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Introductory Courses on Digital Twins: an Experience Report

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2. Newcastle: a Course for the Water Sector
    - Context, Objectives, Content, Delivery, Experience
3. Aarhus: a Course for Engineering Students
    - Context, Objectives, Content, Delivery, Experience
4. Observations & Discussion Points

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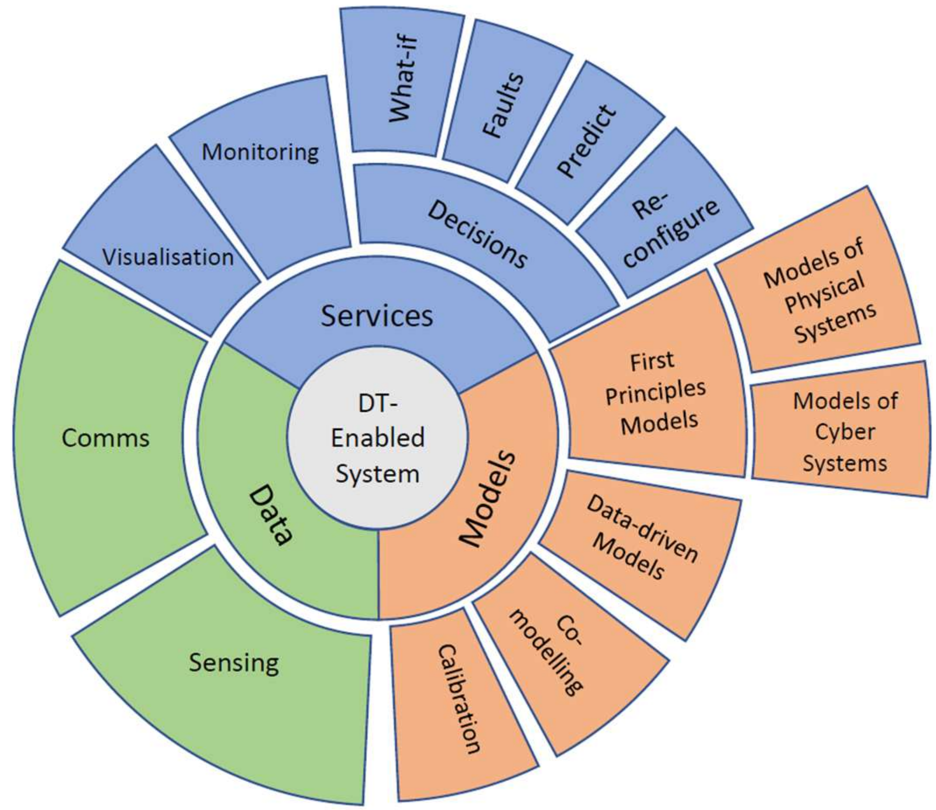
1. Background & Motivation

From Newcastle. For the world.

1. Background & Motivation

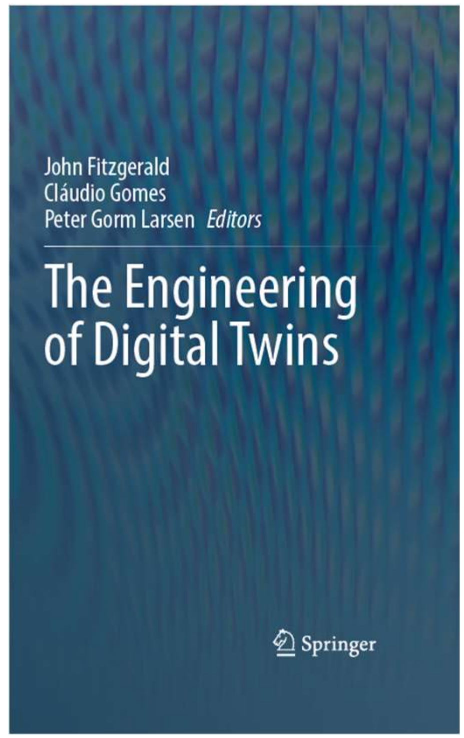
- DT Engineering is a systems discipline
- Much of the value of the DT concept is its wide applicability.
- So – *who* are our methods and tools for?
- This influences our choices about what research we prioritise and how we package the technology that we develop.

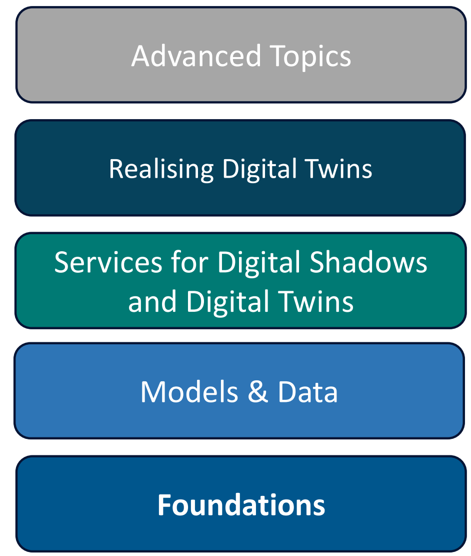


1. Background & Motivation

https://doi.org/10.1007/978-3-031-66719-0
Hardcover, softcover, e-book.
Support Page: https://digital-twin-book.org/

- Presents methods, tools and experience that contribute to the evolution of DT engineering
- Introduces model-based methods including co-modelling and co-simulation via the Functional Mockup Interface technology
- Includes a web page with DT examples, exercises and solutions, and pointers to standards, frameworks and platforms





2. Newcastle: a Course for the Water Sector

From Newcastle. For the world.

2. Newcastle: a Course for the Water Sector

- Water Infrastructure Resilience (WIRe) Centre for Doctoral Training (CDT)
- Training “the next generation of scientists and engineers to transform the management of our civic water resources, assets, and services”
- Module for induction of new cohorts of students.
- Motivated by **digitalisation** – the process of transforming an activity by using digital technology.

“the greatest threats to our water supply can be overcome through the application of digital technologies”

Verma, S. 2021. Digitizing the water sector: An opportunity to improve water quality. Water Online, January 2021

“The enactment of power through digital water technologies is demonstrated through regulating the access to water as well as to mediating technologies and also the power to control and create connections and relations between actors.”

C. Walter, “Digital Technologies for the Future of the Water Sector? Examining the Discourse on Digital Water”. Geoforum 128, Jan 2024

CEG8529: Context

- 15 students
- Early stages of doctoral training (4yr full time)
- Chemistry, biology, civil & mech eng., and public policy.
- 5 ECTS (~100 hrs of study), main delivery over 2 weeks.
- **DTs as a unifying theme.**
- **What stake do they have in DT Engineering?**

CEG8529: Context

- *How 'good' does it need to be? (and what does 'good' mean?)*
- *How do I balance fidelity, performance, uncertainty?*
- *Do I have to build it from scratch, or can I tailor a free one?*
- *How do I integrate this with my real processes and tools?*
- *Can I trust the results?*

CEG8529: Objectives

Equip students to:

- **Appraise** digital solutions
- **Evaluate** the potential of AI in the water sector
- **Examine** the fundamental concepts of Digital Twins from a Systems Engineering perspective
- **Critique** diverse models, data sources and analytic techniques
- **Debate** the challenges of delivering a dependable DT in the water industry

Engineering and Physical Sciences Research Council

WATER INFRASTRUCTURE AND RESILIENCE WIRe

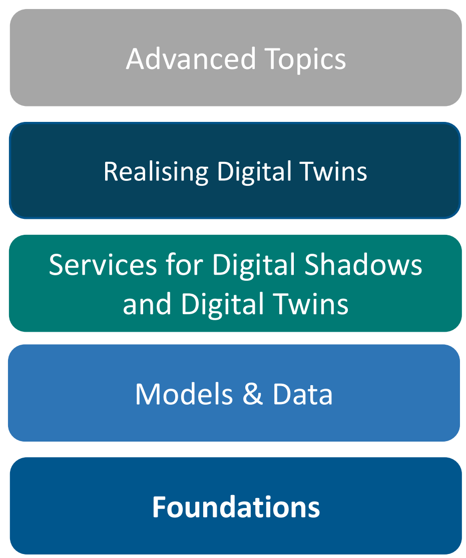
University of Sheffield

Cranfield University

Newcastle University

CEG8529: DT-based Content

DT-based content follows the structure of the book, but with a focus on the “upstream” aspects rather than realisation.



CEG8529: DT-based Content

Advanced Topics

13. Security & Privacy-related Issues
14. (DT-Enabled reconfiguration of the PT)
15. Future Directions & Challenges

Realising Digital Twins

Services for Digital Shadows and Digital Twins

8. Visualisation
9. Monitoring
10. Advanced Services

Models & Data

5. Modelling for Digital Twins
6. Calibration
7. Sensing and Data Communications

Foundations

1. Engineering Digital Twins (Context & Basic Concepts)
2. The Potential of Digital Twins (Industry Perspectives)
3. Foundation Concepts
4. (DT Engineering Processes)

CEG8529: Data-based Content

Data & AI Fundamentals

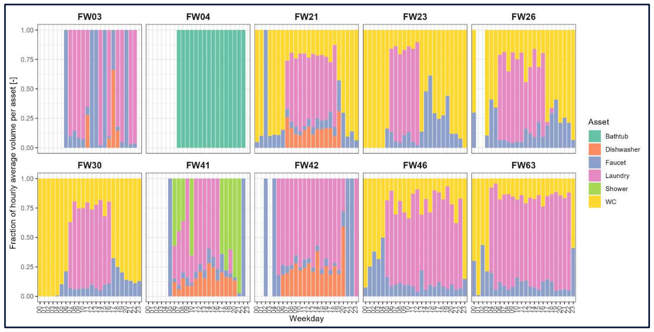
- Types of (digital) data: streaming, historical, spatial, model Outputs, etc.
  - Handling and analysing time series data
  - Media data types, Data Formats & Databases, Metadata
  - Introduction to Google Colab
- AI and ML
  - Supervised and unsupervised learning, with examples from:
    - Machine Vision (supervised learning)
    - K-Means Clustering
    - Gradient Descent
    - LLMs
  - Ethical considerations of ML

CEG8529: Data-based Content

Data from the Fair Water project.

- *Co-develop and test* more effective and sustainable *task-based* water and energy solutions for people's homes
- Leverage learnings to develop *transition pathways* for different individual circumstances and characteristics
- *Retrofittable* to existing housing stock and life-styles
- *Accessible solutions* to reach across breadth of society – heavy water uses to the most vulnerable consumers

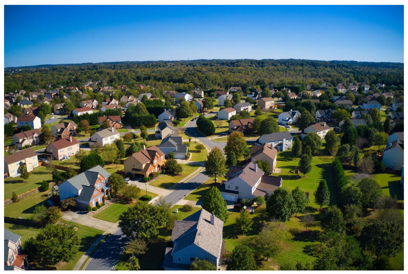
56 sensors monitor 78 water flows in the NGN customer energy village.



CEG8529: Delivery (Week 1/2)

Mon	Tue	Wed	Thu	Fri
Intro & Foundation Concepts	Models & Data	Linking Models to Reality	Digital Twin Services	Futures & Coursework
Data Fundamentals & Colab	Fair Water Data Lab	AI Fundamentals	**Research Seminar** With guests from NU, Grundfos, and Univ. of Amsterdam	

CEG8529: Delivery (Week 2/2)



DT-enabled Homes

- Housing developer creates a pilot development in which each home's occupier has a DT and the developer has access to an estate-wide DT.
- Can a DT help occupiers and developers to engage in sustainable water management practices?

DT-enabled Campus

- A university with a large urban estate (1887-2024) needs to make strategic decisions about what areas to renovate and vacate.
- Can a DT help it take the most sustainable solutions from a water management perspective?

DT-enabled City

- A city in a delta is at risk of coastal, fluvial and pluvial flooding. DTs are promising but may assume access to high-tech and high-finance.
- Can we build an affordable, sustainable DT solution that enables informed decision-making in planning and in flood management?

CEG8529: Delivery (Week 2/2)

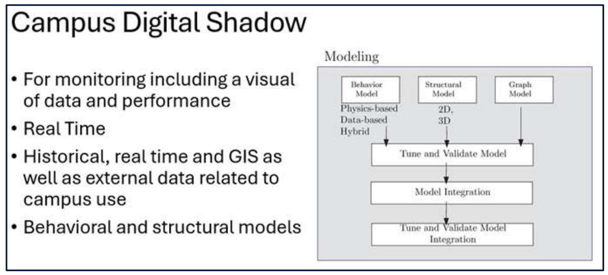
Groups' missions were to:

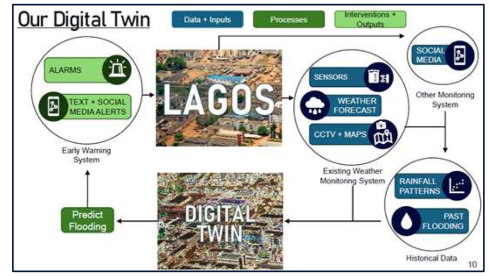
1. Research the potential of a DT solution, identify stakeholders and their needs.
2. Scope a DT solution by identifying a few top-level services that should be offered to some or all stakeholders.
3. Outline a DT solution …
4. Report in a presentation.

- **System** considerations: DT scope, environment, stakeholders
- **Sources** of data
- **Assets** (Data and Models)
- **Constellation** of top-level and intermediate enabler services.
- **Risks** to successful operation (e.g., stakeholder engagement, technology availability, dependability and security).
- **Life-cycle** of the solution: setting it up, maintenance and decommissioning.

Gil S, Oakes BJ, Gomes C, Frasheri M, Larsen PG. Toward a systematic reporting framework for Digital Twins: a cooperative robotics case study. *SIMULATION*. 2024;101(3):313-339. doi:10.1177/00375497241261406

CEG8529: Experience





Coursework

- Stakeholder & asset identification were comprehensive and accurate
- Description of top-level DT services was variable
- DT architectures (service dependencies, etc.) was weak

Student Feedback

- Positive about content and delivery
- Valued DT focus, but also want broader coverage of water sector digitalisation
- More tailored delivery of the software elements
- Would prefer all in-person

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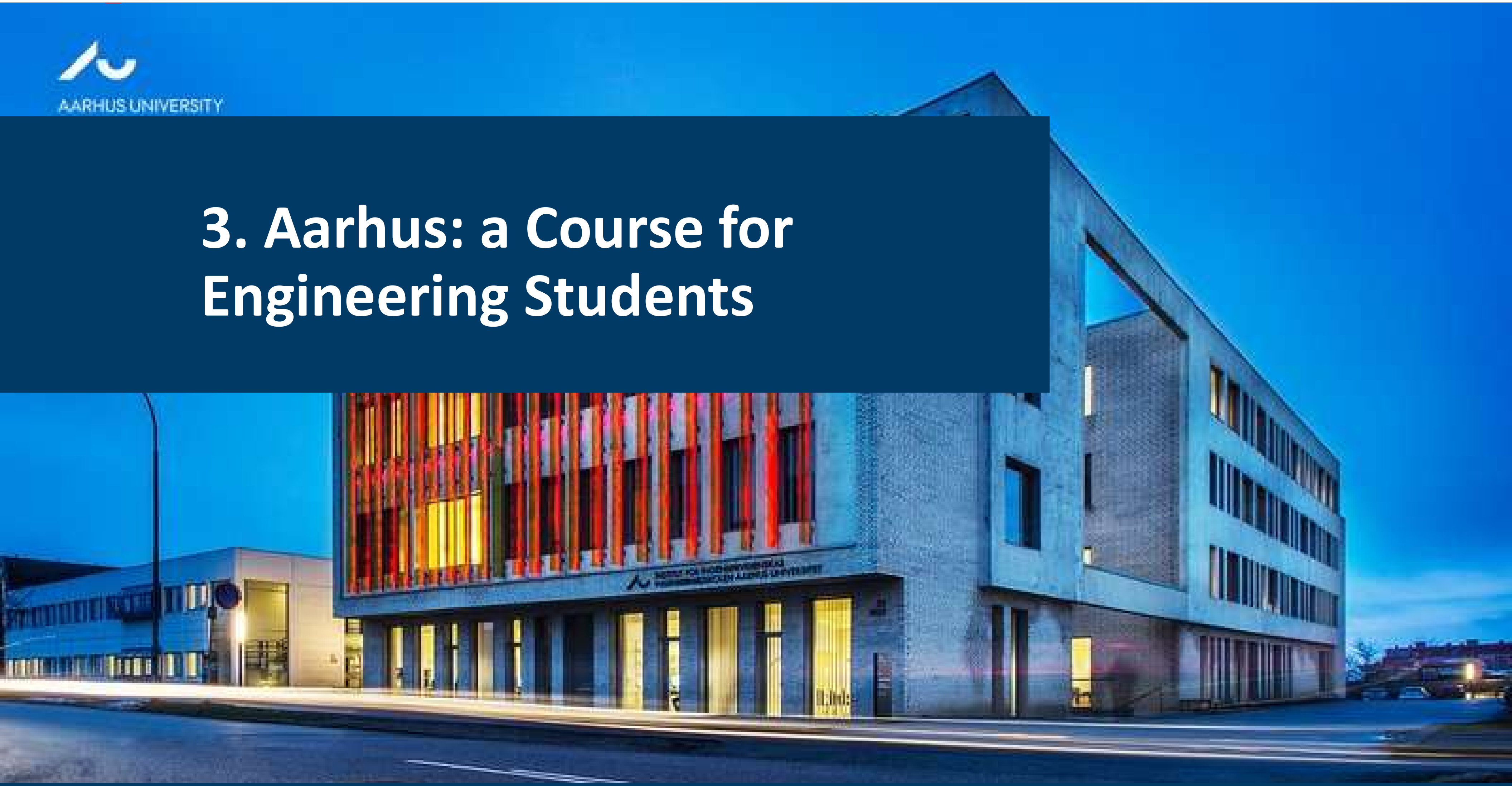
3. Aarhus: a Course for Engineering Students



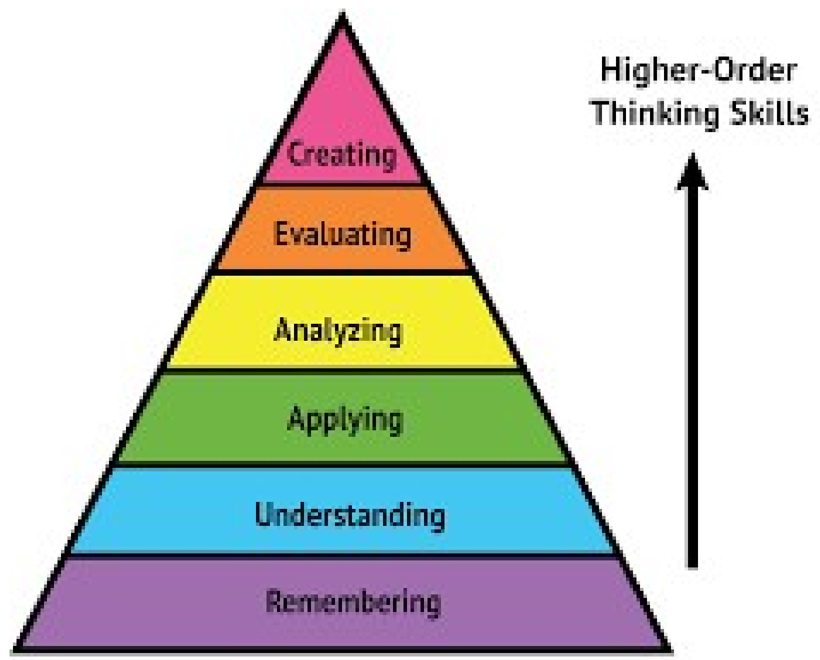
3. Aarhus: a Course for Engineering Students

- Masters level students from:
  - Electrical & Computer Engineering
  - Mechanical & Production Engineering
  - Civil & Architectural Engineering
- 10 ECTS
- Strong focus on underlying technology
- Prerequisitities intended to support this focus:
  - Linear algebra.
  - Additional mathematics courses (e.g., discrete math and calculus).
  - General knowledge about engineering (e.g., systems engineering).
  - Basic programming skills (in e.g., C, C++, or Python)
  - (Ideally) experience in modelling discrete or continuous systems.

3. Aarhus: objectives

On completion of this course, you will be able to:

- Identify and explain the necessary artefacts for a digital twin.
- Compare different models of a physical twin and their pros and cons.
- Evaluate calibration techniques for model fidelity.
- Assess various methods for sensing and data communication from physical twins.
- Discuss alternative digital twin services.
- Engineer a complete digital twin system.



3. Aarhus: content

Advanced Topics

13. Security & Privacy-related Issues
14. DT-Enabled reconfiguration of the PT
15. Future Directions & Challenges

Realising Digital Twins

11. Realising Digital Twins
12. Experiences from Case Studies (Incubator, Desktop Robotti, Flex-cell, Research Vessel)

Services for Digital Shadows and Digital Twins

8. Visualisation
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Models & Data

5. Modelling for Digital Twins
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Foundations

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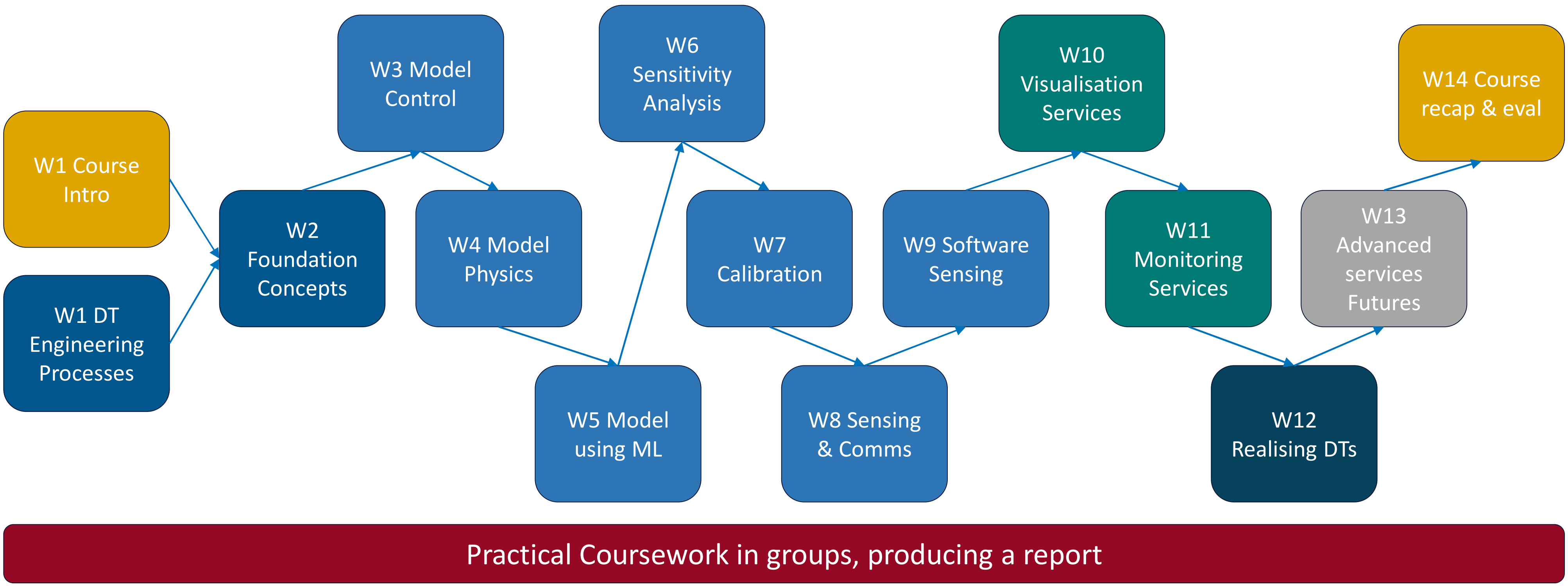
3. Foundation Concepts
4. (DT Engineering Processes)

3. Aarhus: content

1. Introduction to the course, digital twins and to the case studies
2. Overview of concepts for digital twins on the Incubator case study
3. Modelling control aspects of CPSs
4. Modelling physical aspects of CPSs
5. Modelling using machine learning and co-simulation for combining models
6. Sensitivity Analysis
7. Calibration of models
8. Sensing and communication data between twins
9. Software Sensing
10. Adding visualization in a digital twin
11. Adding monitoring capabilities to a digital twin
12. Realising Digital Twins using a DTaaS platform
13. Increasing the Autonomy of DT-Enabled Systems

All accessible in separate SVN for teachers. For access contact Claudio Gomes (claudio.gomes@ece.au.dk)

3. Aarhus: delivery

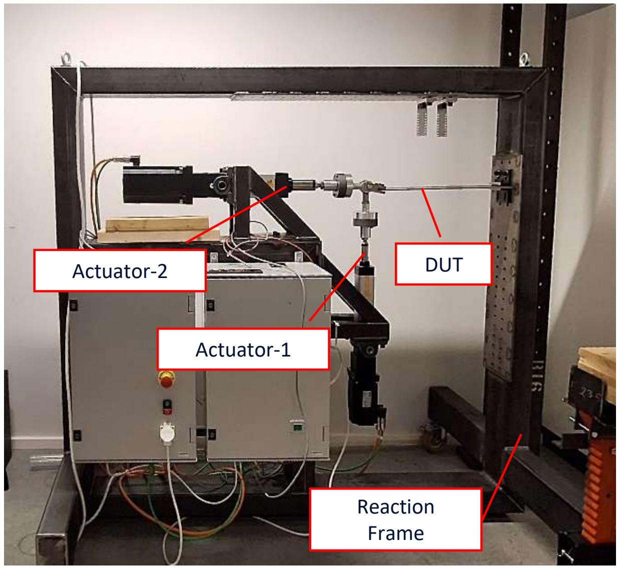


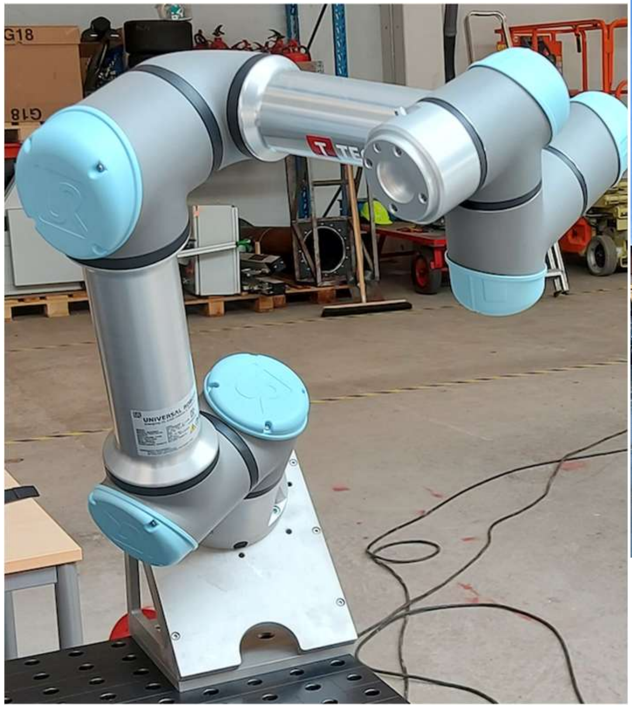
Delivered over 14 weeks. Assessment via report+oral exam.

3. Aarhus: delivery

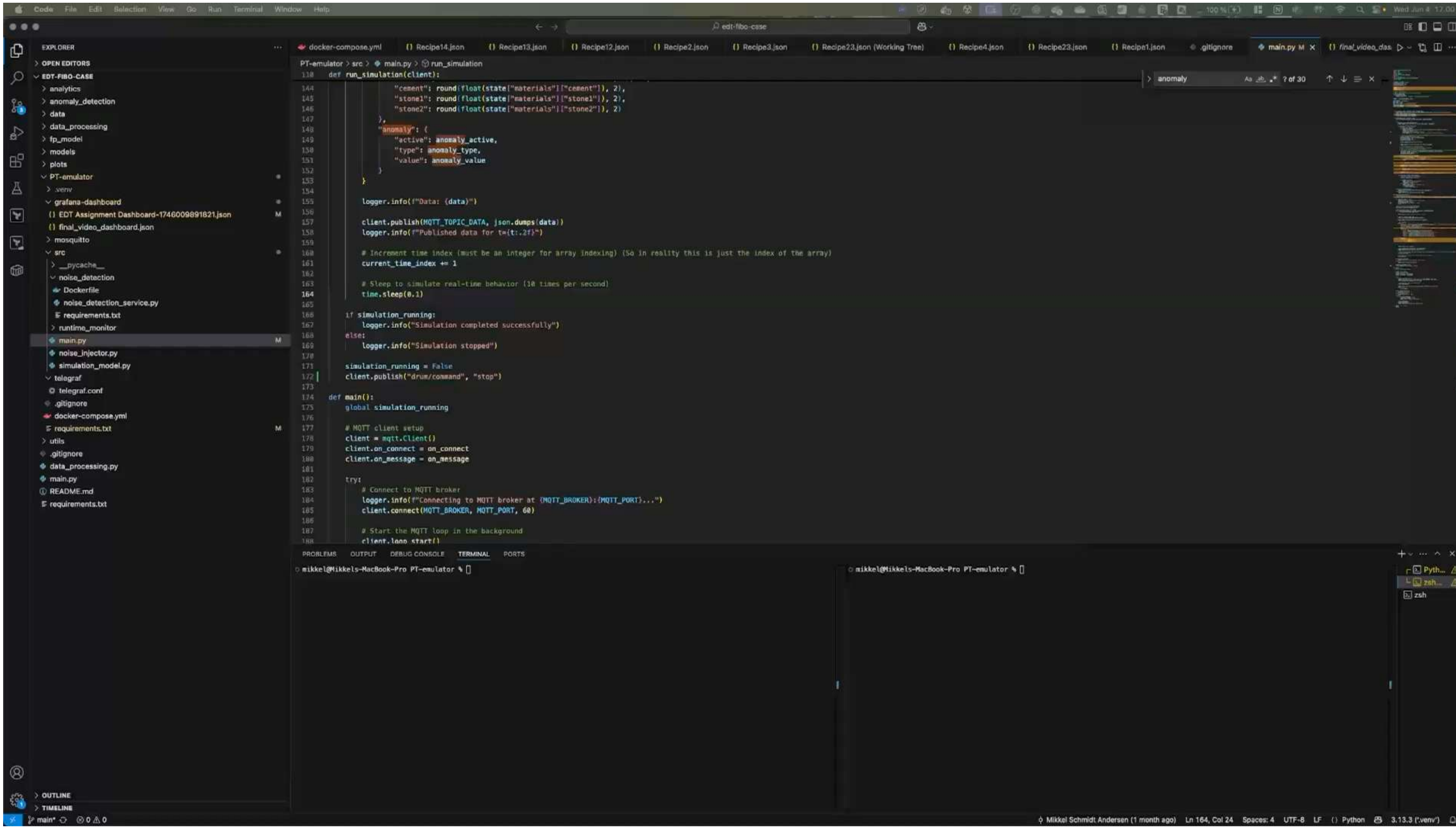
- Spring Semester 2025, 23 students completing
- Jupyter notebooks were prepared in advance for a range of topics that all the students would be expected to appreciate, including:
    - Git management,
    - Docker,
    - RabbitMQ,
    - InfluxDB.
- Optional exercises to those without prerequisites to get up to speed quickly.

3. Aarhus: coursework





Example Video from one group



3. Aarhus: coursework

Groups of 5-6 students. Hand-ins:

1. Planning DT Requirements, including:
   - A plan for the case study.
   - Understand the PT: what does it do? What are the physical processes occurring?–
   - What is the model modelling?
   - Example parameter estimation, fault detection, ML, and software sensing tasks. task (calibration)?
   - How to interact (set inputs/parameters, simulate, get outputs) with the model? How to run simulations? What are the allowed inputs?
2. Modelling the PT.
3. Present the model(s) created for the PT, and example applications of it.
4. Modelling the PT (Cont.) and First DT Service.
5. Visualization and DT Monitoring Services.
6. Final Report and Video Demonstration of DT Services.

Formative feedback for the intermediate hand-ins. Summative assessment of final report and video.

3. Aarhus: oral exam

Describe and compare the processes needed for engineering DTs.

Explain how to calibrate models in a DT context.

Reflect upon pros and cons with alternative ways of realising DTs.

Compare alternative techniques for producing models inside DTs.

Provide an overview of visualisation techniques using in DTs.

Reflect upon the challenges of introducing autonomy in DTs.

Provide an overview of techniques for sensing and communicating between twins.

Explain and compare monitoring capabilities inside DTs.

Describe and compare the processes needed for engineering DTs.

3. Aarhus: experience

- Very positive feedback overall
- Case studies and Jupyter notebook-based supporting material were successful
- First practical should be used to ensure prerequisites are satisfied.
- Group size was not ideal (target 4 per group)
- Case studies varied in maturity levels
- Software engineering skills became increasingly in-demand: care with group composition will be important in future
- Examinations have not yet taken place (tomorrow).

4. Observations and Discussion Points

4. Observations & Discussion Points

- Courses superficially very different, but
  - NU developed “upstream” skills & awareness – better DT demands!
  - AU developed “downstream” realisation knowledge and skills – better DTs!
- NU needs to develop confidence with DT architecture description , e.g. in a light SysML.
- AU needs to revisit group size (NU needs to address group working skills)
- Both need to cope better with the range of baselines either in systems thinking (NU) or computing/software engineering skills (AU).
- We strongly encourage other teachers to engage with the repository!

Thanks to: Justine Easten (Newcastle), and our pioneer students from Aarhus, Newcastle, Cranfield and Sheffield Universities. We gladly acknowledge the Grundfos Foundation's support to the AU Centre for Digital Twins, and EPSRC’s support for the WIRe CDT.

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Thank you!

Q&A