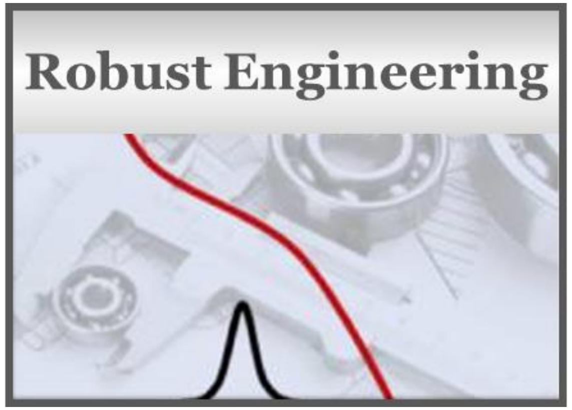
ENM7005-B Modelling and Optimisation

Design of Experiments & Response Surface Modelling



Module Overview – 2023-24

About your lecturer…

Professor Felician Campean

Professor of Automotive Reliability Engineering
Director of Automotive Research Centre
Associate Dean Research & Knowledge Transfer

- Expertise in Systems Engineering, Engineering Design & Product Development, Reliability
- Experience with modelling real world systems – in conjunction with industrial projects
- Extensive experience of teaching statistical modelling methods to industry – the materials used in this module have been developed in conjunction with industry – and taught in industry
  - SAFI Consortium – University of Bradford, Airbus, Renault, PSA, Valeo

- Where you can find me:
  - Room: Chesham B1.34
  - Email: f.campean@bradford.ac.uk

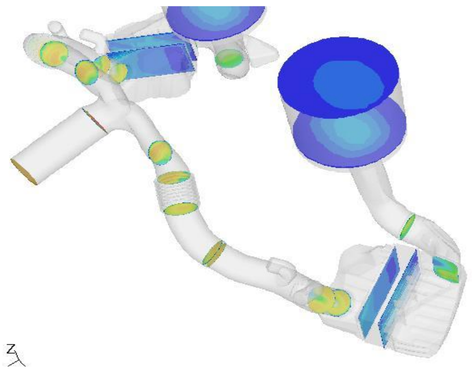
How do we model engineered systems?

- Think of examples of engineering systems modelling* problems you have tackled in the past?
  - What was the problem?
  - How did you approach it – how did you model it?
  - How did you validate your model?
  - What was the most difficult part / the most challenging aspect of the modelling?

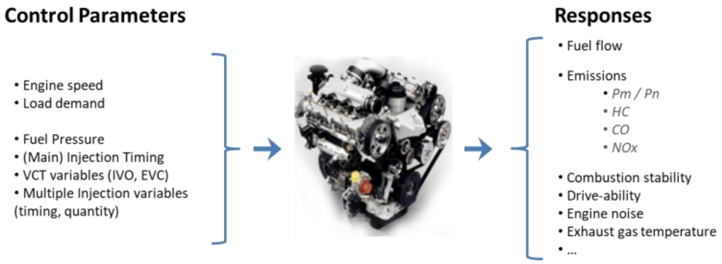
*<u>*Modelling*</u> – we refer here to the mathematical modelling of a system (i.e. the “law” of the system that gives the *function* of the system) rather than its geometrical form…

Approaches to Systems Modelling

- **Phenomenological Modelling**
  - From the fundamental equations of motion, flow, thermodynamics, …
  - Computer / Simulation based

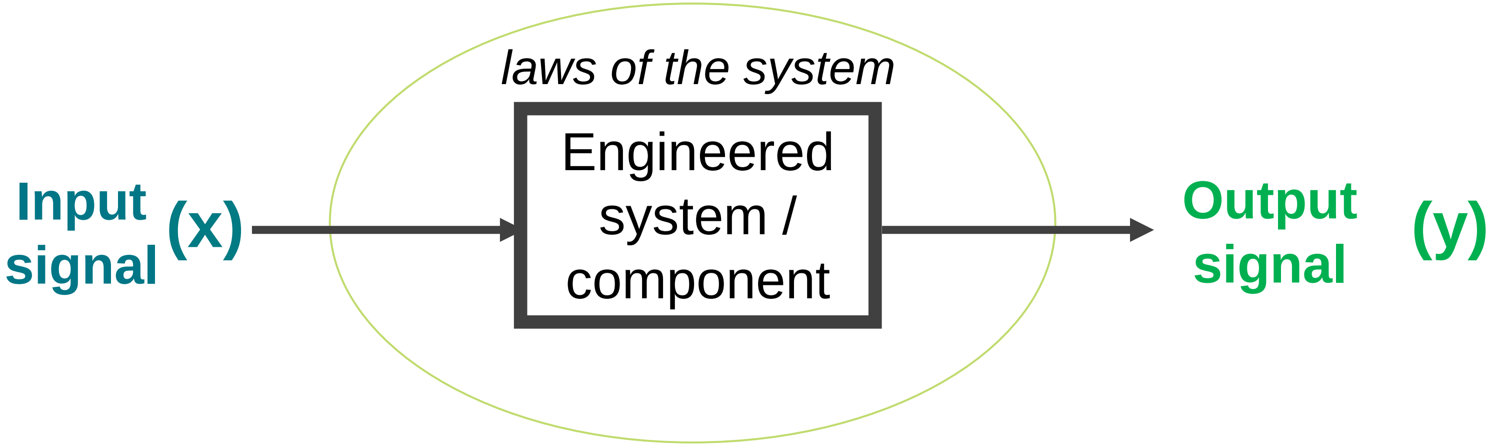


- **Behavioural Modelling**
  - "Black Box" modelling of the system
  - Empirical modelling – based on data collected from "black box" experiments with <u>*the system*</u>



- **Or** based on a <u>*simulation model*</u> of the system
  - Model reduction, surrogate modelling, etc…

Science, Engineering & Statistics



- Abstraction of Engineering activities:

Analysis:	Given the **system**, the **input** and the **laws**	Predict the **Output**	*Deduction*
Science:	Given the **system**, the **input** and the **output**	Derive the **Law**	*Induction*
Design:	Given the **input**, the **laws** and the ***desired* output**	Design the **System**	*Synthesis*

Credit: Prof. T.P. Davis, "Science, Engineering and Statistics", Research Seminar, University of Bradford, 2006

Example: GDI engine calibration problem

Control Parameters

- Engine speed
- Load demand

- Fuel Pressure
- (Main) Injection Timing
- VCT variables (IVO, EVC)
- Multiple Injection variables (timing, quantity)

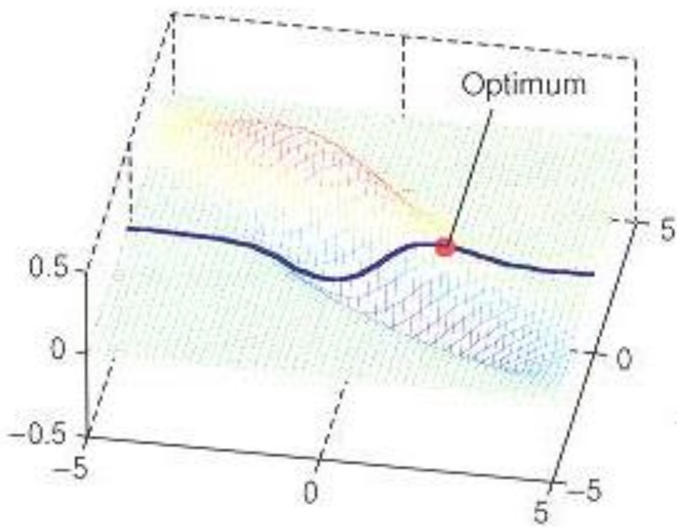
Responses

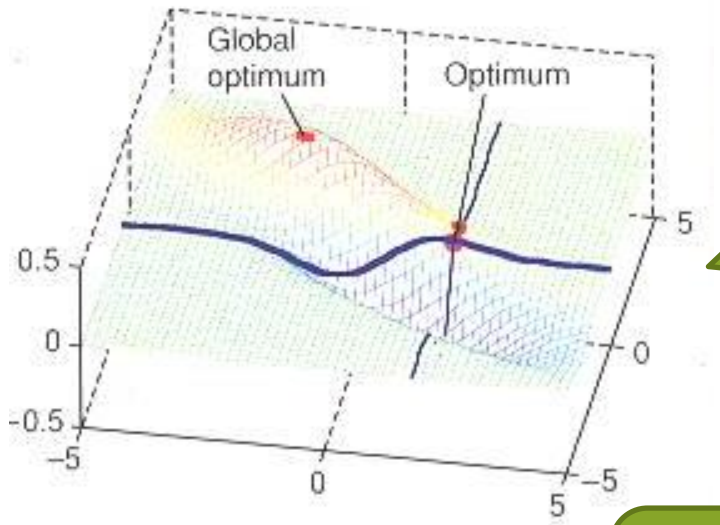
- Fuel flow
- Emissions
  - *Pm / Pn*
  - *HC*
  - *CO*
  - *NOx*
- Combustion stability
- Drive-ability
- Engine noise
- Exhaust gas temperature
- …

- Engine mapping and calibration is best described as multi-objective optimisation problem
  - i.e. find optimal actuator settings to achieve the best trade-off between objectives (power/torque, fuel economy, driveability and noise) while meeting emissions legislation requirements!
- In practice - how do calibration engineers find an optimal setting?

Example: GDI engine calibration problem

- Traditional approach to engine optimisation is one-variable-at-a-time





How do we develop such mathematical models?

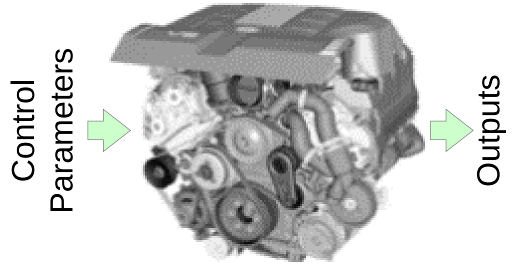
We need a mathematical model for the engine response (fuel flow, emissions) as a function of the input / control variables

..Such that we can apply optimisation techniques to search and find the "global optimum"

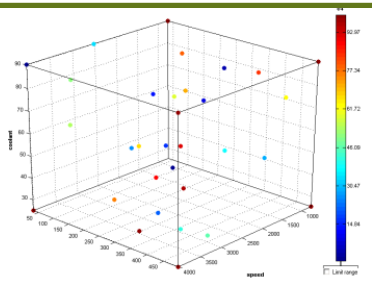
- This is very inefficient and it does not guarantee that the global optimum is found

Engine Mapping / Model Development

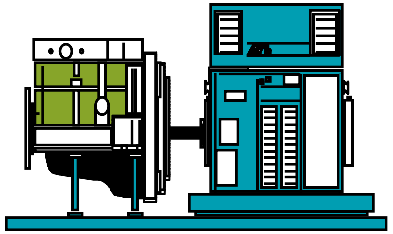
Engine Parameters & Responses



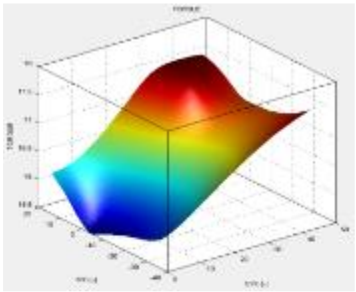
DoE Experimental Plan



Steady State Data Collection

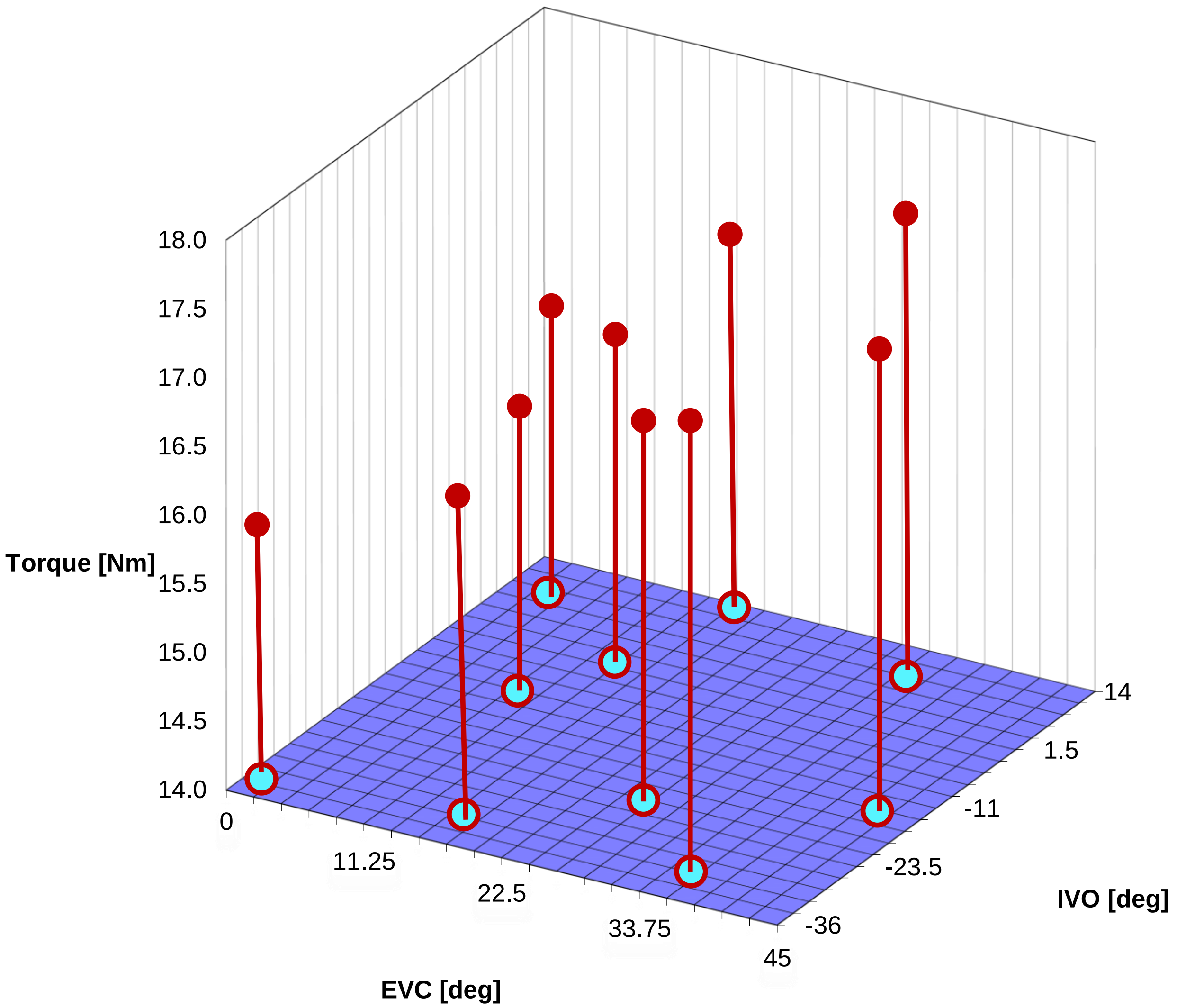


Engine Response Modelling & Validation



- How do we design efficient engine experiments?
- What type of models can we use for engine responses?

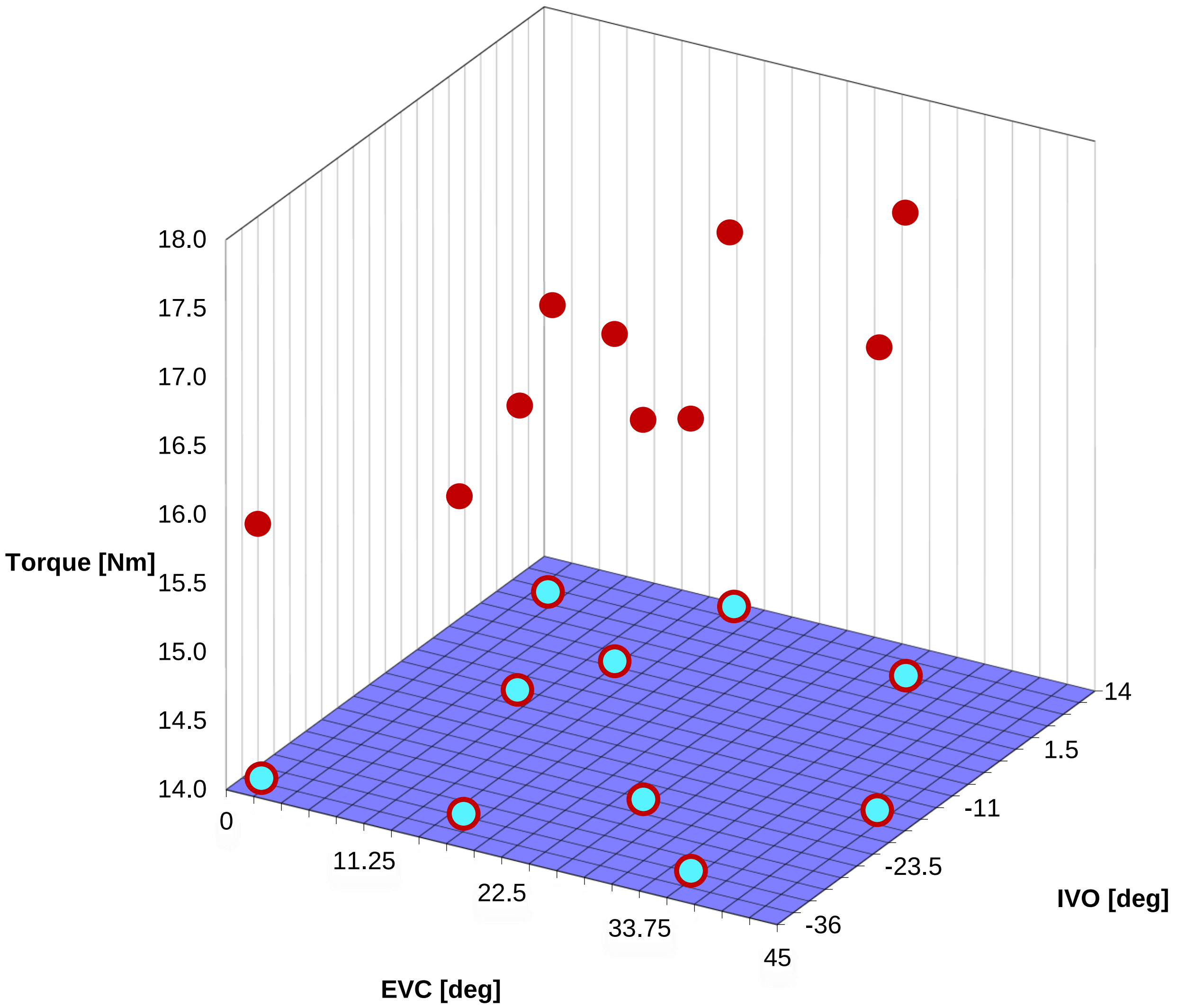
Response Surface Modelling Approach



1. Plan the Experiment (DoE – Design of Experiments)

2. Run the engine experiment / collect test data

Response Surface Modelling Approach



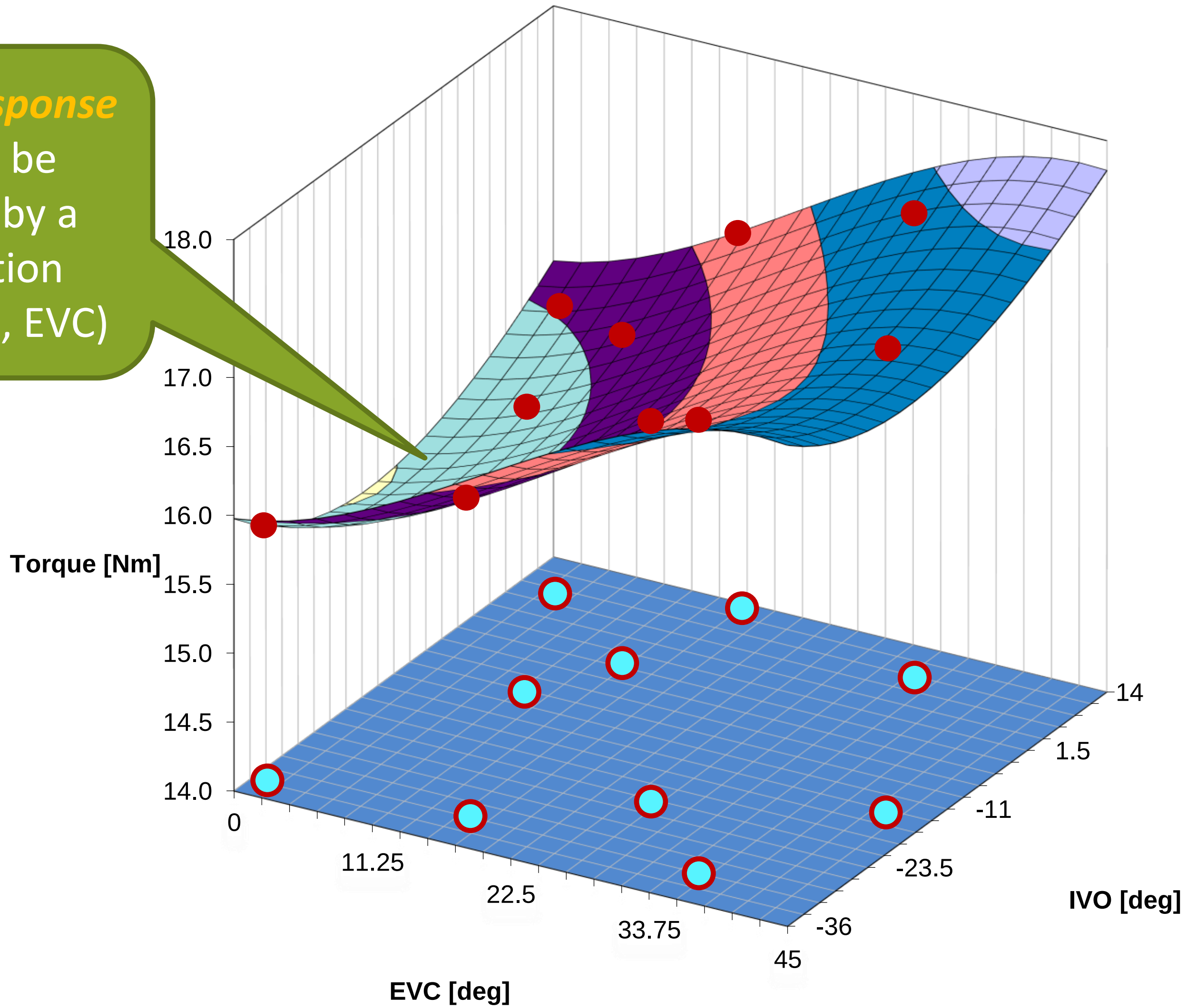
1. Plan the Experiment (DoE – Design of Experiments)

2. Run the engine experiment / collect test data

3. Fit the Response Surface

Response Surface Modelling Approach

This engine *response surface* can be represented by a single equation Torque = f(IVO, EVC)

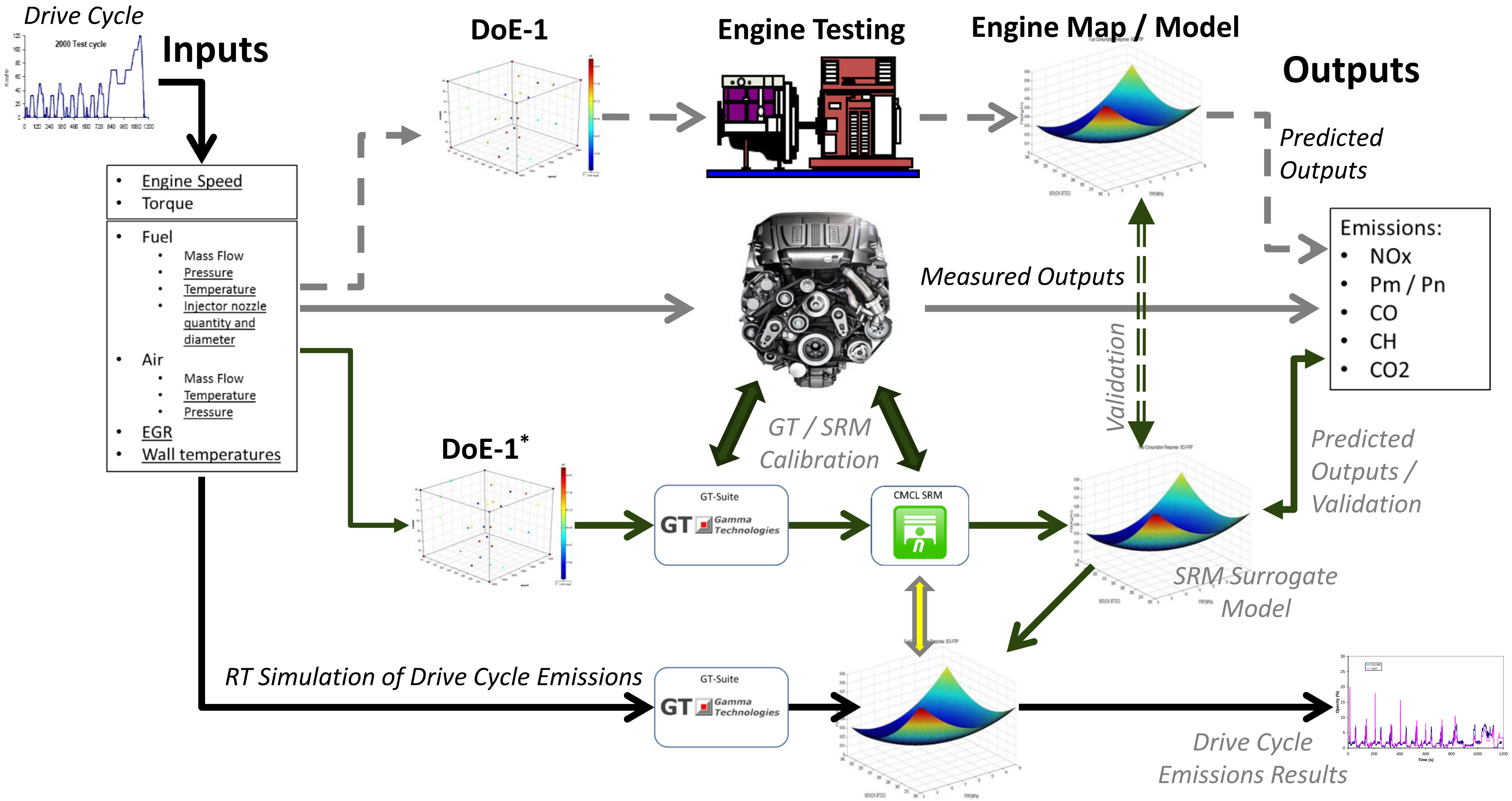


1. Plan the Experiment (DoE – Design of Experiments)

2. Run the engine experiment / collect test data

3. Fit the Response Surface

What if we are dealing with CAE Models?



Physical engine experiments

CAE engine simulation experiments

Evaluation of zero-dimensional stochastic reaction modelling for a Diesel engine application, Int J Engine Research, https://doi.org/10.1177/1468087419845823

Examples of Engineering applications

Table 1 Summary of literature cases: metamodeling techniques and problem characteristics considered

	Metamodelling technique									Problem characteristic				Test problem		
	Polynomial	Kriging	RBF	MLS	NN	MARS	Splines	SVR	Other (e.g. HDMR)	Dimensionality	Nonlinearity	Sample size	Noise	Benchmark functions	Engineering problem	Engineering case study
Simpson et al. (1998)	x	x								x					x	Aerospike nozzle design
Giunta and Watson (1998)	x	x								x				x		
Yang et al. (2000)	x			x	x	x				x					x	Crashworthiness simulation
Varadarajan et al. (200)	x				x										x	Engine combustion modelling
Jin et al. (2001)	x	x	x				x			x	x	x	x	x		
Jin et al. (2003)	x	x	x									x	x		x	Structural design
Seabrook et al. (2003)		x	x		x								x		x	Engine mapping experiments
Forsberg and Nilsson (2004)	x	x													x	Crash simulation
Fang et al. (2005)	x		x									x			x	Crash simulation
Mullur and Messac (2006)	x	x	x							x		x		x		
Chen et al. (2006)	x	x	x		x	x				x		x		x	x	Wastewater treatment
Ben-Ari and Steinberg (2007)		x					x		x	x				x	x	Piston dynamics, electric circuit
Kim et al. (2009)		x	x	x				x				x		x		
Zhu et al. (2009)		x	x		x			x							x	Automotive - body structure
Paiva et al. (2009)	x	x			x					x					x	Aircraft wing design
Zhao and Xue (2010)	x	x	x		x					x		x	x	x		
Campean et al. (2010a, b)	x	x	x										x		x	Engine modelling experiments
Li et al. (2010)		x	x		x	x		x		x			x	x	x	Process simulation
Wang et al. (2011)	x	x	x			x		x		x	x			x	x	Crashworthiness optimisation
Van Gelder et al. (2014)	x	x	x		x	x						x			x	Building simulation
Liu et al. (2016)	x	x	x						x	x		x			x	9 engineering problems
Kroetz et al. (2017)		x			x				x	x		x			x	Structural reliability
Chen et al. (2018, 2019)		x	x					x	x	x	x	x	x	x		
Ostergard et al. (2018)		x			x							x		x		

https://doi.org/10.1007/s00158-019-02352-1 *Performance evaluation of metamodeling techniques: towards a practitioner guide*

Modelling – Course Aims

- Develop Knowledge to master the theory and practice of Design of Experiments and Response Surface Methodology, as applied to Engineering problem-solving and design.
- Develop Skills to be able to plan and run experiments appropriate to a wide variety of Engineering scenarios, fit empirical transfer functions to the resulting data and use transfer functions to understand the impact of variation on system performance.
- Personal Skills - the use software for DoE & RSM analysis
  - **Plan and design** experiments
  - **Build and validate** response models

Outline syllabus – Modelling (DoE & RSM)

- Principles of empirical / behavioural modelling
- Linear regression
  - Correlation & regression, model quality, model selection
- Planning and analysing designed experiments
  - Planning and analysing 2-levels experiments
  - Multi-level DoEs
- Experiments for surrogate modelling with computer based experiments
  - Latin Hypercubes, flexible response models – including neural networks
- Examples and case studies

Suggested reading

• Forrester	Engineering Design via Surrogate Modelling
• Myers&Montgomery	Response Surface Modelling
• Montgomery	Design & Analysis of Experiments
• Grove & Davis	Engineering Quality & Experimental Design
• Montgomery et al	Engineering Statistics

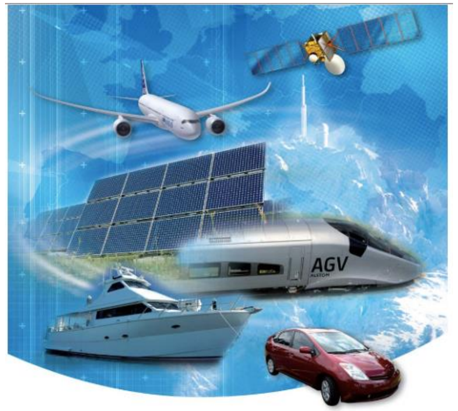
- UoB / Short Course Handbooks / Materials
  - Advanced Statistics for Engineering
  - Design of Experiments & Response Surface Modelling

Learning materials

Short Course Handbooks / Materials

- Advanced Statistics for Engineering
  - Most of the short course materials (including tutorials and exercises) will be made available as background reading via Canvas;
  - Please use this as self-study – and bring questions in the classroom to discuss!
  - Some topics (in particular multiple regression) will be covered in the classroom

- Design of Experiments & Response Surface Modelling
  - We will largely follow the DoE & RSM short course materials in the Modelling part of this module
  - Most sessions will have tutorials – which are available for you to self-study – and we will discuss these in the class – together with the „exercises“;
  - We will expand on complex modelling – and computer based experiments / surrogate modelling



Course Organisation

- Technical Sessions (TS)
- Practice sessions (ES):
  - Python “Tutorials”
    - Aim: to develop practical skills and discuss key issues to ensure understanding;
  - Exercise Task
    - Based on practical examples – combination of team based exercises and application of tools to engineering problems
  - Self-study needed – use classroom for clarification and reinforcement

Tutorials

- Tutorials will be based on Python – using Google Colab
  - Python is becoming a programming environment of choice for many engineering organisations
  - It underpins many of the Machine Learning applications commonly use din industry
  - It is a good skill to develop / have...
  - We will provide you with detailed step-by-step tutorial guidelines

  - Reference to other software (e.g. Matlab or Minitab) can / will be provided

- Exercises:
  - Each session has an „exercise" – based on the tutorial – giving you an opportunity to develop and practice your skills (by modifying the code)
  - You will be asked to submit your exercise files through Canvas
    - This will not be individually marked – but collectively will provide an engagement and skills contribution mark to the modelling coursework – ***<u>10% of the mark</u>***
    - Feedback comments / notes will be provided across the class

Modelling Project / Coursework

- Assessment for the modelling part is based on an individual coursework
  - The coursework will be based on an engineering modelling „problem" of choice
  - A refence problem / task will be provided, but students are encouraged to choose their own technical example
  - The coursework brief will be discussed in **week 6** – once the relevant material (both technical and tutorials / code support) is covered
  - In your technical report you will have to follow the methodology covered in class; you will be expected to apply the methodology independently to the given or chosen technical proble, justify your approach to the designed experiments – including critical considerations for the choice of parameters, experimental strategy, and the fit and analysis of a response surface model and its use – for optimisation!
  - Students can work together, but the reports are individual!

- Coursework submission will be in Week 12 (TBC)
- The timetabled sessions for the last 3 weeks will be devoted to „coursework clinic"

Summary - Delivery, assessment and feedback

Delivery

- Lectures / Tutorials
  see timetable for the weekly schedule
- Technical sessions front-loaded; coursework set up in week 5 with support later in the semester.

Assessment

- Modelling Coursework - 50% of the overall module mark
  - Technical report on your modelling experiments that you will conduct

Feedback

- Tutorial classes
- Formative assessments

Canvas

- All materials will be available in Canvas – see the Modelling section