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# Guidelines for teaching with ill-structured real-world engineering problems: insights from a redesigned engineering project management course

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**ABSTRACT**

Real-world design settings can be complex, ill-structured, open and typically uncertain and/or ambiguous about their goals and solution paths. This study contributes to understanding how to work with these types of problems in a course project setting. The main objective of the study is to identify, propose and validate a set of practical guidelines for dealing with ill-structured, open-problem project assignments in courses that teach design engineering or design development planning. A literature review identifies key practices for proposing the guidelines, which are then validated by intervening in an engineering project management master's course. The intervention took place during the COVID-19 lockdown restrictions with 12 project groups created from 105 enrolled students. During the validation, qualitative and quantitative feedback was gathered from the students, and the results provide positive evidence for achieving the objective. Key to this outcome was the combination of the self-regulation of learning, co-regulation of learning and socially shared regulation of learning. In this sense, the proposed guidelines look promising for redesigning university courses that deal with open problems, thus enhancing students' capacity for handling uncertainty and ambiguity.

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Ill-structured problems; project-based learning; flipped classroom; self-regulation of learning; co-regulation of learning; socially shared regulation of learning

## 1. Introduction

Engineering education must help learners develop complex skillsets, including analytics, communication, independent learning and teamwork capabilities while meeting ever-increasing content demands for solving typical problems from engineering practice (Jonassen 2015). Furthermore, engineering learning and practice have three core distinguishing characteristics (Johri et al. 2011): (1) using tools to create representations (graphs, charts, visuals) to support engineering work; (2) aligning with professional practices from the engineering community and working in groups and teams; (3) emphasising the solving of design problems, which is probably the most common kind of problem regularly solved by engineers (Mills and Treagust 2003; Simon 1996).

Real-world design problems are often complex, multifaceted and ill-structured, and they interact with existing contextual elements (Johri et al. 2011; Jonassen 1997). Ill-structured and open problems, also known as wicked problems, normally require the integration of several content domains; that is, they are usually interdisciplinary (Jonassen 2015; Polman 1998). These problems

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are typically uncertain and/or ambiguous about their goals and solution paths, so problem solvers must be critical and creative in identifying and negotiating potential approaches to a final solution strategy (National Academy of Engineering 2005; Schrader, Riggs, and Smith 1993). In the context of design education, a common practice is using cornerstone and capstone group projects to engage engineering students in design practice (Dynn et al. 2005; Ward 2013). Dringenberg and Purzer (2018) point out that students can only accept ambiguity when they can effectively deal with the multiple perspectives brought by ill-structured problem-solving.

Considering this context and motivation, this work is under the discipline of engineering teaching and relates to the underlying research question of 'How can the learning process be guaranteed in courses that rely on ill-structured and open problems/assignments?'. To contribute to answering this question in the scope of design engineering, this research aims to identify, propose and validate a set of practical guidelines to deal with design and design management project assignments' intrinsic uncertainty and ambiguity. The guidelines are further used during an intervention in a five-point ECTS[1] mechanical engineering master's course entitled Engineering Project Management (EPM), which teaches students how to plan and execute engineering design projects that have typical ill-structured and open problems. In this sense, the insights from this intervention might apply to other learning scenarios that involve projects that resemble engineering practice.

The paper is divided into six sections. Section 1 presents the research context and objective. Section 2 analyses the background of ill-structured design problem-solving, which serves as a base for defining the guidelines presented in section 3. Section 4 describes the intervention, and the results are discussed in section 5. The discussion focuses on understanding if the intervention using the proposed guidelines was capable of: (1) setting a course project that the students think resembles engineering practice; (2) defining a scaffolding structure that allows ambiguity and uncertainty reduction during the project's execution and the assignment's elaboration. Finally, section 6 presents the concluding remarks.

## 2. Background

Although well-structured problems have well-defined initial and final states, clear constraints and solution paths, an ill-structured problem is often open-ended with uncertain or ambiguous goals and/or the means to pursue those goals (Jonassen 1997). Uncertainty relates to a lack of information, and ambiguity is defined as a lack of clarity regarding the relevant variables and their functional relationships (Martin and Meyerson 1988). In the context of design problems, uncertainty and ambiguity might be related to the design problem's parameters (the problem to be solved) or to the design process (how to solve the problem). All design problems include three types of design problem parameters (Jauregui-Becker and Wits 2012; Schotborgh, McMahon, and Van Houten 2012), which can be well-defined, uncertain or ambiguous depending on the problem at hand:

- Design parameters signify knowledge describing the object being designed, for example, its topology and properties. Determining these parameters' values is the main task of the designer and the objective of the design and development process.
- Scenario parameters refer to the set of scenario entities that describe the flow of energy, materials or information the embodiment is exposed to. Scenario parameters are often expressed as use scenario requirements that the designed product must fulfil (i.e. the product shall operate underwater up to 50 m deep).
- Performance parameters determine how well the embodiment behaves under a certain (group of) scenario(s). Expected performance parameters are set by the product's requirements (i.e. the product's max speed shall be 300 km/h or above). The actual performance parameters are determined by analysing, simulating or testing the designed product.

As well as dealing with uncertainty and ambiguity, open-ended problems allow the exploration of transferrable skills such as knowledge acquisition, communication and inter/transdisciplines (Gutiérrez Ortiz, Fitzpatrick, and Byrne 2021). In terms of the design process, solving ambiguous and/or uncertain problems depends on the mental models the solvers choose to use, the resources available and the organisational context (Schrader, Riggs, and Smith 1993). A mental model represents how someone understands how something works in the real world (Johnson-Laird 1983); therefore, having and using the right mental models are central to solving uncertainty and ambiguity. While previous experience and mental models can be sufficient for reducing uncertainty, reducing ambiguity requires the acquisition of further knowledge, the creation of new mental models, evaluating those models and selecting the best fit for further use (Kitchener 1983). To find new paths and efficiently reduce ambiguity, problem-solvers need resources and knowledge that tend to be less available than their previous knowledge (Araz and Sungur 2007).

Price et al. (2021) analyse how actual experts approach the problem-solving process and identify the need for communication, feedback and scaffolding to support less experienced learners in developing appropriate mental models to solve the ill-structured problem at hand. Consequently, the available communication networks and control measures play a key role in this process as they allow the exploration of the knowledge already present in the development organisation and the gathering of external knowledge (Kitchener 1983; Schrader, Riggs, and Smith 1993; Walker, Davis, and Stevenson 2017). Personal opinions or beliefs also often influence the solving process (Ge, Law, and Huang 2016; Schrader, Riggs, and Smith 1993). Problem-solvers must, therefore, self-regulate by making judgements about the problem, their preconceptions and their proposed solutions, whereas the challenge is selecting the skills and resources that fit the problem at hand (Lawanto and Febrian 2017; Schrader, Riggs, and Smith 1993), which requires critical thinking to avoid quickly converging on sub-optimal solutions due to personal biases (Ge, Law, and Huang 2016; Jonassen 1997; Kitchener 1983).

During collaborative learning, teams and team members not only engage in self-regulation (SRL) but also the co-regulation (CRL) and socially shared regulation of learning (SSRL) (Malmberg, Järvelä, and Järvenoja 2017). Both CRL and SSRL are forms of social regulation. In CRL, a member or subset of a group regulate the others, which is similar to the teacher – student relationship in the classroom. In SSRL, there is no mediation, so authority is evenly distributed (Bransen et al. 2022). Therefore, in SRL, learners individually navigate uncertain problem states, fuzzy situations and unclear goals in search of solutions. During CRL, groups are mediated during the learning process, and in SSRL, groups regulate together as a collective and collaborate to construct shared task perceptions or shared goals (Bransen et al. 2022; Panadero and Järvelä 2015; Smith et al. 2009).

In terms of how the regulation of learning operates, Hadwin, Järvelä, and Miller (2017) describe SSRL using a four-phase theoretical model where teams initially negotiate and co-construct a shared understanding of the learning task. Second, they define shared goals and design a plan to complete the task. In sequence, they monitor their progress towards the goal. Finally, the team evaluates the process for future adaptation to further SSRL cycles. Malmberg, Järvelä, and Järvenoja (2017) observe how groups reveal different temporal patterns, where group dynamics vary from SRL, CRL and SSRL to better make sense of and solve the problem. Ge, Law, and Huang (2016) present evidence that SSRL plays an active role when groups solve ill-structured problems, and Bransen et al. (2022) and Malmberg, Järvelä, and Järvenoja (2017) show that groups normally combine SRL, CRL and SSRL during the problem-solving process.

Therefore, the right balance between self/group regulation and direct instruction is necessary to guarantee academic achievement (Jonassen 1997). To be successful, the level of support also needs to be balanced as, on the one hand, scarce support hinders problem-solving and results in demotivation, and on the other hand, excessive support negatively affects self-learning (García-Martín and Pérez-Martínez 2017). According to García-Martín and Pérez-Martínez (2017), support is particularly needed during tasks or phases that students find more difficult as well as in the project's cornerstone points. At these points, three types of support are proposed: providing temporary frameworks by scaffolding, providing a model or example of desired performance and coaching the students. In this context, the flipped classroom setting offers on-demand online content, which can also support self-directed learning when solving ill-structured problems (Lou et al. 2012). As another example, Mann et al. (2021) balance openly scoped projects by including support from an industry representative (or the lecturer) who acts as the senior engineer or co-regulator and who either inputs into the project itself or brings in other experts to help solve the problem, as would happen within an authentic engineering practice. Finally, To, Panadero, and Carless (2022) review the use of exemplars, which also mention the co-creation of rubrics by the students.

## 3. Intervention guidelines

Figure 1 summarises the findings from the previously presented background. Uncertainty and ambiguity can either fall within the design problem's parameters or in the design process, where the former represents understanding the problem and the latter represents knowing how to solve the design problem. The design objective might be creating a product, service, process or any solution that combines them, but the design problem's parameters relate to different aspects (Table 1).

By defining the course project and related assignments' structure and complexity, the lecturer consciously or unconsciously set the overall problem's and process' ambiguity and uncertainty (Jonassen 2000). Based on the summary in Figure 1, the SRL + CRL + SSRL dynamic supported by the communication infrastructure helps eliminate ambiguity and uncertainty during problem-solving. The communication infrastructure, besides the communication channels, includes the use of scaffolding, modelling and coaching, which requires collaboration, self-regulation and feedback.

Table 2 presents the guidelines for helping the lecturer consciously tune the uncertainty and ambiguity from the design problem's parameters and the design process according to the course's learning objectives (LOs). In this work, an ambiguous design problem parameter means that the parameter is not known by the design team, while an uncertain design problem parameter means that the parameters are known but their values are unknown. Similarly, an uncertain design process means that the group of students has previous knowledge or has been provided with a scaffolding structure, and the challenge is to select and integrate the right knowledge. An ambiguous design process means that the group of students must acquire new knowledge about how to solve the problem, and the challenge is to make the right knowledge selection and integration. In

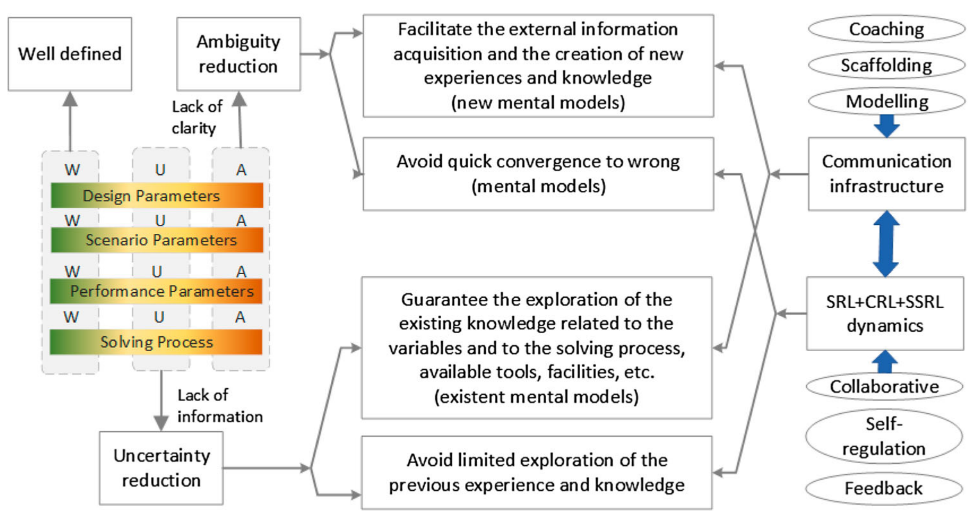


**Figure 1.** Main findings from the background analysis.

**Table 1.** Design objective and design parameters.

| Design objective | Product and/or service | Process |
|---|---|---|
| **Design parameters** | Determine the choice of solution. | Determine the activities and deliverables to be included as part of the process. |
| **Scenario parameters** | Determine where/how the product will be used. | The context where the process will be executed. |
| **Performance parameters** | The expected solution in terms of quality/ performance. | The expected level of detail from the process activities and deliverables. |
| **Solving process** | Expected steps for designing the product and the related deliverables. | Expected steps for designing the process. |

**Table 2.** Guidelines for setting the project's design problem parameters

| | |
|---|---|
| **GDL1** | The parameters of the design problem that is part of the course project should include:<br>a) ***Disclosed design parameters and parameter values.*** The LOs benefit from the presentation of a solved problem that the students will analyse (reverse engineer) to understand the design parameters' relationship with use scenarios and expected performance.<br>b) ***Disclosed design parameters and undisclosed parameter values.*** The LOs benefit from the students working on defining the values for a predefined set of design parameters.<br>c) ***Undisclosed design parameters and parameter values.*** The LOs benefit from the students working on the production of original designs.<br>The students' previous design experience, the available course time and the expected student effort must also be considered to select the best choice. |
| **GDL2** | The parameters of the design problem that is part of the course project should include:<br>a) ***Disclosed scenario parameters and parameter values.*** The LOs benefit from a clear predefined use scenario (or scenarios).<br>b) ***Disclosed scenario parameters and undisclosed parameter values.*** The LOs benefit from scaffolding the scenario to avoid adding unnecessary ambiguity to the project's tasks; students can still determine parameter values.<br>c) ***Undisclosed scenario parameters and parameter values.*** The LOs benefit from investigating alternative possible use scenarios.<br>Scenario parameters determine the context in which the problem to be solved is inserted. Undefined scenario parameters require students to clarify the problem itself, which is time-consuming and might be outside the scope of the LOs. It also prevents the definition of wrong parameters (convergence to wrong mental models). To avoid adding unnecessary uncertainty to the project's tasks, undefined scenario parameter values must only be those that are identified to explicitly support the course's LOs. |
| **GDL3** | The parameters of the design problem that is part of the course project should include:<br>a) ***Disclosed performance parameters and parameter values.*** The LOs benefit from clear predefined performance requirements.<br>b) ***Disclosed performance parameters and undisclosed parameter values.*** The LOs benefit from scaffolding the performance to avoid adding unnecessary ambiguity to the project's tasks; students are still expected to define the parameters' acceptable values (acceptable performance).<br>c) ***Undisclosed performance parameters and parameter values.*** The LOs benefit from investigating alternative possible performance parameters and their values.<br>Disclosed performance parameters and values (including assessment rubric parameters) determine clear acceptance criteria of the designed object, which helps the design alternative that best delivers the performance. If the performance parameters are undisclosed, the team must further identify the expected performance.<br>Performance parameters formatted as a rubric support the assessment of the project's result quality, and transparency is a good practice for learning assessment. On the one hand, disclosing performance parameters provide scaffolding by avoiding convergence to the wrong performance parameters, which would not support LO achievement. On the other hand, undisclosed performance parameter values require students to self-regulate and converge to a common understanding of the values. It leads to student collaboration by having a common and clear reference knowledge for assessing the project's results and the achievement of LOs.<br>Allowing students to define the rubrics is in line with the holistic assessment proposed by Sadler (2009) because students have further involvement in the assessment process. |
| **GDL4** | The course project instructions should provide:<br>a) ***Prescribed and clear step-by-step directions on how to perform the project tasks.*** Students need to follow a strict set of steps to achieve the expected LOs.<br>b) ***Prescribed but general direction.*** LOs are better achieved by providing general models and/or looser scaffolding, both of which allow students to explore alternatives and prevent the groups from quickly adopting a previously known but inadequate mental model, which might hinder the achievement of the LOs.<br>c) ***No prescribed direction.*** Suitable if students are more mature and experienced and when the LOs benefit from a wider exploration of alternatives and/or the creation of new methods.<br>The project's instructions determine how students are expected to proceed to achieve the objective. The looser the instructions the more support from the lecturer the students might need to converge to a direction that leads to achieving the LOs. |

any case, the students must be given the means or discover by themselves how to identify that the chosen design process leads to a good result. In this sense, solving uncertainty and ambiguity in the design process requires both understanding how to proceed to solve the problem and how to identify that the achieved solution is indeed fitting. Note that the proposed guidelines aim to define a scaffold structure that regulates (not eliminates) the initial uncertainty and ambiguity. Having the right uncertainty and ambiguity levels guarantee the achievement of the LOs, reduces students' frustration and provides a real-world experience as much as possible.

The second set of guidelines (Table 3) relates to creating the communication infrastructure and supporting a course dynamic for learning regulation, which combines SRL, CRL and SSRL. Effective communication and group self-regulation are paramount for attaining a smooth ambiguity and uncertainty reduction and preventing the groups from quickly adopting a previously known but inadequate mental model, which might hinder the achievement of the LOs. In this context, lecture – student, student – student and student – lecture feedback play an important role.

## 4. EPM course intervention

EPM is a mechanical engineering master's course worth five ECTS points, and it teaches students how to plan and execute engineering design projects. Before the intervention, the EPM already implemented a flipped classroom (Bergmann and Sams 2014; Zainuddin and Halili 2016) and used project-based learning. Considering the already received positive student feedback (Pereira Pessoa and Pei 2022), these two pedagogical approaches were not changed during the intervention. Table 4 lists the course's LOs and indicates how they are assessed. The course grade is based on assessing online quizzes (10%), three project assignments (70% in total) and the final exam (20%).

The backbone of the programme is a course-long project with three related assignments. The class is divided into project groups of nine students with each group member having a specific role based on the project management knowledge areas (Project Management Institute 2017) and being responsible for producing different deliverables (Figure 2), which together have to represent a coherent project management plan. During the intervention, which took place from 1 May to 26 June 2020, 12 project groups were created from 105 enrolled students. The project

**Table 3.** Guidelines for setting project communication and learning regulation dynamics

| | |
|---|---|
| **GDL5** | The course SHALL have ***mechanisms for students requesting just-in-time lecturer support***, where the lecturer could support (1) uncertainty reduction by sharing previous experiences along well-established paths; (2) ambiguity reduction by providing resources and capabilities that are outside the student teams' previous experience. Just-in-time response to the students' enquiries is key to avoiding an incorrect interpretation of ambiguous points. It also builds up confidence in the lecturer and allows the lecturer to co-regulate and make just-in-time adjustments, which might relate, for instance, to providing further coaching, scaffolding or models to the students. Note that ideally the lecturer must prefer coaching and giving examples instead of giving direct, specific and prescriptive answers, which might prevent the students from reflecting on what they are doing and why. |
| **GDL6** | The course SHALL ***prevent self-regulated groups from solving problems using undesirable approaches***, which means there are mechanisms to monitor and give feedback during the solution process and before students propose their final solution. This is particularly important to identify misinterpretations and/or the wrong influence of previous beliefs and knowledge. |
| **GDL7** | The course SHALL include an ***intra-group self-regulation mechanism*** that guarantees that all group members have the same understanding and are likely to achieve similar learning results. This mechanism must encourage all team members to actively contribute by exchanging their knowledge, experience and opinions, and allowing new and more creative solutions to be developed. |
| **GDL8** | The course SHALL include an ***across-group self-regulation mechanism*** that guarantees that all the course students have the same understanding and are likely to achieve similar learning results. This guideline extends GDL7 to exchange information across different groups. |
| **GDL9** | The course SHALL guarantee that ***all groups receive the same quality of support from experts***, which means that all groups must receive or have access to the same supporting information provided by the lecturer, tutors or any other experts. |
| **GDL10** | The course SHALL include a formal mechanism to provide feedback on students' results (***outcome feedback***) and students' task execution (***cognitive feedback***). Feedback must be meaningful so students can use it as part of the regulation of the learning dynamic. |

**Table 4.** Learning objectives and related assessment approach

| Learning objectives (LOs) | Assessment |
|---|---|
| LO1. Identify and differentiate the concepts related to project management, strategic management, operations management and crisis management. | Quizzes |
| LO2. Identify and differentiate the concepts related to the portfolio, programme, project and subproject. | Quizzes |
| LO3. Create a project management plan according to the five project management process groups: Initiating, Planning, Executing, Monitoring & Controlling and Closing. | Project |
| LO4. Reflect on the strengths, weaknesses and applications of traditional and agile project management. | Exam |
| LO5. Apply, by exercising during a practical project, tools and techniques from the project management knowledge areas (integration, scope, schedule, cost, quality, resource, communication, risk, procurement and stakeholder management). | Project |
| LO6. Apply, by exercising during a practical project, the team canvas, the project management canvas, agile management and value function development. | Project |
| LO7. Integrate, by exercising during a practical project, aspects from lean product development, systems engineering, system modularisation and the function-behaviour-structure ontology during project planning and execution. | Project, exam |

setting also encourages cross-team collaboration once each team plans the development of a different subsystem for the same product. The project challenge changes every year. During this intervention, each group planned the development of different aeroplane subsystems.

To better resemble the reality of engineering project management, particularly when planning the design and development of a new product/system/solution, the project assignments are purposefully ill-structured and open. However, in a previous course evaluation, 36% of the students considered that the vague and ambiguous project assignment goals hindered their learning process, which could be caused by unclear assignment tasks, open project goals and/or the reduced amount or quality of feedback. Unfortunately, providing rigid and detailed guidance would also hinder the learning and creativity processes. In this case, why a certain strategy is chosen is more important than the strategy itself (in the course, learning how to plan is more important than the final plan). Therefore, while quality and opportune feedback are key to the learning process, they must avoid prescribing the 'right' solution and must lead to reflection. Although assignment templates were offered, the students struggled with how to transfer their general knowledge to the specifics of their project. Therefore, determining what to do, how to do it and how to access the quality of what has been done in each specific situation is no trivial task.

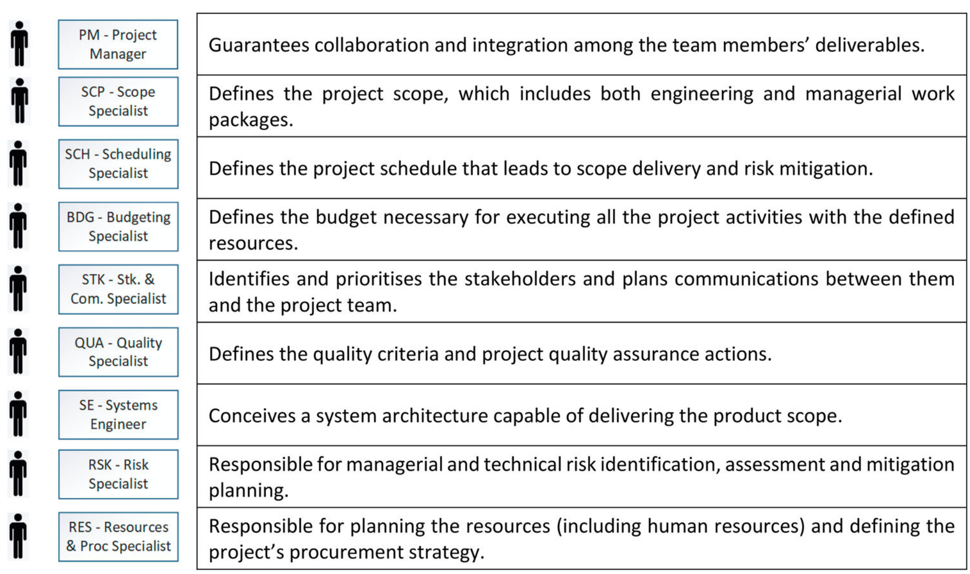


**Figure 2.** Project team's roles.

### *4.1. Implementing the guidelines*

The intervention objective was to regulate the uncertainty and ambiguity levels of the course assignments to create a closer-to-real-world setting while not hindering the learning process. The previously presented LOs (Table 1) and the project groups and roles (Figure 2) were not changed, but the course material and course dynamics were redesigned to better handle ambiguity and uncertainty reduction. Considering that the students had previous empirical experience in project work but never had contact with project management theory and formal project management practice (LOs 3, 5, 6 and 7), the choice for applying the GDLs was:

GDL1. Disclosed design parameters and undisclosed values: A project management plan template was provided and students were informed about which deliverables should be on the plan, although no further description of the deliverables themselves was provided. To achieve the LOs, students had to adapt the predefined architecture.

GDL2. Disclosed scenario parameters and values: A clear problem scenario was provided in the lecture notes; thus, students had to focus on solving the problem rather than on understanding the scenario's peculiarities. The lecture notes booklet also included the learning goals, lecture plans, assessment approaches, supporting information for the assignments, project roles and deliverables and the regulation of the learning dynamic.

GDL3. Disclosed performance parameters and undisclosed values: A rubric was provided to the students that contained ambiguous criteria to be clarified through SSRL. The rubric did not add unnecessary ambiguity to the project's tasks but provided a scaffolding structure that students had to use to remove the ambiguity and define the parameters' acceptable values (which can be done through SSRL).

GDL4. Prescribed yet general direction: The planning process was divided into three different and sequential project assignments. In each assignment, instead of detailed instructions (how to do them), a list of deliverables from each specialist (what) was provided. The students had to ask the lecturer or figure out (with the help of the books, videos and quizzes) how to create and integrate the individual deliverables.

GDL5. Just-in-time lecturer support was provided both synchronously (lectures) and asynchronously (discussion forum and email). The course implements an entirely flipped classroom, where lecture time is reserved exclusively for the lecturer to meet and coach the project groups and the functional groups (groups of students who perform the same function across different groups).

GDL6. Preventing problem-solving through undesired approaches. During the lectures, students presented and discussed their progress and received feedback and guidance. This enabled a just-in-time teaching approach where the lecture content was partially informed by the students' needs (Brandenburg and Ellinger 2003).

GDL7. The intra-project group self-regulation mechanism. The project group members were responsible for different deliverables that had to be integrated to create a meaningful project plan. This created social pressure for the regulation of learning in the groups.

GDL8. The across-group self-regulation mechanism. Students who performed the same function in the various groups made up a functional group that was responsible for defining the rubric's final shape. This created social pressure for the regulation of learning across the groups. Peer feedback also contributed to cross-group regulation.

GDL9. Guaranteeing the groups received the same information. The discussion forum was the main media for asynchronous communication and was accessible to all students (the use of email was limited to strictly personal subjects). Meetings with the functional groups guaranteed that all the students who performed the same function got the same information.

GDL10. Formal feedback on the students' results. A software tool was used to support peer feedback. Each group gave feedback to another group. The groups had the opportunity to give feedback on the feedback and to flag dubious points to receive further feedback from the lecturer.

Figure 3 lists the course material and activities (M&A) and relates them to the guidelines. M&A in the grey background cells were already used in previous courses and were updated according to the guidelines. M&A in the white background cells were added to incorporate all guidelines. The elements are further described in the guidelines' implementation section.

| | GDL 1 | GDL 2 | GDL 3 | GDL 4 | GDL 5 | GDL 6 | GDL 7 | GDL 8 | GDL 9 | GDL 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Lecture notes | X | X | | X | | | | | X | |
| Lectures | | | | X | X | X** | | | X | |
| Disc. forums & email | | | | | X | X | | | X | X |
| Project groups | | | | | | X** | X | | | X** |
| Functional groups & rubrics | | | X | | | X** | | X | | X** |
| Assignment & peer feedback | | | | | | X* | | | X* | X |

* Request lecturer feedback on the received peer feedback.

** Receive coaching from the lecturer/tutor during group meetings or during the Q&A lectures.

**Figure 3.** The guidelines and EPM course materials and activities.

### *4.2. Redesigned course dynamics*

The flipped classroom was maintained to support the individual student's dynamic where they could access the reference materials (lecture notes, reading materials and videos) and answer quizzes online. Due to COVID-19 restrictions, individual lecturer coaching and scaffolding instructions were also online (synchronous lectures and asynchronous discussion forums). As part of the intervention, a new group dynamic was designed, which further supported the implementation of the guidelines. The regulation of learning was enforced by encouraging the students to interact in their project groups to produce their assignment's deliverables as well as in their functional groups (groups with all the students performing the same function across diverse project teams) to define the rubric to be used during peer feedback and summative assessment. CRL was achieved through synchronous and asynchronous interaction with the lecturer and peer feedback. During the final exam, students individually reflected on their learning progress and achievements.

The group dynamic supported the project assignment's ambiguity and uncertainty reduction through a sequence of seven steps (Figure 4). This is compatible with the process for solving ill-structured and open problems proposed by Ge and Land (2003), which structures how a course combines SRL, CRL and SSRL. The project assignments' assessment rubrics were key elements that supported the use of SSRL. To better understand the performance intent behind SRL, CRL and SSRL, each task was related to the SRL, CRL and SSRL categories proposed by Malmberg, Järvelä, and Järvenoja (2017), where planning includes task understanding, planning and goal setting; monitoring includes categories such as monitoring, strategy use and evaluation; and task execution relates to the fulfilment of the assignment. Note that only the most prominent categories are mentioned, which does not mean that other categories also take place, particularly in the case of SRL.

1. The lecturer provides a partially filled rubric for the assignment that lists a set of ambiguous criteria for assessing each function/role's deliverables. At this moment, each student is expected to engage in SRL planning.

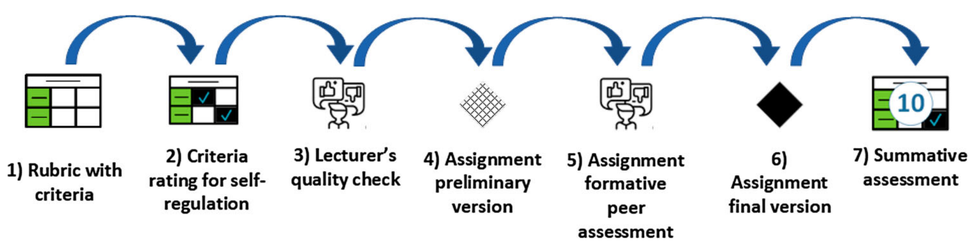


**Figure 4.** Group dynamic steps that lead to the gradual uncertainty and ambiguity reduction.

2. The students from each functional group collaborate to remove ambiguity. For instance, one criterion could be: 'The areas that should be covered by this project are clearly defined'. Although the criterion is given, the precise understanding of 'clearly defined' has to emerge by consensus, which is then used as a reference during peer feedback and summative assessment. To reach a consensus on the criteria, the groups engage in SSRL planning while each student works on SRL monitoring.
3. The lecturer performs a quality check on the criteria defined by the students, mainly focusing on feasibility (not too ambitious) and LO alignment. From the lecturer's perspective, this step relates to CRL planning, and the groups also use this moment for SSRL monitoring.
4. In parallel to defining the rubric in the functional groups, the project groups execute the task by creating a preliminary version of the assignment. When meeting with the groups, the lecturer performs both CRL planning and monitoring.
5. Further SSRL monitoring takes place during the peer review when each project group gives feedback on the preliminary assignment to another group. The groups can request support from the lecturer, especially if they disagree with the received feedback; this allows the lecturer to guarantee the quality of reference knowledge.
6. By considering the learning from giving and receiving feedback, a final version of the assignment is produced (task execution).
7. Finally, the lecturer uses the rubric to perform a summative assessment of the assignment's final version.

### *4.3. Implementation of the EPM course intervention*

The EPM course intervention took place from 1 May to 26 June 2020. Twelve project groups were created from 105 enrolled students: 10 with nine members, one with eight members and one with seven members. There was only one lecturer and no tutors or student assistants. Course students were mostly from the Mechanical Engineering and Industrial Design Engineering master's programmes, but some students were from Liberal Arts and Sciences, Business, Computer Science, Biomedical Engineering and Civil Engineering.

During all three project assignments, students were part of the same project group, but they had to change roles in each assignment. They were also part of a functional group related to the role they were performing. This role-switching had two objectives. First, it allowed students to benefit from a broader experience and learn from the perspective of different roles in the project management team. In an earlier version of the course, the students complained that having the same role in all the assignments limited their learning experience. Second, it helped balance the work; as different roles might require different workloads, the rotation of roles facilitated levelling the overall course workload for all students.

The intervention took place while the university was in lockdown due to the Dutch measures against COVID-19. Consequently, the course's synchronous and asynchronous interaction with the lecturer and among the students was exclusively online. During course execution, special attention was given to understanding if or how the full online setting influenced the results. Figure 5 outlines the course pace by identifying the lecture dates, deadlines for the preliminary and final assignments, the preliminary versions' peer review and the final exam. Compressing the 5 ECTS in 9 + 1 weeks (the last week is the exam week) made the course very dense; however, it did not result in student complaints.

## 5. Intervention implementation assessment

The EPM course intervention was assessed with the objective of understanding to what extent the proposed guidelines could guarantee the learning process while dealing with the intrinsic uncertainty and ambiguity of the course project. Four questions allowed the gathering of qualitative and quantitative feedback. Additionally, students were asked about their perceptions of the impact of the COVID-19 lockdown measures on the course.

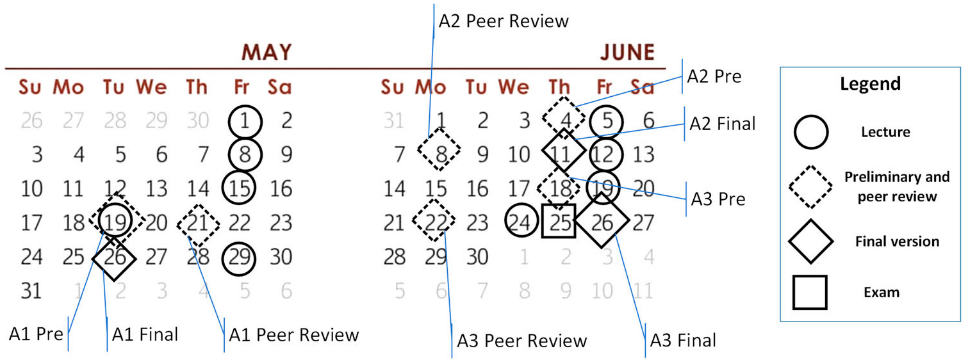


**Figure 5.** Course calendar and activities.

**To what extent did the intervention help gradual uncertainty and ambiguity reduction?** Considering the intervention, students should provide evidence of learning, even though the project presents some initial uncertainty and ambiguity. In this sense, applying the guidelines in the intervention must lead students to converge to satisfactory learning achievements. The students were surveyed before and after each project assignment. Before the assignments, ambiguity and uncertainty levels were assessed by answering if they understood what was expected or if expectations were unclear or ambiguous. After the assignments, they were asked if they could (1) recall; (2) explain; (3) implement independently; (4) integrate/adapt the acquired knowledge, which corresponded to levels 1, 2, 3 and 4–6 of Heer's adaptation of Bloom's taxonomy (Krathwohl 2002). A mean above two (the students can explain) was set as the success threshold for the LOs.

To what extent did each course's M&A help gradual uncertainty and ambiguity reduction? To give further insight into the guidelines' capabilities, it is important to understand the effectiveness of the M&A that were updated or added to the course. All the students were surveyed after each assignment to determine the extent to which each course's M&A helped them understand what they needed to do, how they should do it and evaluate their results to make improvements (1 – did not help/use; 2 – minimum help; 3 – medium help; 4 – helped a lot). M&A success criterion was defined as having at least one course M&A with a mean above three in each of the three items and each of the assignments. The individual course M&A success criterion supported a situation from at least one assignment with a mean above two. The idea behind the four-point scale was to have a three-point Likert scale with the option of an absolute negative opinion (did not help). The decision to not use a five-point Likert scale was because the absolute positive opinion that would contrast with the absolute negative was considered unrealistic by the author. As mentioned, this was the author's decision.

**What are the positive aspects and opportunities for improving the course?** This open question brought insight into the student's experience during the course. The objective of this question was to qualitatively assess students' opinions about the course, particularly the use of SSRL.

**To what extent did the lockdown have an impact on the course?** The COVID-19 lockdown was imposed on a fully online course and prevented students from meeting face-to-face at the university. This objective was to understand how the impact of this situation was perceived by students. Although this question was not directly related to the research question and objective, it brought insight into how this particular situation impacted the course and limited the research results.

### *5.1. To what extent did the intervention help gradual uncertainty and ambiguity reduction?*

Table 5 presents the survey results for each project assignment. All the assignments were rated as having high initial uncertainty and ambiguity levels, particularly the third assignment. After finishing the assignments, the students had a good understanding of the theory and its application, and a representative subset felt able to perform future implementations and even integrate/adapt the acquired learning. Considering the success threshold (mean >2), it is possible to say that the course's M&A contributed to reducing the initial assignments' ambiguity and uncertainty while guaranteeing effective learning. This result, considering the standard deviation, is not outstanding and points to the need for further improvement.

### 5.2. To what extent did each course M&A help gradual uncertainty and ambiguity reduction?

Individually assessing the course M&A's impact on uncertainty and ambiguity reduction helped understand what, when and to what extent they contributed to the reduction (Table 6). All the M&A reached the success criteria by having a mean above two at least once. In terms of what to do, the rubrics created by the functional groups and the lecture notes were the most effective M&A, although the lecture notes lacked information in the third assignment. The lectures, group work and peer feedback also provided good to medium help. The results on how to create the expected assignments were mainly supported by the creation of rubrics and work by the functional groups. Lectures, group work and peer feedback also provided good support. To assess the quality of the assignments before final submission, the functional groups' definition of rubrics and peer feedback were the most effective course M&A. Working in groups, the discussion forums and lectures also gave good support at this stage.

### 5.3. What are the positive aspects and opportunities for improving the course?

The students provided rich feedback about the course. A summary of the most relevant/recurrent positive aspects and improvement opportunities is listed in the sequence of findings (F) below. The comments from the students also help explain the values presented in Tables 5 and 6.

F1. The course was considered highly relevant and close to engineering practice: The project setting, including the lecturer's mentoring/coaching role, was considered realistic. The students pointed out that engineering management courses are rather theoretical and full of 'buzzwords', so they appreciated having a course focused on practice and where the theory is left online.

F2. The project and functional group work kept the students engaged and motivated: The level of cooperation required by working on an individual role in the project group and participating in the functional groups was highlighted as a reason to keep engaged with the project work and motivation to come to the classes. '*Working in the project and functional groups required a level of effort in cooperation that I have not previously encountered/ felt the urge to put so much effort in during typical assignments where there was no (grade) dependency on my peers*'. '*What I really liked about the project is that you were also communicating with people who had the same role as you. I think I learned the most from this as a discussion*'. '*Cross-team cooperation with our teammates and with students in the same function was an intense but useful process as there was a lot to learn and teach others*'

F3. The individual and changing roles in the different project assignments guaranteed participation and allowed broader learning: The obligation of changing roles helped students to see the project from the perspective of different specialists. Broader learning was also guaranteed by the required collaboration among the roles. '*I believe the recent change to the course, where every member performs different functional tasks in each assignment, is definitely a good decision*'. '*Even with the project groups being so large, I like that we all had a specific role, so you*

**Table 5.** Survey results on the course's M&A uncertainty and ambiguity reduction capacity

| | Assignment 1 | | | Assignment 2 | | | Assignment 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | 90 respondents out of 105 | | | 92 respondents out of 105 | | | 93 respondents out of 105 | | |
| Begin (ambiguity) | 27% | | | 21% | | | 43% | | |
| End (Bloom) | Mean | Stdv | Median | Mean | Stdv | Median | Mean | Stdv | Median |
| | 2.27 | 1.03 | 2 | 2.14 | 1.09 | 2 | 2.26 | 1.12 | 2 |

**Table 6.** Course M&A contribution to understanding what/how/to what extent they impacted uncertainty and ambiguity reduction

| | | Assignment 1 | | | Assignment 2 | | | Assignment 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 90 respondents out of 105 | | | 100 respondents out of 105 | | | 96 respondents out of 105 | | |
| | | Mean | Stdv | Median | Mean | Stdv | Median | Mean | Stdv | Median |
| Course elements's impact on understanding WHAT was needed to be done | Lecture notes | 3.51 | 0.72 | 4 | 3.18 | 0.83 | 3 | 2.49 | 0.97 | 2.5 |
| | Lectures | 2.78 | 0.86 | 3 | 2.65 | 0.84 | 3 | 2.50 | 0.88 | 3 |
| | Disc. forums & email | 2.11 | 1.04 | 2 | 2.48 | 1.12 | 3 | 2.45 | 1.10 | 2 |
| | Project groups | 2.84 | 0.86 | 3 | 2.72 | 0.96 | 3 | 2.50 | 1.06 | 2 |
| | Func. groups & rubric | 3.08 | 0.94 | 3 | 3.44 | 0.77 | 4 | 3.47 | 0.71 | 4 |
| | Assign. & peer feedback | 2.53 | 0.98 | 3 | 2.62 | 1.07 | 3 | 2.55 | 1.02 | 3 |
| Course elements's impact on understanding HOW to create the assignment | Lecture notes | 2.88 | 1.00 | 3 | 2.54 | 0.95 | 3 | 2.13 | 0.96 | 2 |
| | Lectures | 2.70 | 0.80 | 3 | 2.59 | 0.79 | 3 | 2.40 | 0.87 | 2 |
| | Disc. forums & email | 2.00 | 1.03 | 2 | 2.46 | 1.09 | 3 | 2.40 | 1.07 | 2 |
| | Project groups | 2.91 | 0.89 | 3 | 2.72 | 0.98 | 3 | 2.50 | 1.12 | 2.5 |
| | Func. groups & rubric | 3.05 | 0.98 | 3 | 3.40 | 0.80 | 4 | 3.36 | 0.77 | 4 |
| | Assign. & peer feedback | 2.48 | 1.03 | 3 | 2.73 | 1.00 | 3 | 2.52 | 1.03 | 3 |
| Course elements's impact on evaluating the created assignment's quality | Lecture notes | 3.03 | 0.98 | 3 | 1.78 | 0.82 | 2 | 1.68 | 0.84 | 1 |
| | Lectures | 2.28 | 1.04 | 2 | 2.13 | 0.89 | 2 | 2.00 | 0.98 | 2 |
| | Disc. forums & email | 2.27 | 0.97 | 2 | 2.23 | 1.12 | 2 | 2.15 | 1.05 | 2 |
| | Project groups | 1.86 | 0.97 | 2 | 2.85 | 0.97 | 3 | 2.59 | 1.11 | 3 |
| | Func. groups & rubric | 2.89 | 0.90 | 3 | 3.43 | 0.74 | 4 | 3.29 | 0.83 | 4 |
| | Assign. & peer feedback | 3.01 | 0.98 | 3 | 3.23 | 0.87 | 3 | 3.16 | 0.99 | 4 |

*do not get people who do not contribute anything to the project. Although you work in a group you still get an individual grade, which I like'.*

F4. Rubric creation was considered a very positive aspect: The rubric creation process based on SSRL (Figure 4) was highly capable of reducing uncertainty and ambiguity in the open project assignments. '*Even though the requirements were at times confusing, the discussion forums, the rubrics and the Q&A sessions helped a lot'. 'I think it (the rubric creation) helped with thinking about how to approach the assignment together'. 'I thought it was a great idea to give us the criteria and have us define the final assessment criteria. By giving us the initial criteria, it also became clearer what should be done for an assignment and by defining the assessment ourselves, it made us think better about the quality of the deliverables to get a certain grade'.*

F5. You cannot please everyone: Some students still felt the need for more structure and less uncertainty and ambiguity. *'I think it would be better if the rubric was just there and that the group is used to discuss the best tactic on how to execute the project plan'.*

F6. The flipped classroom worked well in this course: The students appreciated the possibility of studying the theory at their pace and availability. '*The flipped classroom method enhances the commitment of students and makes it more relevant for students to prepare themselves before lectures'. 'The division of lectures into small chunks followed by quizzes might have brought my first experience with a course during which I did not miss at least 50% of the covered content because I was daydreaming during lectures'.*

F7. The flipped classroom setting can be further improved: Although the lecturer can just-in-time adjust and give examples according to the needs of the students in a live classroom, this flexibility does not happen in video lectures. '*The course material did not cover in the same depth the information required for the different assignments'. 'The micro-lectures could have more practical examples besides the theory so that you understand not only the theory but also how to apply it in the right way'.*

### *5.4. To what extent did the lockdown have an impact on the course?*

Initially, the course intended to implement a flipped classroom and have synchronous interaction (lectures and group meetings) face-to-face. This section summarises the students' perceived impact of the COVID-19 restrictions in place during the course intervention implementation. However, a deeper analysis of this impact and a comparison with other experiences from the literature is outside the scope of this work. Consequently, this summary aims to solely support the reflections on the limitations of this research.

Even though the students appreciated the flipped classroom, they lacked face-to-face interaction during synchronous interaction (lectures), particularly for performing group work. They highlighted that uncertainty and ambiguity reduction would have been more effective and that the lectures, project and functional groups would have performed better with face-to-face interaction. Moreover, planning and executing lecture activities was particularly challenging, especially with supposedly having more than 100 students on the other side of the camera. As mentioned by the students, the lectures ended up lacking energy and content. It is also interesting to highlight that the students did not complain about the recorded theory (videos); on the contrary, they gave mostly positive feedback on the flipped classroom setting. In summary:

- The flipped classroom was a valuable addition as it kept the well-established theoretical content in videos but freed up valuable classroom time for richer lecturer – student interaction.
- Although the online setting reduced the richness of interaction and made it more difficult for the lecturer/tutor to oversee the student groups, project work and individual deliverables reduced this impact.
- The quality of the student groups' interaction was negatively impacted by having only online synchronous interaction.
- The lecturer – group feedback was hindered by the lack of body language exchange during group coaching sessions; however, it was facilitated by sharing the online tools, which the students could use to show their work.

### 5.5. Discussion

Considering the results from the intervention implementation assessment, the guidelines were capable of reducing the negative impact of ambiguous project assignments on the learning process, which affected 36% of the students according to the previous course evaluation. The share of students that initially considered the assignments ambiguous was 27%, 21% and 40% in assignments 1, 2 and 3, respectively. Despite this initial ambiguity, all the students were able to recall the theory, most of them were able to explain the theory after finishing the assignments, and they considered themselves capable of using the theory in future tasks. This indicates that using the guidelines helped create course materials and activities that accommodated initially ambiguous project assignments and allowed gradual uncertainty and ambiguity reduction during the execution of the assignments, where SSRL was recognised by the students as playing a central role. Qualitative feedback revealed that the students recognised the course's relevance to engineering practice (F1), the intervention's engaging and motivating capability (F2) and the rubric creation's usefulness (F4). These results are in line with Jonassen (1997) and Ge, Law, and Huang (2016) who argue that ill-structured problem-solving is a design process based on decision-making and model building, where SRL, CRL and SSRL help the problem-solvers reconcile conflicting problem conceptualisations and construct its solution. The positive effect of the students participating in the rubric creation is also in line with Sadler (2009).

Quantitative and qualitative feedback outlined the role of lecture notes in defining the scaffolding structure and regulating the project assignments' initial uncertainty and ambiguity. The implementation of GDLs 1, 2 and 4, which were applied to the lecture notes, determined the ambiguity level (parameters that were disclosed to the students) and uncertainty level (parameter values that were predefined to the students).

The use of SSRL during the creation of rubrics was a particularly helpful strategy for reducing initial uncertainty and ambiguity while the assignments were executed. Although the COVID-19 restriction hindered synchronous interaction, the students appreciated working as part of a project group and part of a functional group, which also supported gradual ambiguity and uncertainty reduction and contributed to the learning process. In this sense and in line with Butler and Winne (1995), the use of peer and lecture feedback played a central role in the groups' monitoring process and allowed progressive updates and the construction of mental models. Finally, the students' praise of the flipped classroom corroborates with Lou et al. (2012) who demonstrate the positive effect of using a flipped classroom to support self-directed learning when solving ill-structured problems.

Opportunities for further improvement were also identified. An important open challenge is to further motivate the students to collaborate in their project and functional groups and to stop group members from negatively influencing each other's final grading. Another point is to use either uniform terminology across the course material or to map the different terms used interchangeably. The lack of energy during the lectures might be solved when returning to face-to-face synchronous interaction. The final question is how much should the ambiguity and uncertainty scaffolding structure change? Most students appreciated the intervention, but there were still complaints regarding ambiguity and uncertainty. Although it was clear that the last assignment lacked more structure, it seems that the goal should not be satisfying all students but providing a course design that supports the learning of all students regardless of whether or not they are comfortable dealing with uncertainty and ambiguity.

## 6. Conclusion

This study identified, proposed and validated a set of practical guidelines to handle the uncertainty and ambiguity of ill-structured and open project assignments in courses that teach design engineering or design development planning. The literature review identified concepts and key practices for proposing the set guidelines, which were then validated by intervening in an engineering project management master's course. As part of the intervention, the educational materials and activities already used in the course were updated according to the guidelines, and new materials and activities were added. Note that the presented course redesign is one possible example of applying the proposed guidelines, and different implementations might better fit different scenarios. Whatever the shape of the final course design or redesign, it is important that all guidelines are considered.

The intervention occurred when the university was in lockdown and there was no possibility of face-to-face interaction between the lecturer and students and the students among themselves. In the original setting, in-class time was planned face-to-face when group work and lecturer feedback would mostly have taken place. Therefore, this situation posed an additional challenge to group communication during the project work (both in the project and functional groups). Indeed, this was a general complaint among the students. In the flipped classroom setting, where most of the theory was recorded on video, lecturing was hindered by the online setting. Although online synchronous interaction with student groups during the group coaching sessions prevented body language exchange, it also facilitated the sharing of student work. By analysing the academic results, the shift to full online lecturing did not decisively affect the achievement of the LOs.

Nevertheless, the results obtained provide positive evidence that the intervention was capable of better handling the uncertainty and ambiguity of the open assignment than in previous years. Although 36% of students in the previous year pointed out that the uncertainty and ambiguity of the assignments hindered the learning process, during the intervention, students were able to work on initially uncertain and ambiguous assignments and successfully acknowledge their learning. Evidence also suggests that SSRL (rubric creation and peer feedback) was key to this outcome. The achieved results also align with the literature (Bransen et al. 2022; Malmberg, Järvelä, and Järvenoja 2017), which encourages the use of SRL, CRL and SSRL during the teaching of open problems to face their intrinsic uncertainty and ambiguity. No contradictions or new findings resulted from this research.

Even with this evidence, this research was limited by providing only one application that took place in a very specific situation (lockdown). Additionally, most of the students were North European and from the mechanical engineering master's programme, which created a group with a similar mindset. Therefore, these constraints mean that the achieved results might not be replicable in different conditions. To obtain definite evidence, further work in applying the guidelines to other scenarios is required, particularly in a scenario where face-to-face interaction is allowed. Some questions for future research include (1) how to define the ideal ambiguity and uncertainty levels for a given group of students and, therefore, determine the best way to apply guidelines 1–4; (2) how to even out the participation of the group and functional members; (3) how to monitor the impact of actual ambiguity and uncertainty levels on the learning experience and use it to adjust guideline implementation during the course execution.

## Note

1. Each ECTS relates to 28 h of student involvement combining in-class and outside-class work.

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