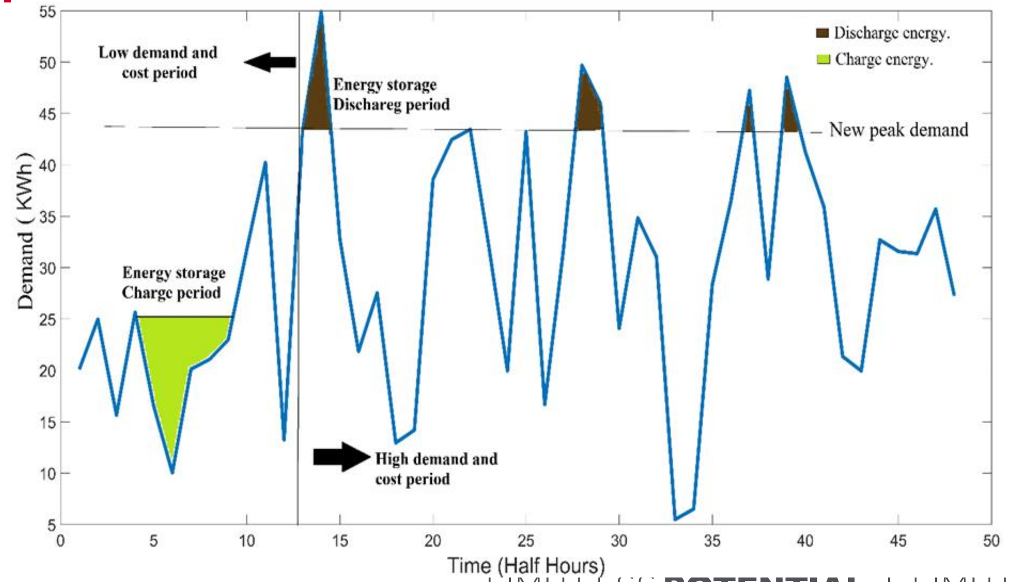
- Model . 1: assuming both exogenous variables are known.
- Model . 2: estimates the number of crane moves while assuming the container gross weight is known.
- Model . 3: estimates the container gross weight while assuming the number of crane moves is known.
- Model .4: estimates both of the exogenous variables.

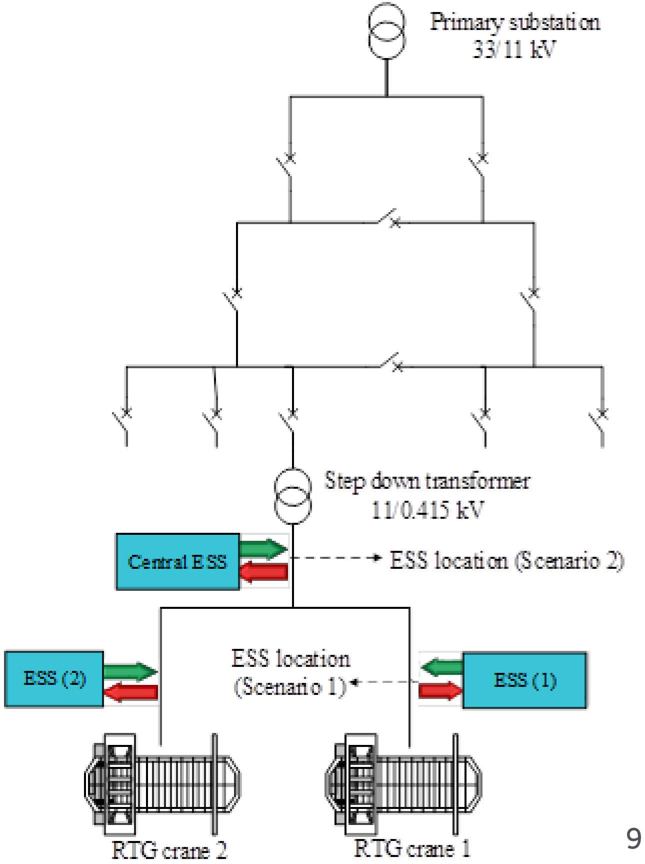
OPTIMAL ESS CONTROL STRATEGIES

University of Reading

Optimal energy management , MPC and SMPC:

Uses a cost function to maximise the peak reduction and reduce the electricity bill at network of RTG crane.

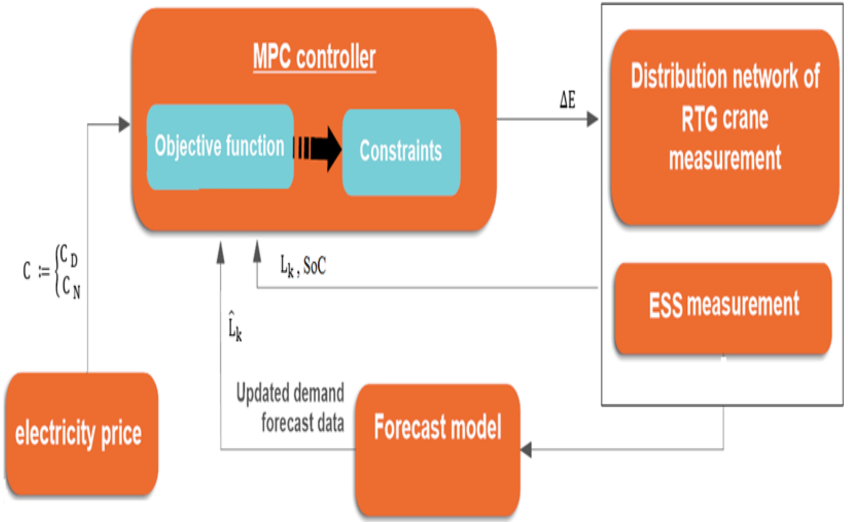




MPC CONTROLLER

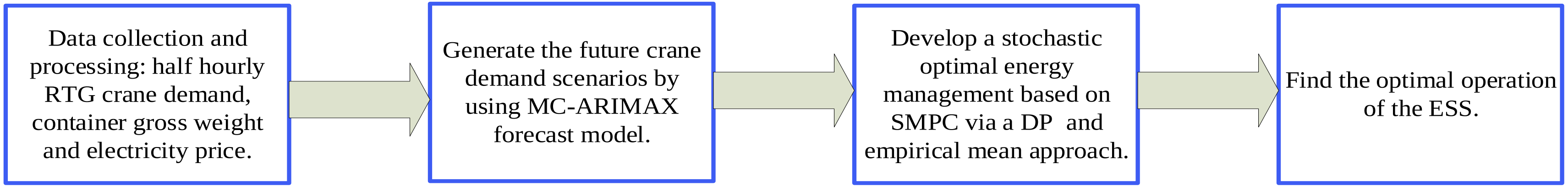
University of Reading

The MPC controller is formulated as a controller that creates a sequence of decision-variables to minimise a cost function over a future time horizon uses an adjustments at every time step.



$$\arg\min_{\Delta E} \sum_{n=1}^{N} \max \left(\hat{L}_k(n) + \Delta E(n)\right)^2,$$

SMPC CONTROLLER



*The future RTG crane demand profile for day k, $\hat{L}_k$, is modelled as a stochastic variable by generating M profiles, future demand profiles using the MC-ARIMAX forecast model, where $m \in \{1, \ldots, M\}$ and n is the half hourly period of the day $(n \in \{1, 2, \ldots, N = 48\})$ defined by:

$$\hat{L}_k{}^m = \left(\hat{L}_k{}^m(1), \ldots, \hat{L}_k{}^m(N)\right)^T$$

*The SMPC method aims to create an energy storage control policy to minimise the maximum total demand over all M future scenarios for the periods n, …, N using the empirical mean for the cost function, in other words find

$$\Delta E^*(n:N) = \underset{\Delta E(n:N)}{\arg\min} \frac{1}{M} \sum_{m=1}^{M} J\left(\hat{L}_k{}^m, \Delta E, n\right).$$

Where $$J\left(\hat{L}_k{}^m, \Delta E, \ell\right) := \max_{s \geq \ell} \left\{\left(\hat{L}_k{}^m(s) + \Delta E(s)\right)^2\right\}$$

RESULTS AND DISCUSSION

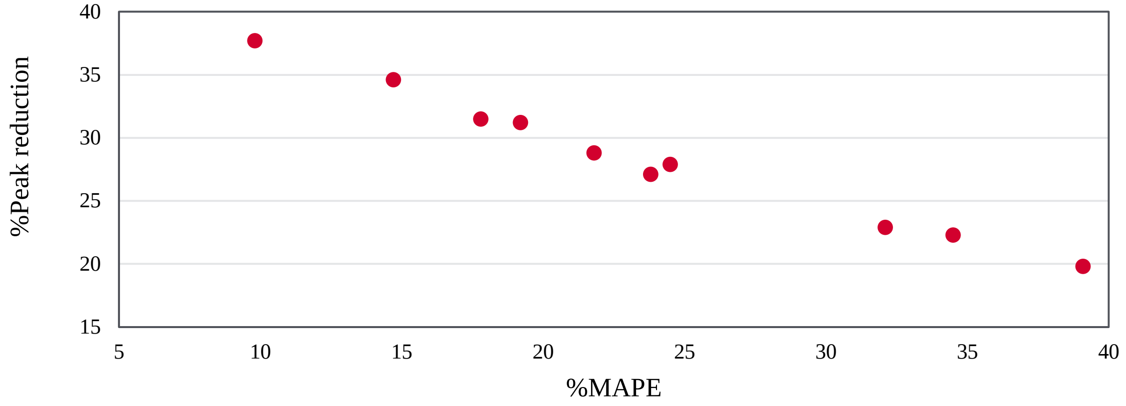
*The percentage of demand reduction results for a specific network of crane operation case study

ESS Location scenario	Set-point	MPC	SMPC
scenario 1			
Two ESS (1) and (2)	22.9%	29.3%	**31.2%**
Scenario 2			
One ESS (option 1)	23.8%	30.3%	**32.8%**
One ESS (option 2)	18.3%	22.1%	**23.5%**

*The ESS scenarios viability results

	Annual cost saving (K £)			NPV (K £)			IRR (%)			Payback period (years)		
	S.P	MPC	SMPC	S.P	MPC	SMPC	S.P	MPC	SMPC	S.P	MPC	SMPC
Scenario 1	1.18	1.59	1.73	-8.5	-2.4	-0.8	-0.94	1.96	2.87	22.6	16.9	16.2
Scenario 2 (option 1)	1.21	1.65	1.79	-8.0	-1.5	**0.5**	-0.71	2.35	**3.28**	21.5	16.3	**15.1**
Scenario 2 (option 2)	1.09	1.19	1.21	-4.4	-1.8	-1.7	1.05	1.94	2.11	19.6	17.4	16.6

*The relationship between MAPE and the percentage of daily peak reduction for the SMPC controller.



*The average peak demand reduction for the ESS controllers with average forecast errors.

ESS control model	Accurate forecast model	MAPE	Peak reduction%	Inaccurate forecast model	MAPE	Peak reduction%
MPC	ANN (Model B.2)	14.2%	30.2%	ANN (Model A)	28.3%	20.2%
SMPC	ARIMAX (Model C.2)	17.2%	32.6%	ARIMA (Model F)	30.1%	24.2%

CONTRIBUTION TO THE LITERATURE

University of Reading

- This research provides an analysis of the network of electrified RTG cranes demand under a real operation time periods and identifies the correlation between the current time electric demand, the historical demand and exogenous variables.

- Forecast models to generate a future demand profile for an electrified RTG crane and network of electrified RTG cranes (substation demand) for up to one-day ahead are developed .

- MPC and Stochastic MPC for RTG crane network connected to an energy storage device are developed. This research shows a receding horizon controller that helps to decrease the electricity energy costs and achieve maximum possible peak reduction, taking into account the high volatile demand behaviour and uncertainty in the crane demand prediction.

- This research investigates the energy storage performance for a network of two RTG cranes at different location scenarios to give sea ports an initial indicator regarding the possible location of ESS in line with economic evaluation and cost saving analysis.