FROM FRUSTRATION TO SUCCESS: A CASE-STUDY IN ADVANCED DESIGN-BUILD EXPERIENCES

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ABSTRACT

A 4th semester CDIO project course has been designed and implemented by the authors as part of the general development of a CDIO-based curriculum for the diploma IT education at the Technical University of Denmark. The course provides a design-build experience at an advanced level that concludes the mandatory part of the education.

Among key aims of the design were to cover all four components of the CDIO model at comparable levels, and to provide students with an exciting product development task inspiring creativity, originality and independent work. Among key learning objectives were the ability to successfully apply previously acquired knowledge and skills in novel contexts, and to independently research and acquire new knowledge.

To achieve the design aims, a CDIO project was designed in which the students had to conceive, design, and implement a robotic multi-agent system “from scratch” integrating knowledge and skills from most of the courses of the mandatory part of the education. The accompanying project description was very brief and open-ended, ensuring that the conceive phase became a significant part of the design-build experience.

Among key features of the course were an organization of the students in relatively large groups (5-7), and the inclusion of an end-to-end management process adapted from common methods in industry, including regular steering committee meetings and accompanying status reports. The course concluded with a real-time competition between the robotic systems developed by the different groups, ensuring that the operate phase also became a significant part of the design-build experience.

In the first part of the course many students went through a phase of frustration as they were not used to such open problem statements and such high demands on their independence. However, through effective project management all groups produced working solutions in the end, turning frustration into a success experience and strong sense of accomplishment. Along the road from frustration to success all the required learning objectives were met, in particular the students became much more independent and much better at finding and integrating methods and solutions from different sources.

The result metrics from the first conducted implementation of the course were above average for non-CDIO type courses at the university, both in terms of student learning, completion rate and satisfaction. All students passed the course, and it received the best student evaluation among all courses in the diploma IT degree program at the university. Time invested by students as well as by faculty and material resources provided was within the norm.

KEYWORDS

Design-build experiences, project-based learning, general guidelines for CDIO-course design; resource-efficient and reusable concept; fit-tailored project management; boosting the students ability for independent work.

INTRODUCTION

As stated in the abstract, this paper presents a case study of a CDIO course. Many questions, such as e.g.: “What is the optimum design of a CDIO course, and how does this compare in effectiveness and efficiency to other course models?”, are highly relevant but difficult to answer with scientific rigour. In addition to the practical difficulties of implementing double-blind experiments and the ethical issues in experimenting on students, data from a single institution only, could never be provably unbiased.

This paper does *not* attempt to answer these “bigger” questions. We present only conclusions justifiable by the data at hand. However, the Concept, Design considerations, Implementation method and Operational results of the course are reported, in somewhat more detail than absolutely required to justify the conclusions presented. This is done with two aims in mind:

1. To serve as possible inspiration for others, faced with the need to implement CDIO courses, while the scientifically proven optimal “recipe” for doing so is still not fully known.
2. In the hope that the evidence presented, in time and in combination with data from other courses and institutions, may eventually allow Meta-studies, which could indeed provide proven answers to more fundamental questions.

For the same reasons, we occasionally allow ourselves to present observations of a qualitative nature.

The paper is structured according to our slightly modified version of CDIO: Concept, Design, Implement and Operate.

CONCEPT

Since September 2008, seven of the B.Eng. study programmes at the Technical University of Denmark (DTU) have been based on the CDIO concept [1], and for most study programmes this change called for significant revisions of the study programmes. The CDIO standards form the basis for the new study plans, and it was decided to introduce cross-disciplinary projects on each of the first 4 semesters. For the B.Eng. in IT study these 4 cross-disciplinary projects replaced 11 smaller and course-specific projects in the old study plan.

In the IT study, each semester consists of a lecture period (13 weeks), an exam period (2 weeks) and a lab period (3 weeks). The 4 cross-disciplinary projects cover all three periods of a single semester. They are all 10 ECTS, meaning they roughly correspond to a student workload of 250 hours in total. For further details on the 4 projects and their interrelationship and relationship to the overall study plan, consult [2].

This paper concerns the design and implementation of the 4th semester cross-disciplinary project. According to the action plan for the introduction of the CDIO-based IT-education at DTU, the 4th semester project should be an advanced design-build project, and at the same time a full-blown and stand-alone CDIO-project covering all 4 phases (conceive, design, implement and operate). The course represents the conclusion of the first 4 semesters, and the conclusion of the compulsory part of the study. A natural goal of the course was thus to provide a cross-disciplinary link between all the courses of the mandatory part of the education. The course had to focus on the CDIO-process and the cross-disciplinarity, but not necessarily introduce any new technical curriculum.

Classical engineering courses usually focus on the design and implement phases, and even CDIO courses often tend to have primary focus in these two phases, and only a rather minor degree of conceiving and operating. In the present CDIO project course it was the ambition to include all four main components of the CDIO model at comparable levels. Another key aim was to provide the students with a challenging, ambitious, and exciting product development task inspiring creativity, originality and independent work.

Student response

DTU conducts an evaluation of all its courses in the last week of teaching in every term. The evaluation consists of a number of predefined questions about the course and the lecturers. It is also possible to submit individual free-text comments. The predefined questions have to be answered on a five-step scale, ranging from "very good" to "very bad" or from "strongly agree" to "strongly disagree" as relevant. Student responses are collected before students receive their grades. This evaluation mechanism would apply to the course regardless of any other considerations.

DESIGN

Aims of the design

To inspire originality and independent work we wanted to make the problem specification very brief and open-ended. To our experience, this is the best way to make the students motivated and work hard, since it encourages them to come up with their own unique product design, which makes the project more personal to them, and gives them a stronger sense of ownership.

In terms of learning outcomes, the primary goal of the project was not to provide the students with new technical disciplinary knowledge and skills, but rather to achieve outcomes difficult or impossible in a standard lecture-based course:

- Abilities to successfully apply previously acquired knowledge and skills in novel contexts.
- Independently research and acquire new knowledge (e.g. through literature search).
- Achieve and demonstrate project management skills.
- Achieve personal skills in presenting and representing both project and deliverables.

Regarding the first item, a more specific aim was to design a project that would require the students to combine and integrate curriculum elements from most of the other courses in the mandatory part of the education. Applying knowledge outside the context in which it was originally achieved is a competence of central importance to the working engineer. Of particular importance is the ability to assess which parts of the previously obtained knowledge is relevant to a given problem. Classical engineering courses usually do not train such skills, as the relevant material is most often known and given (e.g. certain chapters of a certain textbook). Since the exercises and problems considered in such courses often explore the curriculum in relatively isolated and "protected" environments, it can be very hard for the students to apply the knowledge obtained, when it suddenly appears in a completely different context, and has to be integrated with knowledge and skills from other courses and sources. Many students will not even see the relevance of the obtained knowledge, when it appears in a novel and less clear-cut context. A design aim of the present course was to train the students' skills in:

- Applying their basic technical knowledge in novel contexts.
- Assessing what knowledge is relevant in a given context.
- Successfully combining and integrating knowledge from different sources, areas, or courses.

Designing a course that achieves all the aims mentioned above unfortunately often tends to be very expensive in terms of teacher resources - and usually also student resources. Our aim was to design a course that does not suffer from this problem, but is efficient in terms of the overall ratio between the obtained learning outcomes and the teacher/student resources invested. Finally, we aimed at achieving a reusable course model.

Project Management

Given the overall course concept and design considerations above, each group of students would be undertaking a project. In terms of the current understanding of projects and project management (see e.g. [5], compatible with ISO standard 21500 expected 2012), these projects would inherently face a number of significant risks. To wit:

- The project must produce a fully working real-time unsupervised sensor-control system. This must be considered a non-trivial project.
- The project must be executed in a relatively short calendar time and has a predefined hard deadline (the competition).
- The project has a (moderately hard) upper limit of manpower- and other resources. This limit is not too much above the (unknowable) absolute minimum required, to produce the desired result. The available manpower may vary between groups, which may consist of 5-7 students. Smaller groups should not a priori be disadvantaged, compared to larger groups.
- The minimum workable solution requires use of technologies and components, of which none of the group members are guaranteed to have prior specific experience or even knowledge.
- While some or all group members might have prior experience working with or in comparable projects, in the worst case none of the group members would ever have undertaken or participated in projects of comparable complexity and challenges.
- While some or all group members might know each other in advance, in the worst case none of the group members would ever have worked together before, or be known to each other in advance.

- While some or all group members might have some knowledge of and even experience with project planning and management, in the worst case all group members would be entirely without practical project planning and -management skills.

Under these circumstances, current best practice (both under e.g. [5] and [6]), would be not to undertake the project.

The only reasonable expectation would be, that a significant percentage (no applicable standard model for quantification of this percentage exists) of the projects would fail entirely, to produce an acceptable result on the specified date.

To precede the actual execution of the project with a general training in current project management best practice, as part of the course, would obviously be unfeasible. Most (introductory) texts on the subject are well in excess of 500 pages (and i.e. PMP certification requires at least a B-degree and 4500 hours documented prior project management experience, to even begin the certification process).

To attempt to improve the expected (though unquantified) ratio of successful projects, it was decided to design and apply a course specific lightweight project management model. The design aims for this model were:

- Must not require any previous knowledge of, or experience with, project management.
- Must have a very steep learning curve. Students should be able to successfully apply the model on their own, after only a few hours study/training.
- Should be sequentially applicable, i.e. students should be able to apply the first parts of the model before having learned the entire model.
- Must not undermine the open-endedness of the course, by unduly restricting the freedom of the students to define their own solution or how they work to implement it.
- Should improve students' chances of successful project completion and effective/efficient use of their time, as much as possible under the circumstances.
- Must provide students with realistic perspective on their learning, i.e. even if students succeed in the course, they should not be led to assume they are now fully qualified in general project management. However, at the same time, students should not be robbed of their sense of - very real - achievement.

Learning objectives

The above design considerations led to a course description with the following learning objectives. A student who has met the objectives of the course will be able to:

- independently use his/her professional competences to solve practical engineering problems
- work with loosely formulated problems
- explain the main concepts of at least one of the project management methods currently used by the industry
- combine the knowledge and competence from different areas in a larger cross-disciplinary project
- work efficiently in larger groups
- independently explore the relevant literature and software involved in solving a loosely formulated problem
- integrate different techniques and technologies into a larger coherent system
- divide a larger project into minor parts with the relevant partial objectives

- present the status of an ongoing project in both written and oral form
- present a final product in both written and oral form.

The specific learning objectives above are mapped to the local standard DTU Syllabus through a process of staff review and -meetings described in [3]. The DTU Syllabus is a version of the CDIO Syllabus [4], adapted to account for e.g. requirements of national regulatory authorities.

We note here, that validation of the scope of the learning objectives, both in terms of topics covered and required end result for each student in each topic, is through a faculty review process, not a judgment made only by faculty members responsible for the course. The measure of ECTS points (10) awarded for the course is thus the best comparison measure of the total learning objective scope available. It is further noted, that this measure is only directly comparable to courses reviewed by the same process and by the same body of reviewers.

It would be interesting to be able to compare "Bloom vectors" for courses among e.g. institutions and to e.g. compute overall learning scope as "length" of such vectors. But, in the absence of shared, highly standardized and detailed syllabus definitions and outcome measurement methods, such an apparently precise learning outcome indicator would merely be misleading.

Project description

To meet the design aims and learning objectives, we decided to construct a project in which the students had to conceive, design, and implement a robotic multi-agent system "from scratch" integrating physical robot design, wireless communication, communication protocols, signal processing, image analysis, real-time systems engineering, software engineering, motion planning and path finding. The project description was very brief:

"You are given the necessary parts to design and build two Lego NXT robots, a web camera, building blocks for constructing mazes and a number of boxes. Use these components to build a robotic system that can remove arbitrarily placed boxes from within arbitrarily constructed mazes."

Except for a few geometrical constraints on the mazes this was the entire project description, and it constituted the only hard requirement the students had to meet. Other key features of the course were:

- Organization of the students in relatively large groups (5-7) encouraged to cooperate/compete at the same time.
- Inclusion of an end-to-end management process adapted from common methods in industry, including regular steering committee meetings and accompanying status reports.
- Lectures in project management supported by our own hands-on material.
- No lectures in problem-domain topics, and no specific solution methods, techniques or technologies provided.
- Final competition where the systems built by the different groups competed against each other in real-time.

The very brief and open problem description ensured that the conceive phase became a significant part of the design-build experience. The competition at the end ensured that the same was the case for the operate phase. The fact that no specific solution methods were provided forced the students to do independent research in - and assessment of - different

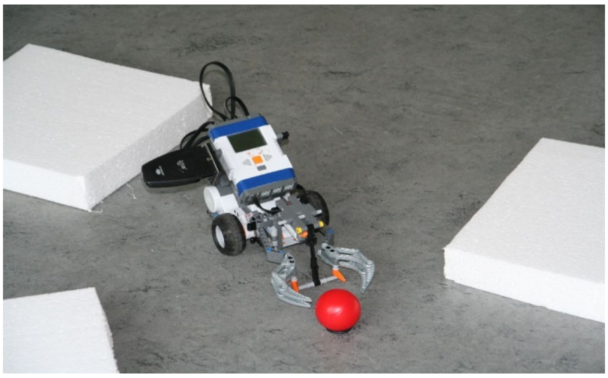

Figure 1. Simple remote-controlled robot prototype used to demonstrate the goal of the project to the students.

Figure 2. Early experimentation by a group of students.

possible technologies and methods; both among those methods previously learned during their studies and among new methods discovered through independent literature studies. The students were free to choose whichever technologies and methods they preferred. Throughout the course, they were encouraged to independently search for relevant literature, software, etc.

Student response

It was not a design goal of the course, to create any particular student response profile. However, the issue was considered, and the immediate expectation was to find a (possibly skewed) bimodal distribution (i.e. one would either love or hate the course), possibly covariant with the grade received.

IMPLEMENTATION

Project Management

The Project management model was implemented as a process, governed by a Steering Committee (SC):

- Notes on project management were developed, tailored specifically to the course and the project management process for it. The notes were kept very brief (24 A4 pages incl. Index, references, etc.) and were made available to students at the start of the course.
- SC meeting dates and detailed agendas (4 A4 pages in total) were also written and made available to students from the outset of the course.
- 3 lectures (1 hour each incl. Q&A) were given, at the beginning, middle and towards the end of the 13-week period.
- 3 SC reports (4 A4 pages) and 4 status reports (effectively 2-4 A4 pages) were required from each group. These were timed to follow after lectures and to precede SC meetings.
- 3 SC meetings (2 of 10 minutes each, the last of 30 minutes) were held with each group. Each group was required to present their status and plans, faculty members asked questions and commented.
- Groups had the option to resubmit SC reports, if changes were agreed at SC meetings.

- Groups had the option to raise project management questions at weekly general Q&A sessions.
- Groups could request individual coaching meetings with some or all faculty SC members if needed.

The SC for each project consisted of all group members and the course faculty members. The group of faculty members were chosen so as to ensure, that at least one faculty member had extensive practical experience with project management and SC management.

Course structure and course material

As previously mentioned, the course covered all three periods of a semester: the lecture period (13 weeks), an exam period (2 weeks) and a lab period (3 weeks) - in that order. Every week of the lecture period included a 4 hour module, where the teaching and supervision of the students took place. These modules started with a questions and answers session with all students present. At these sessions, the lecturers were available to provide help with overall challenges and problems, but not with detailed technical ones. The detailed technical problems were dealt with in the following exercise session hosted by teaching assistants.

Overall, the course was structured as follows:

Week 1 and 2 of the lecture period: Presentation of the project, forming of groups, handing out hardware (2 Lego NXT robots, Lego bricks, webcamera, camera stand, obstacles and boxes for transportation).
Week 2-13: Weekly questions and answers sessions followed by exercise sessions.
Week 2, 6 and 11: Lectures on project management.
Week 4, 8 and exam period: Deadlines for SC reports. SC meetings following up on SC reports.
Exam period: Students give a physical demonstration to the SC of the working parts of their robotic systems.
Week 10, 12 and first week of 3-weeks period: Deadlines for status reports.
Lab period (3-weeks period): Completing the system and the final report. Handing in the final report. Final competition.

The material used in the course was the brief project description, the notes on project management, the reporting requirements, the hardware, and some links to manuals and tutorials. No text book was provided, and as previously mentioned, no lectures in problem-domain topics were offered. The lecturers and teaching assistants only provided hints at possible solution methods and techniques, and were available for questions. This forced the students to do independent research.

Concerning the reusability, we composed the course-packs (robots, tripods, webcam, etc) for the groups in such a way that modified tasks can be performed with little or no change. We arranged the facilities storing the equipment and allowing the students access it at any time and implemented the administrative procedures for distributing and returning the equipment. Written material on project management is adapted to the course type – not the specific task to be solved. We have monitored the time we spent during the course carefully and concluded that with the preparations just named, we could accomplish the course without using more resources than in other (non-CDIO) courses.

The reusability of the concept is also demonstrated by the fact that only minor changes had to be made for the current (second) version. We have prepared a number of different tasks which will allow us to run this concept during the next couple of years with only small adaption. These include different kinds of obstacles, different objects to fetched, to have an

Figure 3. Students preparing for the final competition.

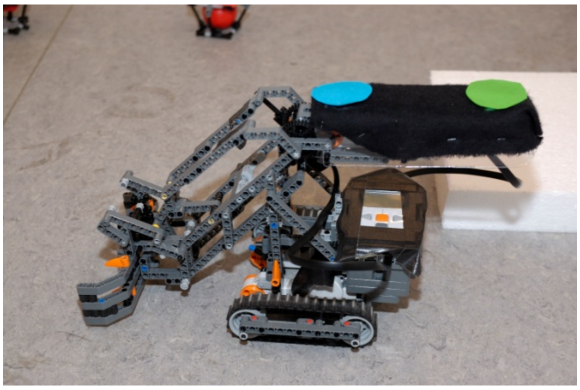

Figure 4. One of the custom robot designs used in the competition. The blue and green marks allow the webcamera to track the position of the robot.

“adversary robot”, etc. We also consider using a “snow-ploughing” task, where Styrofoam chips have to be removed from “streets”.

Assessment

The course was evaluated on the basis of the following 3 mandatory elements:

- The 3 reports for the SC and the corresponding SC meetings.
- The competition at the end of the lab period.
- The final report.

The grade was given as an overall assessment based on these 3 elements. All reports and oral presentations were carried out jointly by the entire group. In the final report there had to be a clear indication of who did which parts of the report, as well as who did which parts of the project as a whole.

OPERATION

During the course, we could observe the students’ emotions going through a number of phases:

Frustration: The open problem formulation, the teachers’ reluctance to answer questions about small details, and high demands on independence created a noticeable frustration amongst the students in the first weeks. The basic questions at that time were: “Where do we start?", “Where do we find ?”, “How do we structure ?”

Aha!: With the technical help provided by the TAs, the help to effective project management and the first SC-meeting, the students experienced the first feelings of success. The structure of the project became clear, sub-problems were conceived, and solutions were found and evaluated. These first steps resulted in a “It can be done” attitude. A more independent and individual approach to tackling the problems became visible.

Convergence: Solutions of sub-problems were integrated into one for the overall problem. All groups produced working solutions. There was a strong sense of accomplishment among students (in our opinion significantly more than if they hadn't first been frustrated). The result was a proud "we did it!"

Altogether, the conduct of the course gave some positive surprises: The model we chose for project management turned out to work surprisingly well. All groups managed to do more and make better solutions than we expected. There were no drop-outs. The students' level of ambitions was surprisingly high. This was probably due to the competition element. For instance, all groups dared to make advanced custom design of their robots rather than using a default model.

Project Management

	Relative (%)	Absolute (n / m)	Comments
Student completion (received grade / started course)	97%	35 / 36	1 student had surgery (unrelated to the course) and complications.
Group completion (members received grades / group formally established)	100%	6 / 6	
Student pass rate (pass grade or better / received a grade)	100%	35 / 35	Individual grades varied from D (Danish 4) to A (Danish 12) with an average of 9.1 (B).
Mandatory reports submitted	100%	42 / 42	3 reports were submitted up to 8 hours after deadline, mostly due to technical problems.
SC reports approved by SC on first submission	83%	15 / 18	
SC reports approved after agreement to change and resubmission	100%	3 / 3	
Individual coaching sessions held	N.A.	3	1 group had 2, 1 group had 1. 2 sessions were recommended by SC, 1 was requested without preamble.
Groups presenting workable solution on deadline (competition)	100%	6 / 6	
Groups achieving own success criteria (as of third SC report)	100%	6 / 6	50% (3 / 6) groups did not have "Pass grade or above" among initial success criteria. 3 / 3 of these chose to include such a criteria, when questioned at SC meeting.

Table 1
Observed results relevant to Project Management process/aims

It is noteworthy, that only 1 group experienced difficulties in student cooperation requiring faculty intervention (and this was due to 1 member having significant health problems). Given that most students had never cooperated before, and the general stress level observed, we would have expected complaints of cooperation problems to be significant.

Surprisingly few (no quantitative data available) questions of any kind were raised at the general Q&A sessions, even on issues groups actively considered themselves to be struggling with.
Practical details of status evaluation and reporting was found (no quantitative data available) to be time consuming by most groups. This was hardly surprising given their lack of experience, but is nevertheless an issue as the use of project-planning tools is not a learning objective.

Competition

The final competition took place at the beginning of the last week in the 3-weeks lab-period. This way the students could incorporate the experience into the final report, which was due at the end of the week. Three tracks were defined by the lecturers for the competition. Moreover every group could specify a track to demonstrate the strengths of their own particular solution. The competition stimulated the students' interest in making unique and creative solutions, both in order to seek to win the competition, and in order to impress the co-students.

Student response

In spring 2010, the first time the course was run, 62% (22/36) of the students on the CDIO-course participated in the evaluation. Out of these 41%, respectively, 45% “strongly agreed” respectively, “agreed” to the question "I have learnt a lot in this course". For the question "I think the teaching method encourages my active participation", 60% strongly agreed and 27% agreed. For the question "In general, I think this is a good course" the figures are 50% and 37%.

To our surprise, the evaluations of the teachers were only a little bit lower, but clearly over average. The fact that we sometimes refused to help, did not seem to affect the evaluation negatively. On the other hand, there were some comments like: "It is hard to evaluate the teachers because most of the work was up to us".

For the question whether the expected workload of 9 hours a week was met, 40% answered "yes", 40% said they did "somewhat more", and 10% said "much more". Our expectation here had been that a majority would vote for "much more". We are convinced that the fact that we asked the students early in course to make a time budget (available man-hours/estimated demand) and ensured that this was continuously updated lead to a quite realistic estimate.

The free-text comments supplied by the students emphasized the positive reception of the course. Especially the following subjects were considered as strong points:

- The high degree of freedom in the project. It made us work harder and do more independent research.
- Open-ended project description inspired creativity.
- Competition gave motivation and was a great experience.
- The meetings with the steering committee and the feedback received there.

Negative comments were mostly dealing with technical problems that occurred during the course. Some of those were expected and a part of the intended challenges of the course (software incompatibilities, imprecision of robot motion), others were unexpected and had to be solved ad hoc (insufficient lighting, physical properties of the objects to be fetched out of the maze). The latter have been addressed and will not affect the course in future.

CONCLUSIONS

While the first implementation of the course does not provide data sufficient for wide-ranging conclusions in the purely scientific sense, we are nevertheless forced to conclude on insufficient data, on a number of issues pertinent to the next iteration of the course. What we consider the most important of these - we might call them provisional conclusions - are:

- It is essential - and very difficult - to ensure that very open problem definitions are chosen, so as to be (just) soluble with the resources available to student groups. Despite the apparent easiness of defining open problems, this does in fact require very experienced faculty and careful thought, to do right.
- Students unused to working with highly open problem definitions and to research and apply answers and solutions (seemingly) on their own, are very likely to experience the process as both stressful and frustrating. Surprisingly - or perhaps not, students seem to react more to relatively minor practical obstacles, than to more fundamental (and difficult) obstacles.
- This stress and frustration does seem to translate into both learning and a sense of real achievement, when (if) students ultimately experience a successful result of their work.
- Providing students with adequate tools and support to manage their work in such situations, (probably) has a significant effect on completion rate and quality of results. It is difficult, but would be highly interesting, to measure the effect in quantitative terms.
- There is a very fine line to be walked, between allowing freedom in choice of solution and method to achieve it, and risking student time being used on unexpected and undesired learning targets (such as operating specific project planning tools). We intend to experiment with providing generic templates, as a possible means of addressing this issue.
- General Q&A sessions do not seem highly efficient in terms of student/faculty time. A better solution is not obvious, but will be an issue for further study and experimentation.
- Students seem to intuitively focus mainly on finding an original/creative solution to the open problem (and derived equally or even more open sub-problems), rather than a robust and “safe” one. Whether this issue should be addressed at all is debatable. How it might be so without compromising other learning targets, will be an issue for further study and experimentation.

Overall, we conclude that the first iteration of the course has, for all intents and purposes, met the aims originally set. Communicating the overall intent of the course to students seems to have succeeded, and students seem to have responded positively, both in terms of learning targets achieved and student evaluation responses.

The authors have monitored the use of their and the students resources during the course and observed that it has been equivalent to the average use of resources for courses with the same ECTS allocation. Also, additional resources allocated to the course have been equivalent to the norm, for courses with the same ECTS allocation.

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