Electronic Supplementary Material

A "Study and Research Path" enriching the learning of Mechanical Engineering

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S1. List of competences associated to SM

Table S1

List of competences associated to the SM course.

Specific competences
E15: Knowledge and use of Mechanical SM principles. *Learning results* **E15.01**: List the basic laws of SM. **E15.02**: Apply the theoretical concepts of SM in the analysis of mechanical structures. **E15.03**: Apply the theoretical and practical knowledge to determine the distribution of stresses and deformations in any given solid under any system of loads. **E15.04**: Solve problems on SM. **E15.05**: Use the correct techniques and instruments to test the mechanical SM. **E15.06**: Apply the analysis and interpretation of laboratory tests on SM. **E15.07**: Report results on mechanical tests performed on materials.
Transversal competences
T06: Work in multidisciplinary teams, assuming different roles, showing absolute respect for fundamental rights and equality between men and women. **T11**: Assume the ethical responsibility and the economic, environmental, social, legal, and prevention boundaries in normal professional practice.

Note that the two transversal competences are related to ‘team work’ and ‘accounting for boundaries in professional practice’.

S2. Training the students in the SRP

One aspect considered during the *a priori* analysis of the DE was the need to explicitly introduce SRP methodology to the students. In fact, this issue ('what degree of explicitness should be adopted with students?') has been recently addressed (Author, 2015). In the research presented in this paper, we chose to explain the SRP methodology by means of a practical example during the first session while breaking the ice and initiating class participation. The initial question used was (Fig. S1): *Q_0: How do you make a Spanish 'paella'?*

We made a 'braimstorming' with the students and drew up a Q-A map as several ideas to tackle the question emerged. Students proposed different secondary questions Q_i (e.g. what exactly is a paella, are there different types, which ingredients would be necessary, can we find a recipe ? etc.). In the Q-A map the partial answers found in the media ($A_i^{\blacklozenge}$) (e.g. cooking books, asking grandma, trying to cook one…) also appeared. The collective knowledge constructed on paella cooking constituted the class 'own answer' ($A^{\blacktriangledown}$).

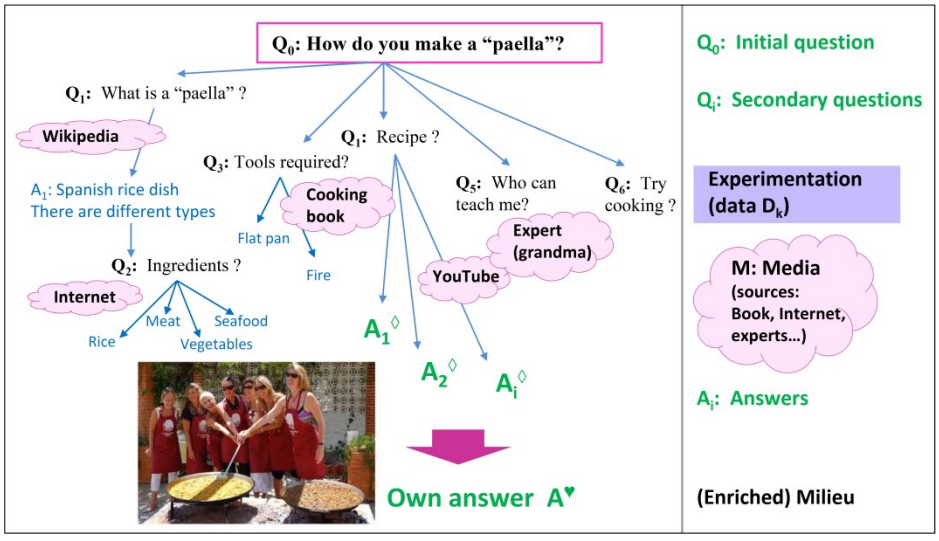

Figure S1. Introductory SRP: 'Q_0: How do you make a 'paella?'

S3. Results of the Survey of the SRP in SM

In order to evaluate the students' opinion on the SRP all students filled out an anonymous questionnaire. The survey was structured in five chapters: General aspects, Team-individual work, Structure and contents, Language (considering it was a course taught in English in Spain) and General evaluation of the course. Each section was composed of a different number of questions evaluated by a four-level scale (Completely disagree – Disagree – Agree – Completely agree). Results are shown in Table S2.

Table S2

Results of the Survey of the SRP in SM.

General aspects				
	Too short	Short	**Adequate**	Too long
Duration	0	10%	90%	0%
	Too little	Little	**Adequate**	Too much
Theoretical contents	10%	30%	60%	0%
	Too little	Little	**Adequate**	Too much
Practical contents	0%	0%	90%	10%
	Too difficult	Difficult	**Easy**	Too easy
Difficulty	0%	30%	60%	10%
	Too little	**Little**	Adequate	Too much
Work load	0%	70%	20%	10%
	Too little	**Little**	Adequate	Too much
Amount of individual work	0%	70%	20%	10%
	Too little	Little	**Adequate**	Too much
Amount of team work	0%	0%	70%	30%
Team work				
Managing tasks in the group	Very difficult	Difficult	**Easy**	Very easy
has been...	10%	30%	50%	10%
Work atmosphere with the	Very bad	Bad	Good	**Very good**
group has been...	10%	0%	30%	60%
It was difficult to get	agree	Agree	Disagree	**disagree**
used to work in group...	10%	20%	30%	40%
	Completely			**Completely**
Results would have been	disagree	Agree	Disagree	**disagree**
better working alon	0%	30%	20%	50%
	Completely			**Completely**
Discussion with colleagues	disagree	Disagree	Agree	**agree**
helped me learning	0%	20%	10%	70%
Language of the course (English)				
English supposed a problem	Completely	Agree	Disagree	**Completely**
for learning	10%	20%	30%	40%
	Completely			**Completely**
The course helped me improve	disagree	Disagree	Agree	**agree**
English skills	10%	10%	10%	70%

Structure and contents of the course				
This methodology has	Completely	Disagree	**Agree**	Completely
stimulated learning by myself	0%	0%	70%	30%
Work atmosphere in the class	Very bad	Bad	Good	**Very good**
has been...	10%	0%	30%	60%
The teacher has motivated	Completely	Disagree	**Agree**	Completely
and helped me	0%	0%	60%	40%
	Completely			Completely
I found the project useful	disagree	Disagree	**Agree**	agree
	0%	0%	60%	40%
	Completely			Completely
The structure of the course	disagree	Disagree	**Agree**	agree
facilitated reaching the objectives	0%	10%	50%	40%
	Completely			Completely
The presentation of 'Outputs' has	disagree	Disagree	**Agree**	agree
been easy	0%	40%	50%	10%
	Completely			**Completely**
The project gave me a clear idea	disagree	Disagree	Agree	**agree**
about what SM is good for	0%	20%	10%	70%
	Completely			**Completely**
Conceptual maps helped me	disagree	Disagree	Agree	**agree**
clarifying the status of learning	0%	20%	10%	70%
	Completely			**Completely**
I found it easy to adapt to such an	disagree	Disagree	**Agree**	**agree**
opgn project	0%	20%	40%	40%
General evaluation				
I consider very positive to have	Completely	Disagree	**Agree**	**Completely**
participated in the SRP	0%	0%	50%	50%
	Completely			**Completely**
This methodology is more	disagree	Disagree	Agree	**agree**
motivating than traditional classes	0%	0%	10%	90%
	Completely			**Completely**
I would like SRP would be	disagree	Disagree	Agree	**agree**
used in other courses	20%	10%	0%	70%

In addition, the students were encouraged to write down up to three positive and negative aspects of the course. The comments are collected in Table S3.

Table S3

Positive and negative aspects highlighted by students. In parenthesis, number of student highlighting each item.

Positive aspects	Negative aspects
You learn how to work in groups; working in groups helps you understand better (8)	Complicated to work in group with lazy teammates (3)
Very practical, related to future work (7)	Clarify which 'Outputs' to deliver each time (2)
Forces you to find solutions, like you will have to do as an Engineer… (2)	More time to present final report (2)
Freedom to exchange and implement ideas (2)	Nothing negative to comment (2)
The objective is to learn; not just memorizing what is necessary to pass an exam (2)	Improve the order of 'Outputs' delivered within the shared Google Drive file (1)
It is easier to understand the subject (2)	Explain more theory (1)
It helped me improve my English (2)	
Very motivating, supportive teacher (2)	
I would like all the courses to be taught this way (2)	
Motivating project (1)	
I was satisfied with what I learned by myself (1)	

S4. Application of SRPs to larger cohorts

The SRP presented in this work was implemented in a relatively small group (12 students), given the exploratory nature of the study. We would like to note that our institution, groups are limited to a maximum of 40 students, and the typical cohort of students in a class is 25.

The design of the SRP should always take into account, as one of the "ecological restrictions", the ratio of students/teacher. The actual design and structure of the SRP presented in this paper (spanning the whole course, and very open in nature), was conceived for a small cohort. It is worth mentioning that after the 2015-2016 experience reported in this paper, the SRP was successfully repeated in academic years 2017-2018 with larger cohorts (25 and 34, respectively).

For larger cohorts, the design of the SRP should be adapted, and this could be done in different ways: e.g. combining in parallel traditional lectures with SRP sessions, deploying the SRP only in half of the course, or "closing" the SRP (i.e. letting less freedom in the inquiry-process). These solutions have been demonstrated in SRPs conducted in other educational fields (mainly in mathematics), showing that a larger cohort does not need to be *per se* a limitation.

S5. Teacher gestures during the SRP

Teacher gestures in an SRP-course differ from those in a "traditional" course. Generally speaking, in the traditional scheme, the assumed didactic contract implies that the teacher is the main source of knowledge, which he transmits to students. The docent provides answers and solves doubts when students face problems. He also ensures that students acquired the transmitted knowledge through some established assessment scheme.

In the SRP, in contrast, the teacher is not the owner and validator of knowledge. The role of the teacher changes into a "class coach", guiding the inquiry activity by performing many different gestures, e.g:

- During the brainstorming, writes down the questions popping up in a Q-A map, and suggests questions whenever an important aspect is being overlooked.
- Promotes participation in debates and discussion.
- Promotes that students critically consider the validity of "outcomes" presented by other students.
- Instead of directly providing answers, uses Socrative questions to make the knowledge in the students emerge.
- Introduces sometimes knowledge pills, or hints towards possible solutions, whenever students are stuck for too long in a problem.
- Trains students in different inquiry strategies to tackle a problem.
- Leads the general development of the SRP, with the help of a general Q-A map: the teacher has to find a balance between, on the one hand, leave the students initiative and freedom to explore ideas, and on the other, refocus the SRP when it diverges to irrelevant questions, or to ensure all important aspects of the program are studied. In this sense, the development of the SRP depends very much on the particular balance chosen by the docent. .

S6. Inquiry organization modes

Throughout the deployment of the SRP, not all the working groups faced all the questions (and subquestions) from Q1 → Q12. Whenever a new question arose in the class, the inquiry was organized typically following two different modes:

1) *"Parallel inquiry":* all the students faced the same conceptual question, which could adopt several variations, and each group would study a different version. This approach was followed in particular when the teacher felt that a particular concept, or a resolution strategy, should be acquired by the whole class.

For example, in question $\mathbf{Q_{4.1}}$ the students dealt with "how to calculate the axial forces and stresses in the legs o the slatted-bed ?". In this occasion, five groups analyzed different leg geometries (Figure S6.1), and the teacher profited the occasion to teach how to make the analytical calculation of axial stresses of columns under compression. After finishing the calculations, the students compared the results, and could answer the question "which type of leg suffers the most (for the same applied load) ?".

Q4.1 What are the axial forces and stresses in the bed legs ?

↓

Different leg geometries are considered

(same applied load)

5 different groups

Each group calculates:

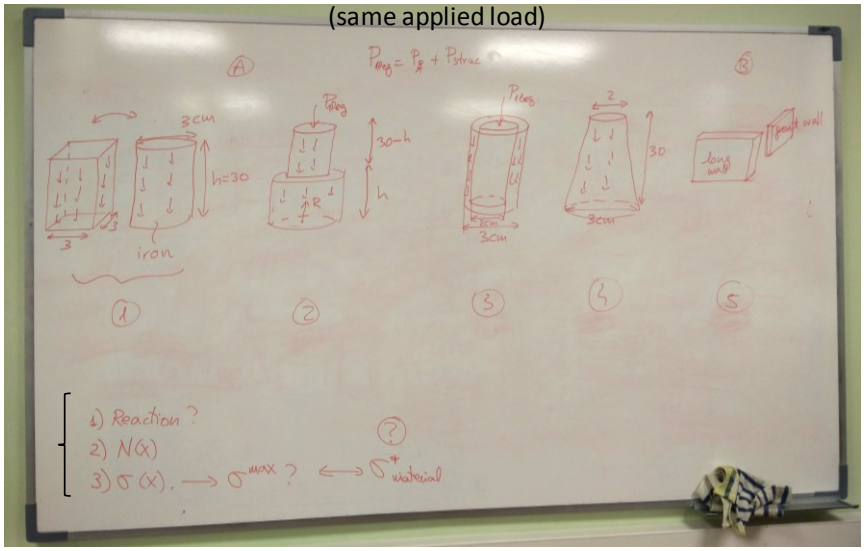

Figure S6.1. *Parallel inquiry* group organization (example 1).

Another example was presented in the study of the slat beams under different load and support configurations (**Q_6**). All the groups faced the problem of calculating the shear forces and bending moments in a slat of the mattress, but each one of the 4 groups formed studied three different possible load configurations (Figure S6.2). Again, after making the calculations, the groups compared the results obtained, so as to conclude which of the cases would be more demanding for the slat.

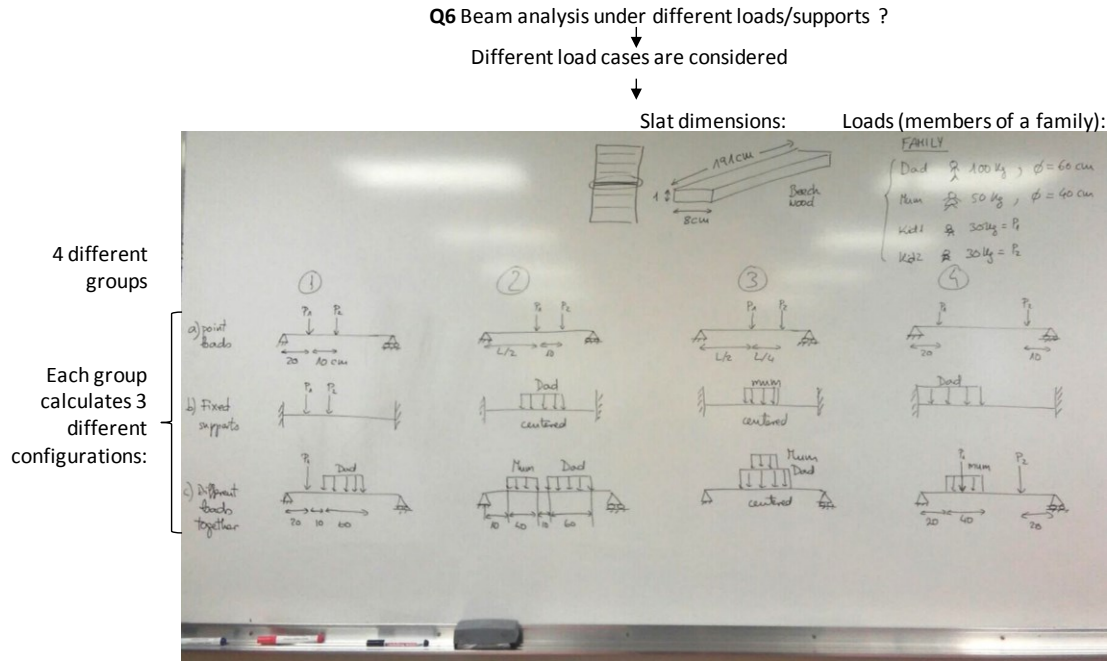

Figure S6.2. *Parallel inquiry* group organization (example 2).

Other examples of *parallel inquiry* occurred when studying experimentally (**Q8.1**) the influence of the beam cross section on the flexure of the beam (different groups tested Al profiles with different cross-sections), or when learning how to calculate the properties of different beam cross sections (**Q8.1.1**).

2) "*Distinct inquiry*": in other occasions, however, depending on the Q-A map arising from the braimstorming, different groups would be working on completely different questions.

For example, when studying the resistance of the frame, one group suggested to study the interconnection between the leg and the frame, which led them to analyze the shear stresses in the screws and welds of the bed legs ($Q_{11.1}$); at the end of their inquiry, they reported the results to the rest of the class. In the meantime, the other groups were making FEM simulations of the frame.

In this type of SRP development, only one group actively works in the inquiry of a particular question, while the others just receive the answer. This scenario resembles the typical teacher-student role.

Also the Long term Questions (LQ1, LQ2, LQ3) were completely different for each group. These questions promoted self-initiative, and search of original solutions.

S7. Usage of Q-A maps

Q-A maps were used both by the teacher and the students through the SRP, in different ways. The main uses, accompanied by illustrative examples, are presented below:

i) Q-A maps were used by the *teacher*:

- To design the SRP course (see the Q-A map of the "Meta SRP" shown in Fig. 1).
- To explain the dynamics of the SRP methodology (see the example, Q_0 –how to make a "paella" ?)
- To organize the questions appearing during the braimstorming.

For instance, Figure S7.1 below shows the initial Q-A map made during the kick-off session of the slatted-bed study.

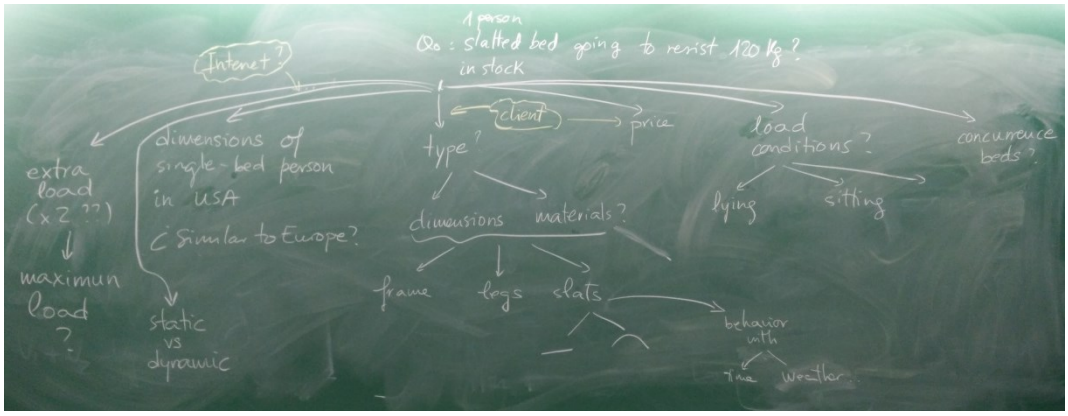

Figure S7.1. Q-A map used by the teacher during the braimstorming session (example 1).

Figure S7.2 shows another example of a Q-A map drawn during a braimstorming, where the students considered in this case the factors influencing the resistance of individual slats of the slatted-bed.

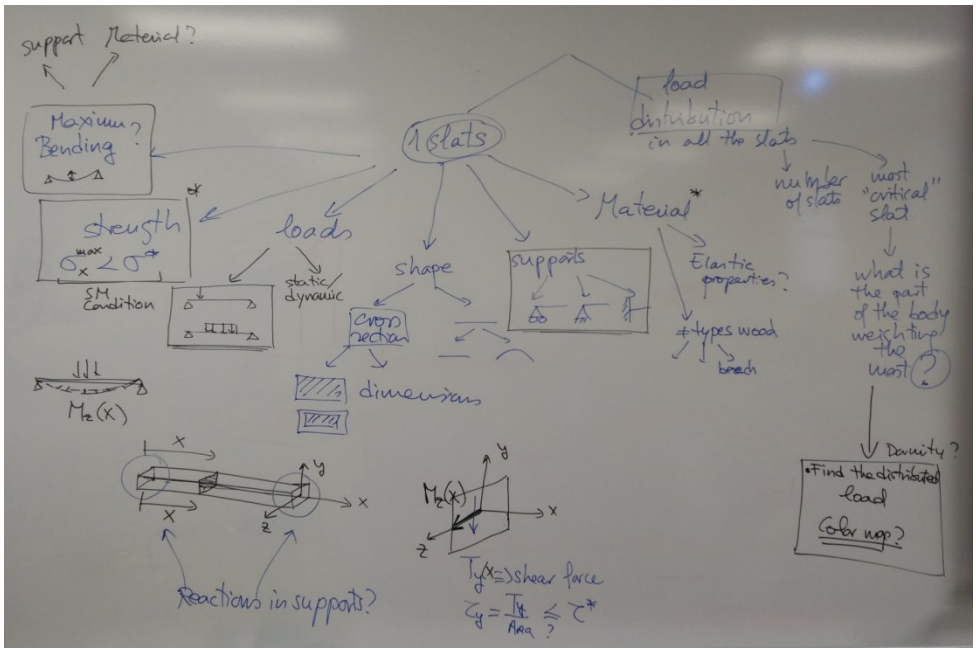

Figure S7.2. Q-A map used by the teacher during the braimstorming (example 2).

- To summarize the state of the project, or the preceding question, at the beginning of a session. For instance, Figure S7.3 below shows the Q-A sketched to remind the students the state of question **Q2**. The teacher reminded that two different slatted-bed models had been considered (Model A including 4 legs, and Model B being supported by a wooden, bulk frame), and that different approximations to take into account the mass had been considered.

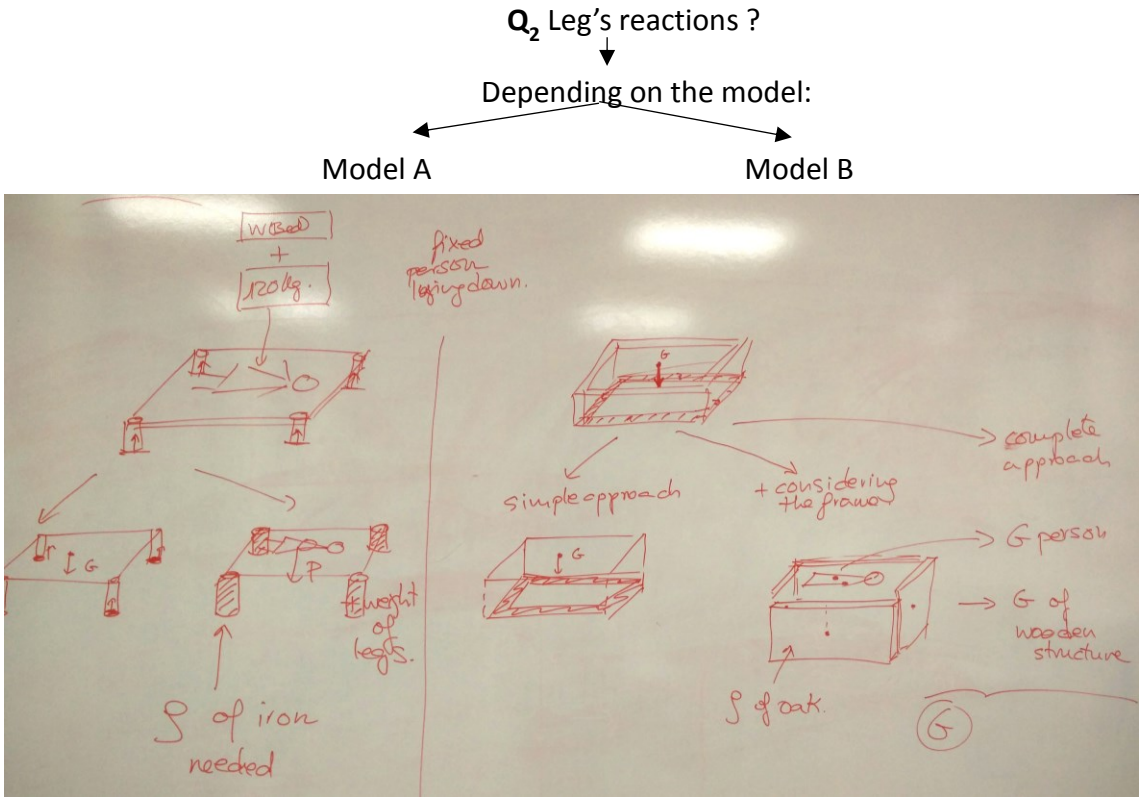

Figure S7.3. Example of Q-A map used by the teacher at the beginning of the session to remind the state of the question.

- To propose variants of a similar question and organize the parallel inquiry (see e.g. Figures S6.1 and S6.2).

ii) Q-A maps were used by *students*:

- To plan their inquiry, following an organized strategy, and distribute the work between the members of the group (*"a priori" Q-A map)*, see example in Figure S7.3.

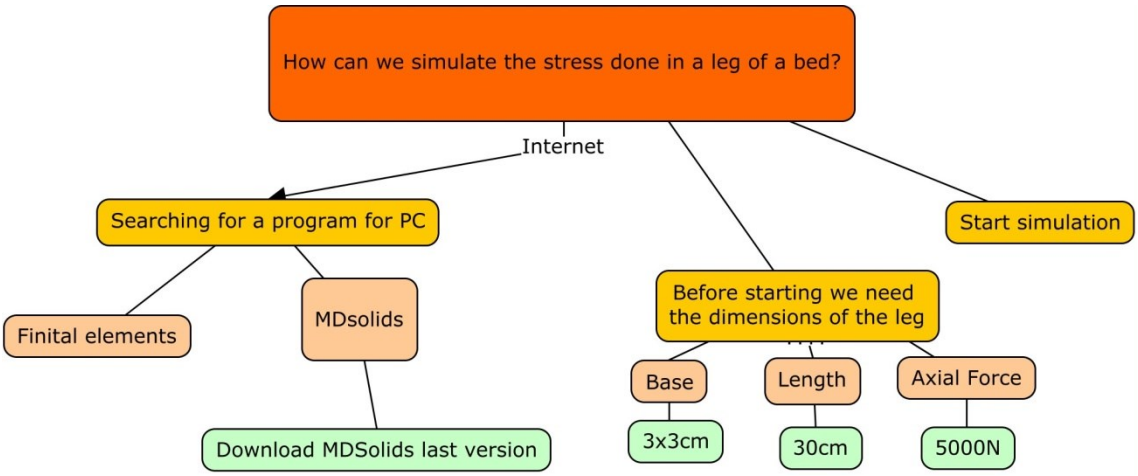

Figure S7.4. Example an "a priori Q-A map" used by students to plan their search.

- To explain the rest of the community (the other students and the teacher) how they deployed their search (*"a posteriori" Q-A map)*, see examples in Figures S7.5-S7.7. A particular subtype were Q-A maps used to summarize a procedure (see S7.8).

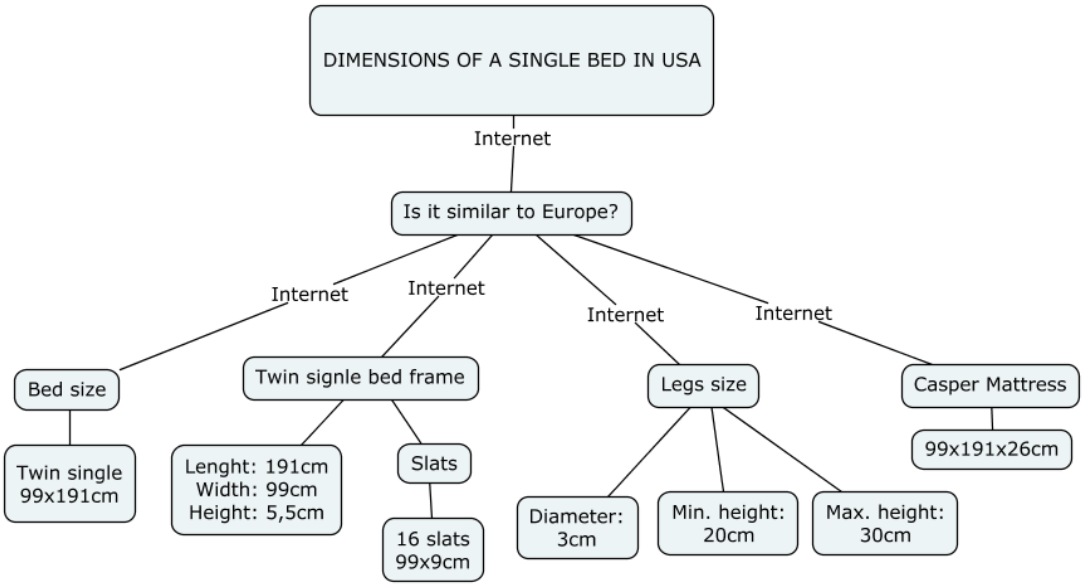

Figure S7.5. "A posterior Q-A map" used by students to summarize their search (ex. 1).

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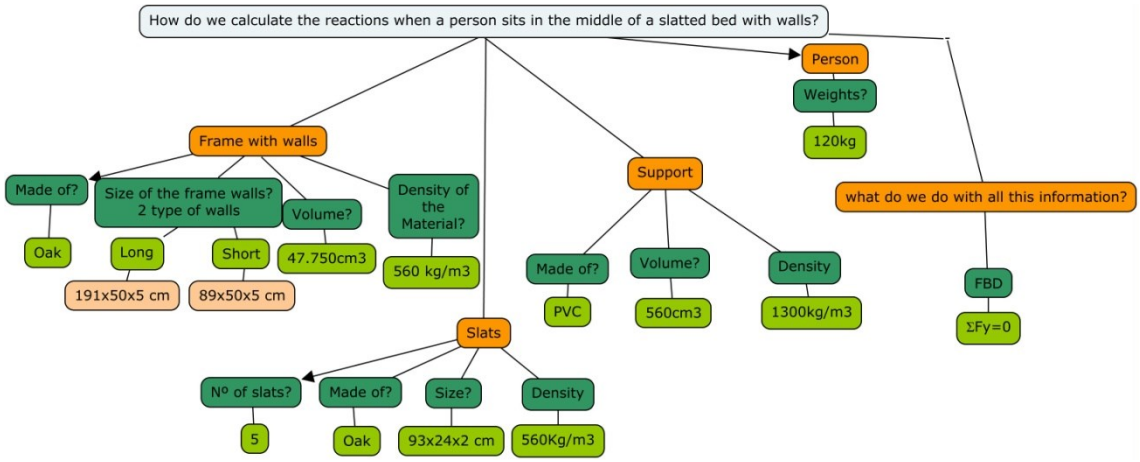

Figure S7.6. "A posterior Q-A map" used by students to summarize their search (ex. 2).

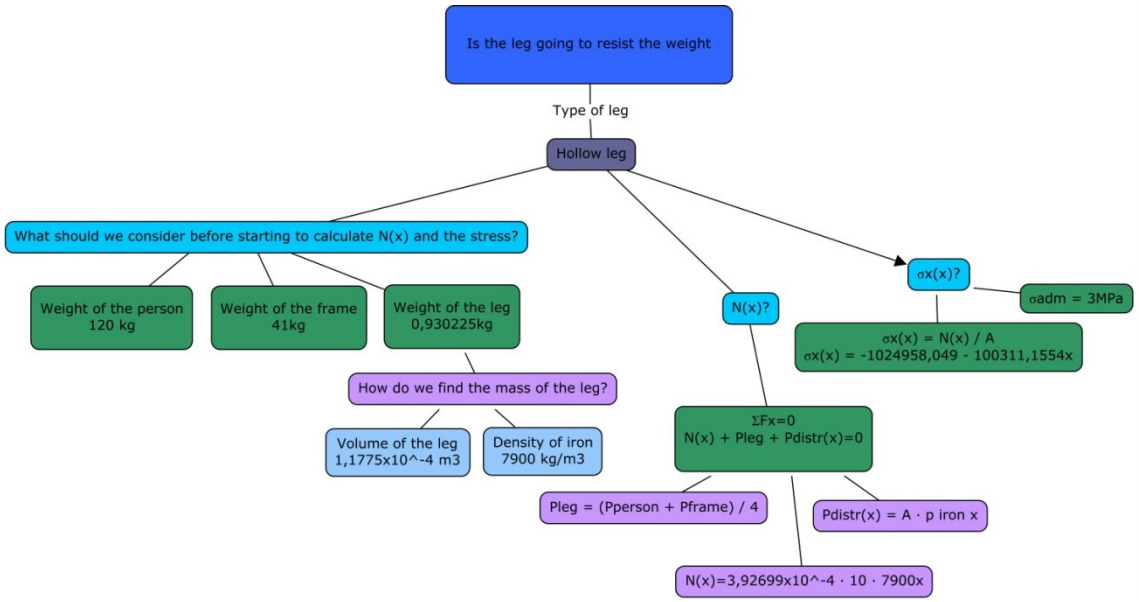

Figure S7.7. "A posterior Q-A map" used by students to summarize their search (ex. 3).

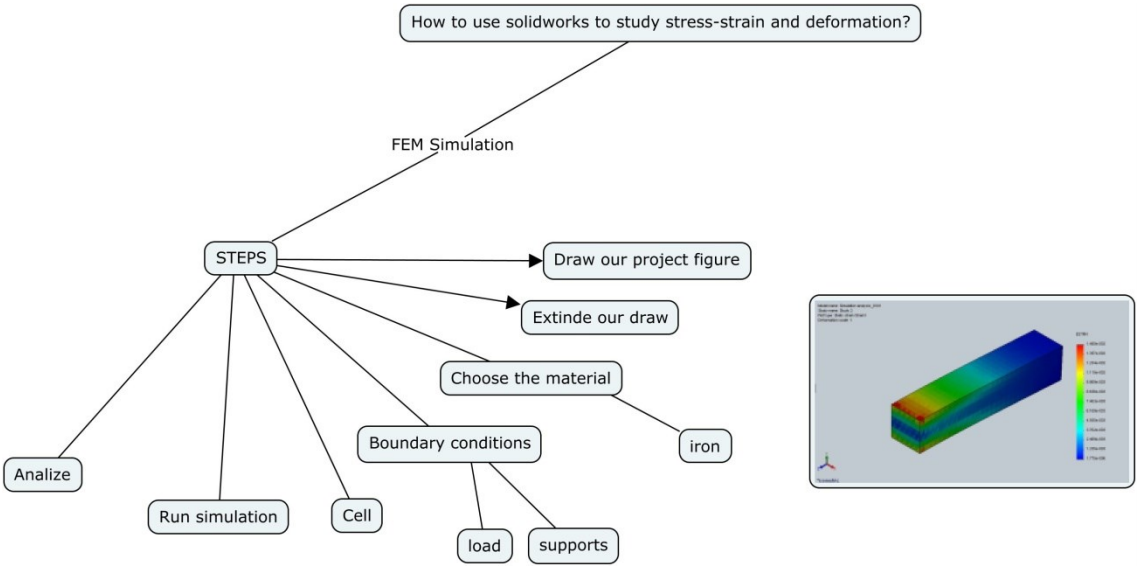

Figure S7.8. "A posterior Q-A map" used by students to summarize a procedure (example 4).

It is worth to remark that there was a certain evolution in the way Q-A maps were used through the SRP. At the beginning of the course, the teacher and students made rather formal Q-A maps in the form of Conceptual maps, using different available software (*Qmaps, Powerpoint, Prezzi*, etc), see for instance Figure S7.4- S7.9.

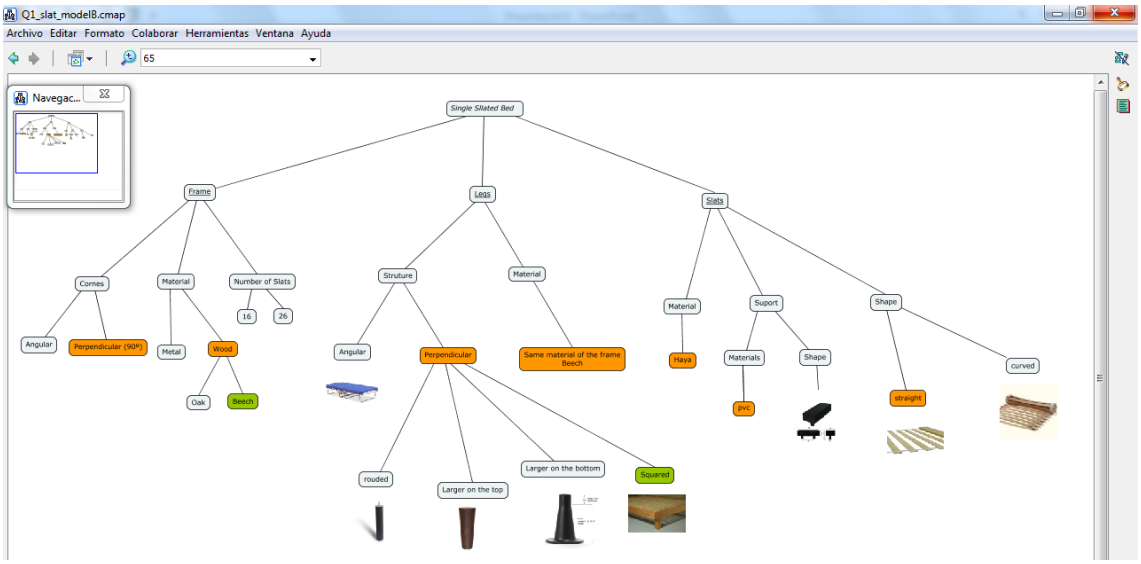

Figure S7.9. Example of Q-A map performed by students using *QMap* software.

As the SRP progressed, the class realized this way of representing diagrams resulted too cumbersome to be practical, and decided to move to a more dynamical work-mode, where Q-A maps were drawn in real time on the blackboard as questions poped up and questions were being found. At the end of the session, one student was responsible for taking a photo of the Q-A map, and loading it up to the common *Google Drive* file for later, collaborative usage (see e.g. Figures S7.1-S7.3).

In our survey, we did not collect the opinion from students about the Q-A maps, but it could be an interesting question to include in future experiences.

S8. Examples of new media influencing the SRP direction

Throughout the SRP the students hat to perform inquiry tasks in order to enlarge the available *media* that was accessible (whether that was information, knowledge, new sources, results of a simulation, an experiment etc), and their findings influenced the direction of the SRP. We comment here a few instances:

Example 1: In question $\mathbf{Q_{10.3}}$, the students had to find the real weight distribution of a person lying on the mattress. The answer was unknown for the class and the teacher, it was not the type of information appearing in a text book, and, after some navigation, it could not be found on the Internet. Some students found out that a bed-shop in the city offered the clients an *in situ* measurement of their weight distribution on a mattress provided with sensors. They contacted the shop and obtained a weight distribution map. The answer obtained (the pressure map) was then used as the input for subsequent questions (e.g. it was used to fix the load in the FEM simulations). Had the students not found this answer, the SRP should have developed in a different direction (e.g. they may have dropped the question, or they could have made an approximation to estimate the weight distribution).

Example 2: In question $\mathbf{Q_5}$, the students wondered if the shortening of the legs could be simulated. On the one hand they proposed to use (Q5.1) FEM-based software, which led them to learn the use of the FEM package in *SolidWorks*. A second group of students searched for software programs based on SM-hypothesis. Although they found one (MD Solids), the software did not include a compression module to simulate the legs. Nevertheless, during their inquiry, the students learned about the conceptually different, "Continuous Media Mechanics" and "Strength of Materials" approaches for analyzing

the stresses in a structural member, which enriched the knowledge of the class on the subject.

Example 3: At the beginning of the SRP course, no "real" slatted-bed was available in the lab. During the long term inquiry activity (**LQ3**), the students considered different options to get a slatted-bed for the study ("Should we just consider a generic, "theoretical" slatted-bed ? Can we find a real one ? Does anyone have a spare slatted-bed at home ? in a waste collection? Shall we buy a cheap one ?..."). After some inquiry, they found a really cheap, second-hand slatted-bed in Wallapop. The particular answer found for LQ3 determined decisively the direction of the SRP, which was thereafter based on that acquired slatted-bed.