Scaffolding Project-based Learning (PjBL) at Scale with Model-based Design (MBD) & Systems Engineering (MBSE)

Francesco Ciriello*

Department of Engineering, King's College London, United Kingdom

Abstract: Here we share our reflections on delivering a new design course at King's College London (KCL) in our General Engineering program. The theme for the course was that of marine restoration. Student teams designed, built, and tested a remote-control ship that collected floating debris in a water tank. The course ran as a ten-week module with 200+ students and was an ambitious implementation of interdisciplinary project-based learning (PjBL) at scale. Our intent was to encourage learners to practice end-to-end model-based design workflows and connect theory across disciplines. Each theme was complemented by a lecture and an instructor-led workshop, which included dives into solid and fluid dynamics, control system design, mechatronics & embedded programming, and wireless communication systems. In the first phase, students focused on the design and testing of a ship simulation. Students started by developing a 3D simulation of ship dynamics, including 1D electromechanical models of DC motors and propeller drivetrains. They then designed an autonomous control system to manoeuvre the ship in simulation and practiced with closed-loop and logic-driven control implementations. Next, students practiced deploying algorithms on a microcontroller to test controllers using hardware-in-the-loop simulation. In the second phase, students built a physical ship in our makerspace and tested their control schemes. The project culminated in a final showcase, in which students competed for best performing ship collection systems in a water tank. We will share the strategies that we adopted for scaffolding learning on the project and reflect on lessons learnt in running it for the first time.

Keywords; Systems Engineering, Project-based Learning, Model-based design, Hardware, Mechatronics, Experiential Learning

**Correspondence to: Francesco Ciriello, Department of Engineering, King's College London, United Kingdom. E-mail: francesco.ciriello@kcl.ac.uk*

1. INTRODUCTION

1.1 KCL Engineering Design Modules draw from organised PjBL & CDIO Philosophies

The General Engineering program was re-launched at King's College London (KCL) in 2019 and has progressively ramped up intake to a cohort of about 200 students per year group. An outline of the modules taken by our students in first and second year is shown in Figure 1, which cover a range of *broadly-defined* (AHEP 2020) engineering themes. The program pedagogy has been considerably influenced by Fink's taxonomy of significant learning (Fink 2013). Learners are encouraged to acquire foundational knowledge, apply it to projects, recognise its relevance within multi-domain systems and embed metacognition, caring and understanding human dimension principles within their learning. The taxonomy has informed the delivery strategy for design modules, which are staged in four term-long, group projects.

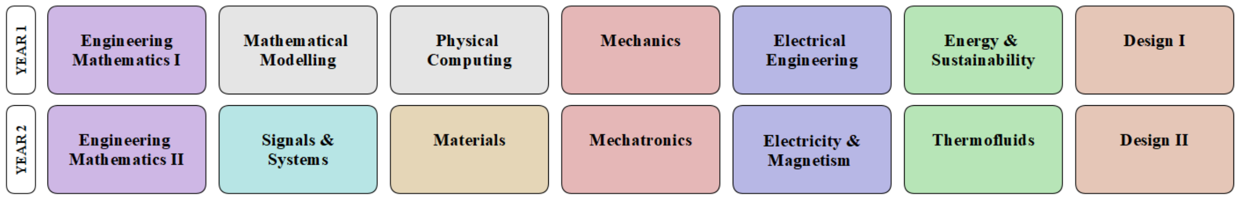

Figure 1: Modules at FHEQ Levels 4-5 at KCL General Engineering for 2019-2022.

The themes for the design modules are shown in Figure 2. The modules are staged according to established, professional design principles. Learners investigate diverse facets of product development, as we recognise that the ideal setting for professional skill development is one that resembles professional practice (Felder & Brent 2016) and that design cultures vary significantly within and across organisations (Julier 2013).

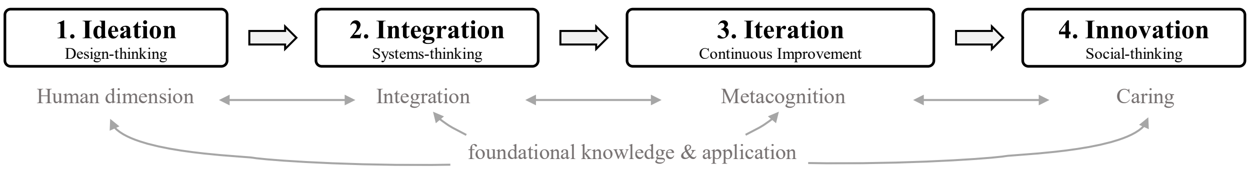

Figure 2: The four design principles that theme in the KCL design modules for years 1 and 2 as mapped to Fink's (2013) taxonomy of significant learning.

The design modules account for 25% of student work time in years 1 and 2. Their delivery is entirely *project-based* and combines principles of organised PjBL and CDIO methods (Crawley *et al.* 2011). As in established definitions of organised PjBL (Kolmos & De Graeff 2014), each project motivates learning and provides a rationale for the investigative and design activities conducted by learners.We diverge from traditional PjBL by carefully aligning both learning outcomes, *e.g.* simulation and hardware implementations, and process, *e.g.* design methods, with professional practice (Edstrom & Kolmos 2014). Learners work in teams of eight to nine members on a design, build and test activity that extends over ten weeks. Each project is scaffolded by skill development workshops, formative design reviews, expert design consultation sessions and supervised time in our makerspace. Teams demonstrate their final product at the end of term and submit a technical report for summative assessment.

The integration module in year 1, semester 2 is titled *Design: Making a Connection*. It encourages learners to apply systems-thinking skills to connect foundational knowledge acquired throughout the first-year program within the development of an integrated engineering system. In this paper, we reflect on the delivery of this module and its effectiveness at supporting learning on the systems integration theme.

1.2 Background on Design: Making a Connection & its Course Structure

In the *Design: Making a Connection* module, learners design, build and test a remote-controlled (RC) ship to manoeuvre within a water tank and collect floating debris (see Figure 3). Learners are encouraged to reflect on their design in the context of environmental restoration and the cleaning up of floating waste that accumulates in rivers and oceanic gyres (NOAA 2021). Groups and the project manager position were allocated randomly. The course structure is shown in Figure 4. To promote student agency, learners choose their role in the first week of term and are assigned role-specific requirements (see §2.1 for role descriptions) towards a well-defined, open-ended problem. Role names were chosen with established industrial positions to raise professional awareness. The first five weeks of term are organised around technical domains. By the end of this period, students submit a simulation-based assessment (see §2.2). In the second stage of the course, students build ship prototypes and are supported by the means of two formative design reviews (group-based) and two consultation sessions (role-based), in which eight members of academic staff review their progress. Students demonstrate their design at the end of term and submit a report and video presentation for summative assessment.

Figure 3: Four ship builds developed by KCL students in the 2022 run of the course.

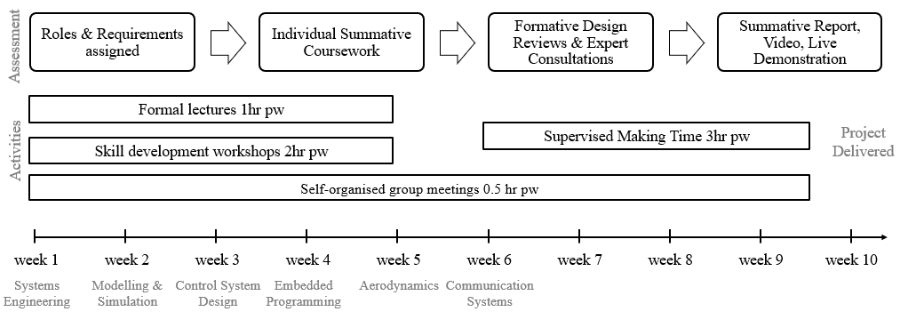

Figure 4: Design course structure over the ten weeks of term with session time given in hours per week, denoted hr pw.

1.3 Reflections on using Model-based design & Systems Engineering for the course

Herein, we investigate the explicit use of model-based design (MBD) and model-based systems engineering (MBSE) principles in the development of the *Design: Making a Connection* module. The adoption of MBD and MBSE principles provided a powerful framework to address well-known challenges in PjBL delivery for large cohorts. These challenges include that of removing limited access to physical resources for each student, overcoming the lack of physical intuition of system behaviour in early stage HE learners and the tension between the open-endedness of design challenges and the scaffolding that can be provided by the instructor. In §2, we comment on the application of MBD to PjBL. We provide a direct mapping between MBD workflow steps with student activities and assessment. In §3, we evaluate student performance with respect to module learning objectives and AHEP requirements, and present lessons learnt from delivery.

2. MODEL-BASED DEVELOPMENT AS A SCAFFOLDING FRAMEWORK

2.1 Model-based development frameworks for PjBL

The model-based design process entails the systematic use of models and simulation throughout the development process of an engineered product (Prabhu et al. 2007, MathWorks 2021). Model-based design is closely intertwined with the science of model-based systems engineering, which involves the design and quality control processes that use model-based development to specify and validate requirements (INCOSE 2022). These development processes are established practices in engineering firms (Wakitani *et al.* 2019), dominate the design culture in safety-critical industries and promote a culture of quality management within professional practice (Hart 2015). Figure 5 demonstrates typical schematics that are used to outline stages within these frameworks.

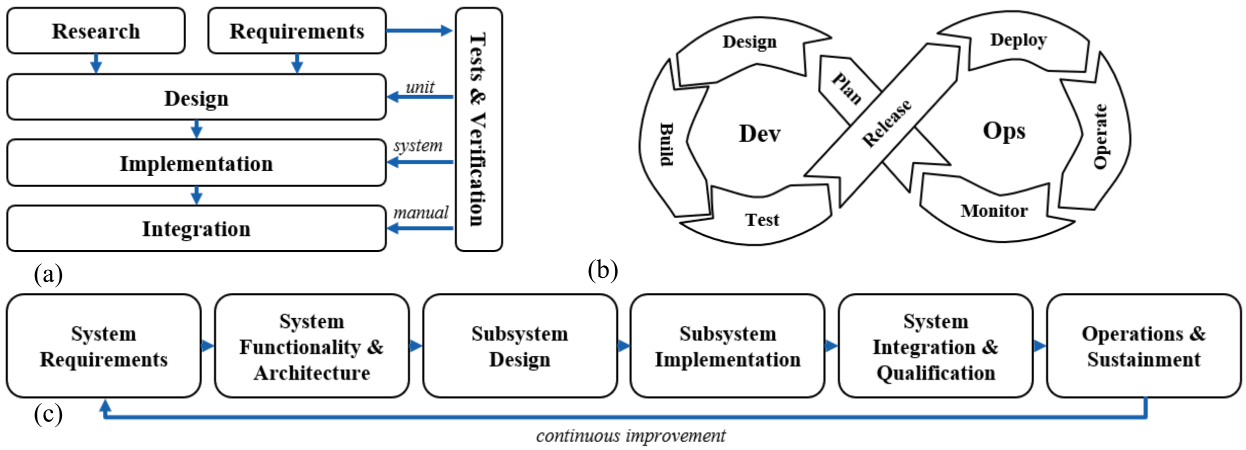

Figure 5: Established model-based design workflow diagrams, (a) cascade, (b) DevOps Infinity and (c) V-Shaped, adapted from MathWorks (2021).

The structured workflow of MBD guides engineering practitioners through the development of product lifecycles and ensures appropriate verification through systematic testing. Here we draw analogies to how it can analogously be applied to guide learners in a PjBL design project.

- **Requirements**: Learners can be asked to deduce requirements at the beginning of the course from a generic problem description, or they are handed requirements from an instructor. An example set of requirements for design sub-teams is shown in Table 1.
- **Research**: Learners are encouraged to extend the list of requirements after reviewing established designs, user experiences, previous product lifecycles, *e.g.* prototypes built by other students in previous runs, and further sources of relevant information.
- **Tests**: Learners deduce tests from requirements at the beginning of the project. They construct a 1-to-1 mapping between requirements and tests, as a live activity or formative assessment submission, and plan when to verify tests at each stage of development.
- **Specification**: System functionality and architecture is deduced from requirements. Learners are asked to draw a system architecture diagram at the beginning of the project and map the flow of information, *e.g.* controller commands and physical quantities such as current or torque, between the components of the system.
- **Subsystem design:** Learners model components they will build or use. Models are used to garner intuition on appropriate component sizing, response, and performance. Component models are deduced from lab experiments or from analytical models provided in lectures or workshops. Learners are asked to integrate component models into the system architecture to investigate overall system response. This exercise makes for an effective mid-term summative assessment in which students submit a system simulation and controller design.
- **Implementation**: Learners manufacture and assemble components and deploy algorithms to hardware. *Unit* and *component-based testing* is used to verify performance.
- **Integration**: Learners integrate hardware components in system prototypes. *System testing* is used to verify performance. Back-stepping and iteration should be encouraged at this stage based on feedback from testing, formative design reviews and role-based consultation sessions.
- **Operations & Sustainment**: Learners operate the system and analyse its performance in a technical report. *Manual testing* is used for final verification of system performance. This

activity can form the final demonstration for summative assessment; however, students should be encouraged to perform testing before assessment.

Team	Requirements
Systems & Quality Control	• Specify system architecture • Report on tests to be verified by design teams • Demonstrate project at end of term to collect 9 floating objects in under 2 min
Ship Design & Build	• Ensure ship flotation & stability • Design & manufacture ship hull • Design & manufacture housing for on-board equipment and propulsion system • Waterproof on-board equipment
Mechanical Systems	• Design motor to propeller mechanism for adequate propulsion • Design adequate floating waste, collection system • Design adequate steering system, *e.g.* rudder or other control surfaces • Design calibration system • Deploy control algorithm to microcontroller
Control & Communication	• Design remote controller and operator interface • Deploy remote control communication, including server-client setup using Wi-Fi or BLE • Design steering controller to ensure adequate ship manoeuvrability • Implement low-level controllers for DC motor(s) • Manage sample times and latency for control and communication

Table 1: A set of requirements for the RC ship design project handed to students in week 1.

2.2 Model-based design readiness in PjBL

Admittedly, effective model-based design development requires considerable technical experience with regards to modelling and the integration of experimental campaigns in a simulation. Instructors should assess the degree of *MBD-readiness* of their students and provide appropriate scaffolding activities to support the project. Likewise, it is also important to train supporting teaching assistants (TAs) as they will require knowledge of software and hardware interfacing. To better support this skill gap, we employ TAs that have already taken the course. The diagram illustrated in Figure 6 can guide instructors on how to assess the maturity of a learner in the context of MBD. It is also recommended to allow students to use this matrix tool for self-assessment.

Examples of scaffolding activities that were used in the design project include providing governing equations and model parameters for component models, demonstrating appropriate control strategies, providing simulation templates to integrate these components into a system model and running workshops on how to deploy algorithms to embedded devices. Advanced modelling of physical processes, which are notoriously troublesome to implement owing to their weak numerical stability, such as rotational drag and spatial contact models, were deemed to be out of scope of the foundational knowledge expected from learners and were provided by the instructor.

2.3 Models & Simulation for scaffolding PjBL

Much of the value of model-based design arises from the digitalization of the physical product. Simulations can be built to analyse system response much faster than real-time. This enables the more rapid exploration of a design space. Students used a template simulation to determine appropriate sizing of components such as the mass, moment of inertia, location of the propellers, and size and location of the control surfaces. The use of customised Simulink block masks, see Figure 8c, was an effective means to support *parameter exploration*.

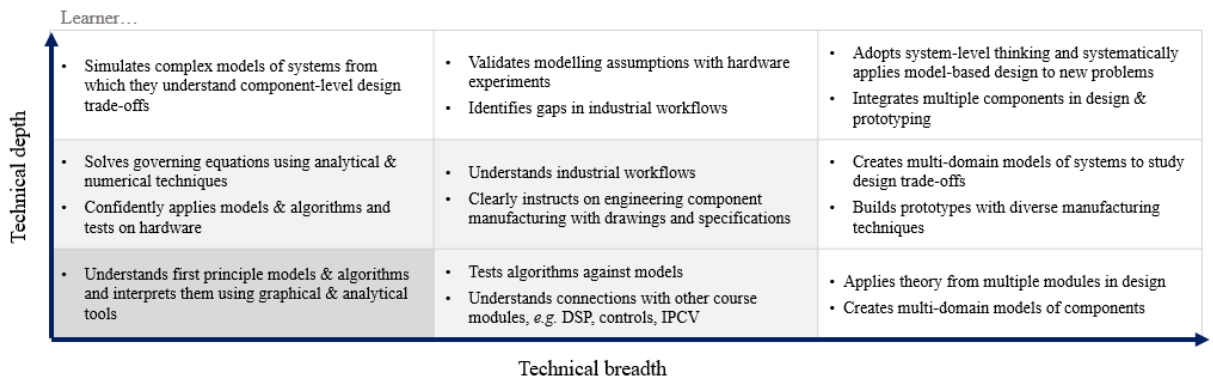

Figure 6: A diagram to assess the maturity with which a learner adopts MBD principles. Learners should progressively push their technical mastery towards the upper right-hand quadrant.

Simulation and visualisation techniques can support intuition on a system's response, see Figure 7a-b. We observed that learners had little trouble understanding the mechanisms by which a ship steers by propulsion and actuating control surfaces.

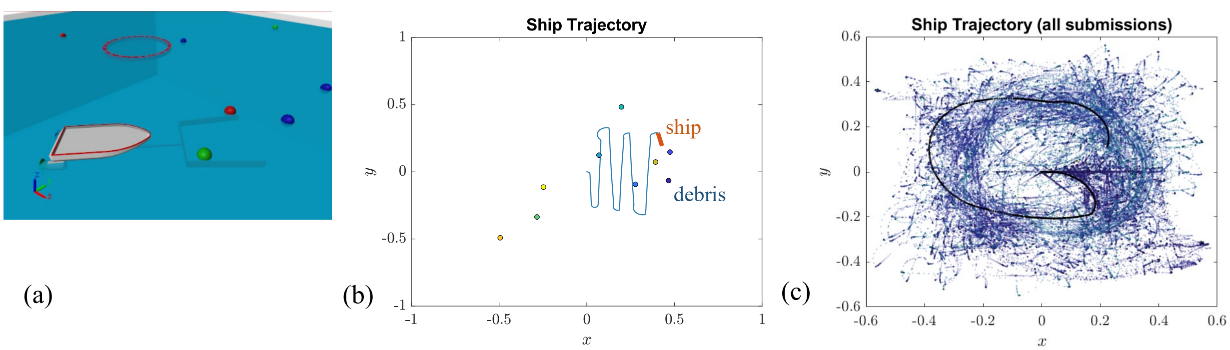

Figure 7: (a) Multibody simulation visualization and (b) 2D visualization of ship and debris. (c) Ship trajectories from all individual simulation submissions.

Simulation reveals unknown, system behaviour from known, component behaviour. Students in the design project were faced with open-ended questions regarding ship design, for example: (i) *should the ship steer with two-propellers or with one propeller and a rudder?* and *(ii) do the motors deliver enough thrust to manoeuvre the ship?* The scale of integration required to answer these questions requires model-based practice. Model variant management features in Simulink were a convenient tool for *design comparison.* The reference model architecture is shown in Figure 8a-b.

Simulation enables automated assessment at scale. The individual coursework was initialised using scenario randomisation to ensure the robustness of controller design and assessed using automated testing procedures. The resulting trajectories of all student submissions is shown in Figure 7c demonstrate that students submit unique solutions, with some convergence toward optimality.

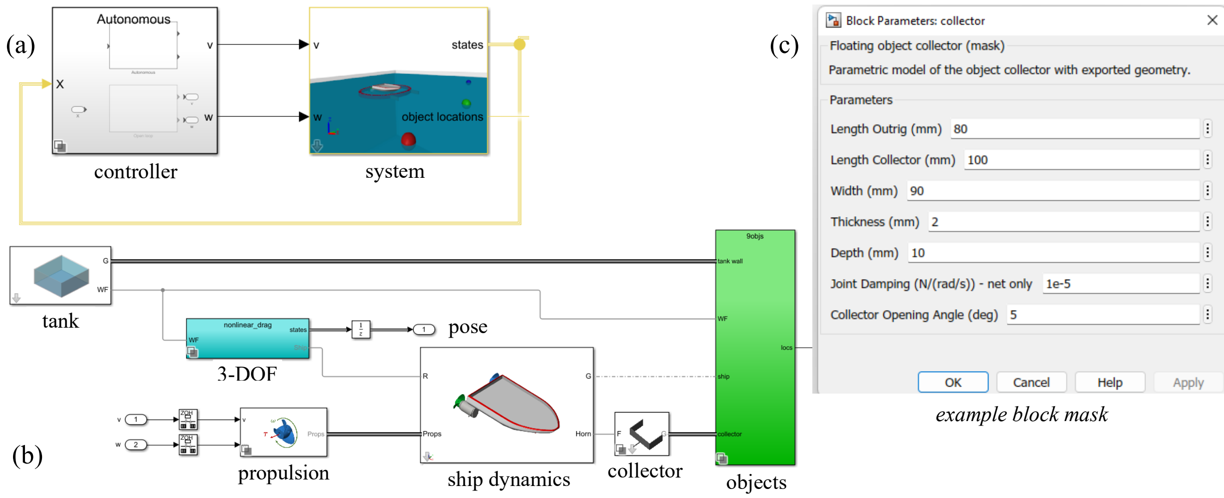

Figure 8: (a) System-level Simulink model of the ship, (b) component models of the ship, collector, and environment (c) an example block mask for the ship collector.

3. EVALUATION & LESSONS LEARNT

The design course was well received by students. Mean student overall satisfaction was of 4.4±0.6 out of 5, which is 0.4 points higher from the average module score in year 1. Figure 9a shows the results of the end-of-module survey. Learners responded that the module was both well-structured, and sufficiently open-ended for them to explore and acquire useful skills. Out of 24 groups, 96% delivered a working final project that satisfied minimum ship performance criteria, 75% delivered a ship that could collect all objects in the tank under 2 min and 58% delivered a ship that could collect objects under 1 min. The final reports were assessed via a comprehensive rubric that mapped outcomes to AHEP4 learning areas and included a reflective section in which students presented a feedforward analysis on their team performance. Figure 9b shows the normalised marks in each area by role. Teams performed well in the engineering design category and underperformed in the analysis category. The latter is possibly due to lack of resources and ability to measure performance to appropriately test the final system. Mechanical design teams performed consistently higher than control design teams, primarily due to the lack of analysis in this domain. Students reported several cases of freeloading, possibly indicating that the group size was too large, and teams with two or more absent, incapacitated, or non-contributing members were severely impacted due to a lack of resource and the scale of the project.

4. CONCLUSION

Learners on the integration design module performed well in project delivery, attainment of learning outcomes and satisfaction with the module. The course design benefitted from the application of model-based design and systems engineering principles and we observed several benefits for improving student design practice and easing the need for physical resources and time spent on assessment for instructors. We provide advice on how model-based design principles were implemented in an extended PjBL setting through this case study and propose a generalised framework for the application of these principles to medium-to-large PjBL courses. Simulation files for the ship simulation are available for download for other instructors to inspect and re-use from https://github.com/FrancescoCiriello/Ship-Design-Project.

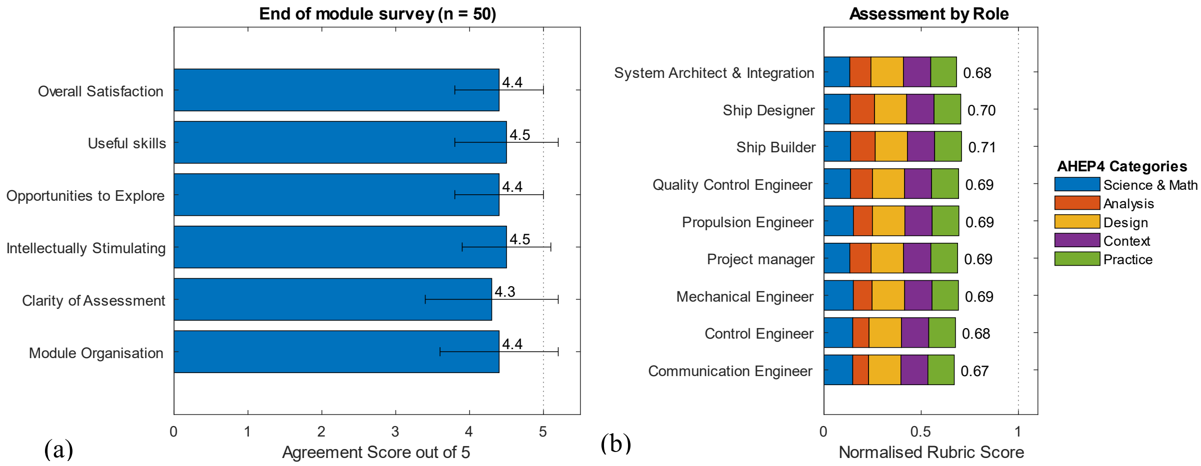

Figure 9: (a) End of module survey results, (b) mean individual grade on report grouped by individual roles and assessed by rubric measuring completion of learning outcomes.

6. REFERENCES

AHEP, 2020. The Accreditation of Higher Education Programmes. 4th ed. Retrieved from www.engc.org.uk/media/3464/ahep-fourth-edition.pdf

Crawley, E. F., J. Malmqvist, W. A. Lucas, D. R. Brodeur. 2011. *The CDIO Syllabus v2.0. An Updated Statement of Goals for Engineering Education.* Proceedings of the 7th international CDIO conference, Technical University of Denmark, Copenhagen, June 20–23.

Edström, K. & Kolmos, A. (2014): *PBL and CDIO: complementary models for engineering education development*, European Journal of Engineering Education.

Felder, R.M. & Brent, R. 2016. *Teaching and Learning in STEM – A Practical Guide*. 1st ed. San Francisco, CA: Jossey-Bass.

Fink, L. D. 2013. *Creating Significant Learning Experiences: An Integrated Approach to Designing College Courses*. San Francisco: Jossey-Bass.

Hart, L. E. 2015. *Introduction To Model-Based System Engineering (MBSE) and SysML.* Delaware Valley INCOSE Chapter Meeting.

INCOSE, 2022. *INCOSE Systems Engineering Vision 2035*. Technical Report. Retrieved from www.incose.org/docs/default-source/se-vision/incose-se-vision-2035.pdf

Julier, G., 2013. *The Culture of Design*. United Kingdom: SAGE Publications.

Kolmos, A., & De Graaff, E., 2014. Problem-Based and Project-Based Learning in Engineering Education: Merging Models. In A. Johri & B. Olds (Eds.), Cambridge Handbook of Engineering Education Research, 141-160. Cambridge: Cambridge University Press.

MathWorks, 2021. *How Engineering Teams adopt Model-based Design*. Technical report. Retrieved from: uk.mathworks.com/content/dam/mathworks/white-paper/how-engineering-teams-adopt-model-based-design.pdf

NOAA, 2021. *Ocean Literacy: The Essential Principles and Fundamental Concepts of Ocean Sciences for Learners of All Ages.* Technical Report. Retrieved from www.aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/education/literacy/OceanLiteracy_ENG_V3.1_2021.pdf

Prabhu, S., Callanan, L., Chambers, Z. Herniter, M. 2007 *Development of Model-Based Design Curriculum.* American Society for Engineering Education, 12 (536), 1-24.

Wakitani, S., Yamamoto, T., Morishige, C., Adachi, T., Harada, Y. & Muraoka, T. 2019. *Practice and Evaluation of Model Based Development (MBD) Education*, IFAC-PapersOnLine, Volume 52, Issue 9, 206-211.