

***Implementation of an Efficient Strategy to Analyse the Mathematical Training Required in Undergraduate Degrees in Engineering and Architecture***

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**Abstract**

Engineering and Architecture studies aim to develop professionals capable of facing and solving complex multidisciplinary problems. This requires abilities that cannot be acquired without a comprehensive training model, addressing real-world problems to provide technical solutions. Furthermore, it is necessary to ensure the acquisition of skills to generalise and think abstractly about reality. For this purpose, fundamental disciplines training, such as mathematics, play a relevant role in technical undergraduate studies and their corresponding contents and temporal order traineeship should be properly analysed when designing their curricula. This work describes an active and collaborative methodology used to analyse the mathematical concepts and tools that should be introduced in the undergraduate degrees in the School of Engineering and Architecture at the University of Zaragoza. The methodology applied is based on the activation of communication mechanisms between the teaching staff of mathematical subjects and those of higher courses, in which the students acquire the specific skills of each degree. Moreover, it has motivated interesting discussions between mathematics teaching staff. As a result, a great deal of information has been gathered about the mathematical knowledge required, and its appropriate scheduling, in all degree programs. Also, some deficiencies that should be addressed in the initial training have been identified. Finally, a strategy has been planned for contextualising the mathematical training in different disciplines to help students to understand the relevance of mathematics formation and motivate them in their study.

Keywords: Mathematics, Engineering and Architecture, University Curriculum Design, Multidisciplinarity

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## Introduction

The School of Engineering and Architecture (the School) is one of the largest teaching centres at the University of Zaragoza. It has more than 5000 students, 670 professors, 140 administration and services professionals and offers a total of 9 undergraduate degrees (eight degrees in Engineering and a degree in Architecture Studies), 11 university master degrees and several courses oriented to life-long learning.

With the goal set on training the best students, increasing their capabilities, skills and talent, the School promotes the highest quality standards within a national and international framework. It is a national benchmark in terms of its Quality Management System. In fact, it has been the first Spanish Engineering and Architecture school to achieve the AUDIT certificate by ANECA, the Spanish Agency for Quality Assessment and Accreditation. Nowadays, four of its undergraduate degrees have obtained the European quality stamp EUR-ACE certifying high-quality engineering degree programs in Europe and abroad. The School also pays special attention to continuous improvement and quality assurance in all its degrees, providing professionals that can be integrated into a globalised and highly competitive world.

Increasing data and information in today's society represents a major challenge to multidisciplinary knowledge. In order to set reference points and knowledge relationships, it becomes necessary to establish links between different knowledge areas (Solorzano Movilla et al., 2017). In this context, the study carried out by Serres Voisin et al. (2012) indicates that in undergraduate studies in Engineering and Architecture, mathematics is a tool, rather than a purpose. However, during the last years, some teachers at the School, not only involved in mathematical training, are warning against the lack of mathematical knowledge necessary for the correct follow-up of the subjects in which students must acquire the specific skills of the corresponding curriculum. Sometimes, teachers have to use a portion of the time allotted to specialised subjects for the introduction of the necessary mathematical tools. Consequently, the specific formation at these subjects or the time available to achieve the corresponding learning objectives is reduced.

Therefore, it is very important to precisely identify which mathematical concepts and tools are essential for students to get specific skills in the corresponding study plans. At the same time, it is convenient to establish the most appropriate time frame to acquire this mathematical knowledge, or the ordering and level in which it should be introduced. In this sense, Ooi (2007) discusses the design of mathematics subjects in engineering undergraduate curricula. Different variables, such as the coexistence of mathematical learning with other more technical subjects or the type of mathematics that the future engineer will need, are considered in that analysis.

Conventional teaching in highly practical careers poses difficulties for students because of the large theoretical load and the disconnection of the learned tools and their subsequent application. For this reason, collaborative interdisciplinary learning and teaching methodologies should be integrated (Muñoz La Rivera et al., 2018). A recent review of Pepin et al. (2021) gathers significant ongoing international research on innovative mathematics teaching and learning practices in Engineering degrees. In particular, they analyse promising innovations in mathematics learning procedures and their implications for engineering curriculum reform.

The establishment of the European Higher Education Area (EHEA) involved a restructuring of higher university education. At all the School undergraduate degrees, it led to a concentration of the mathematical teaching and a reduction of the number of mathematical subjects, giving rise to a considerable shortening in the available time for the mathematical training. It should be stressed that this was not the case in other Spanish universities, such as the University Polytechnic of Catalonia, the University Polytechnic of Valencia, the University Polytechnic of Madrid, the University Polytechnic of Cartagena, the University Carlos III or the University of the Basque Country. In fact, the universities of Zaragoza and Cadiz are the Spanish universities with the lowest number of credits in engineering degrees for mathematical training.

Currently, a new Spanish high studies normative (here in after RD 822/2021) establishes the organisation of university education and its quality assurance procedures. It is based on the experience accumulated through the implementation of the EHEA in the Spanish higher education institutions. With the aim of facilitating university graduates a dignified and qualified job, its goal is to strengthen the employability capabilities conferred by the training received in different degrees, based on the skills and knowledge assumed. According to RD 822/2021, the general principles that should inspire the design of the curricula of university degrees are the following:

- a) The academic rigour of the training project implicit in higher education;
- b) The concordance with the generalist or specialised aspect of the cycles in which the teaching is inscribed;
- c) The coherence between the learning objectives of the curriculum, the fundamental competencies that are pursued and the established student learning assessment systems;
- d) Its social understanding.

Under these considerations, the aforementioned RD 822/2021 provides an excellent opportunity for adapting the degrees of the Spanish Universities to the current needs of society. In the School, the necessary cogitation to identify improvement and upgrading aspects in Engineering and Architecture diplomas at the University of Zaragoza has begun. In this context, the authors have participated in a Centre Strategic Innovation Project (CSIP) to determine the learning outcomes to be obtained by students in mathematical subjects, as a necessary tool in subsequent technological subjects. The performed analysis is similar to that of a complete curriculum versus future work in a company (Fitzpatrick et al., 2009).

In other similar studies, the perceptions of a sample of students regarding the relevance of different learning outcomes obtained in different subjects were collected (Arias-Rueda et al., 2017 and Castro et al. 2008). However, to achieve our objective, effective channels of communication among teachers have also been identified as necessary (Yeomans and Atrens, 2001 and Walkington, 2002). Furthermore, as it is going to be explained, the adopted strategy will facilitate the contextualization of the teaching in the mathematical subjects offered in the study plan of all the undergraduate degrees of the School.

In order to describe the mathematical prerequisites expected for new undergraduate students in STEM, Deeken et al. (2020) carried out a Delphi study with German university professors of first term mathematics courses. This research consisted of an iteration of expert surveys that provided feedback to the participants after each survey round. In contrast, in this work we describe a different strategy, which is based on an active and collaborative methodology

aiming to highlight the mathematical knowledge needed in the technical disciplines of higher courses and to activate communication mechanisms between teachers of mathematical and technological subjects. In Section 2, we describe the strategy followed along the CSIP. The experience of its application and the main results are analysed in Section 3, and finally a Conclusions section closes the paper.

## Methodology

In this section, we describe the strategy followed within the CSIP for the analysis and dissemination of the mathematical training required for the acquisition of specific Engineering and Architecture skills. The CSIP members are part of the teaching staff of different knowledge areas in the School, not only those related to mathematics. This diversity in the training profile of its components has facilitated and enriched the design and implementation of working methodologies, as well as the analysis and dissemination of results. The work has been organised into four phases or stages (see Figure 1):

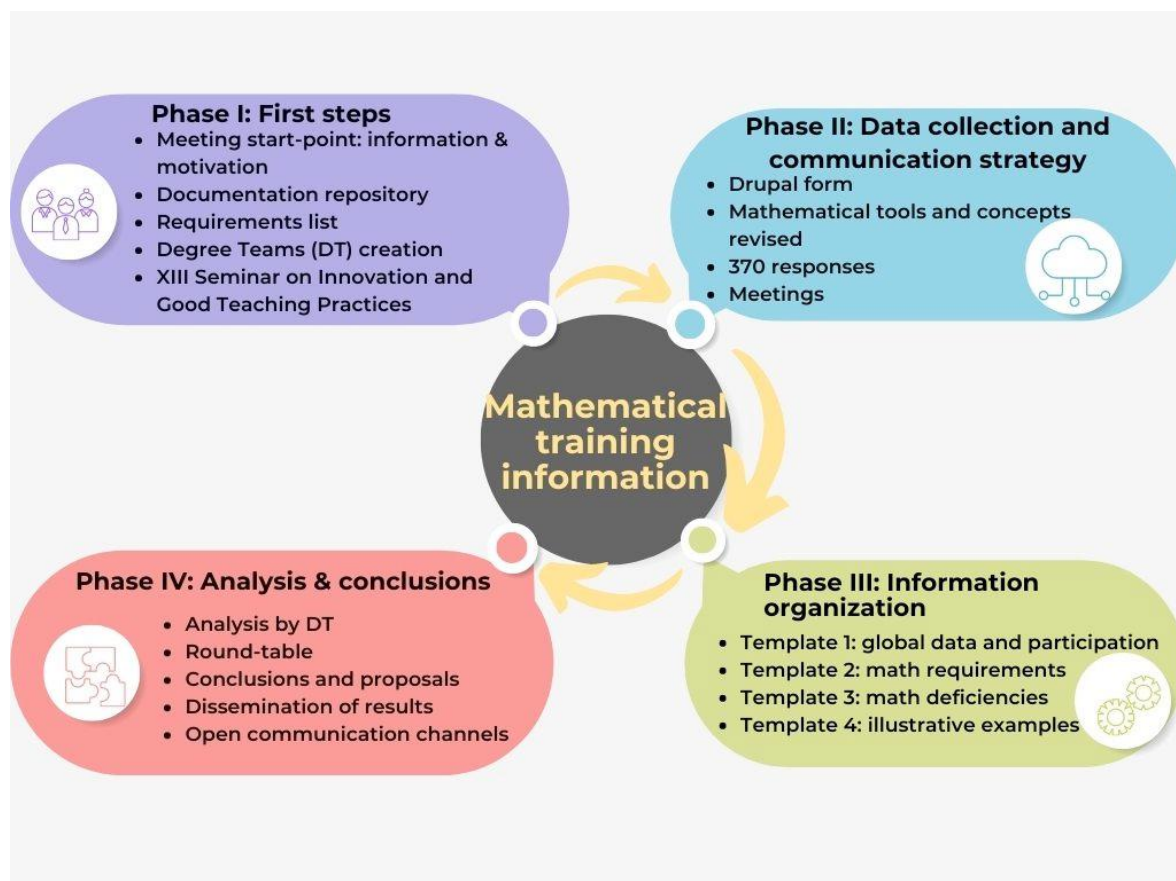


Figure 1: Sketch of the proposed methodology.

### Phase I: First steps and dissemination of the innovation project objectives.

At a first step, the project components held a series of meetings to share concerns that prompted their participation. During these sessions, a comprehensive approach and some methodological aspects were set up. In addition, degree teams (DT) were established for the organization of the tasks. During this period, a virtual platform (Moodle: <https://moodle.unizar.es/add/>) was created as a repository for documentation and efficient communication tool among project members. All the meetings were very rewarding, in

particular due to the exchange of ideas and impressions among professors of mathematics and other subjects. In order to establish efficient communication channels allowing a constant flow of accurate information, the convenience of unifying the nomenclature to refer to mathematical tools was highlighted.

The most important goals of the CSIP, as well as those related to its methodology, were presented at the XIII Seminar on Innovation and Good Teaching Practices (see [https://eina.unizar.es/sites/eina.unizar.es/files/archivos/Calidad/innovaciondocente/xiii\\_seminario\\_innovacion\\_eina.pdf](https://eina.unizar.es/sites/eina.unizar.es/files/archivos/Calidad/innovaciondocente/xiii_seminario_innovacion_eina.pdf)). This presentation sparked interest of other professors who joined the project.

### **Phase II: Design of the data collection and communication strategy.**

At this stage, a Drupal form was elaborated to gather information. Its link was sent to the professors of all degrees of the School, asking for identified mathematical requirements for the subjects, as well as gaps they are finding during their teaching (see <https://eina.unizar.es/requisitos-matematicos-requeridos-para-la-adquisicion-de-las-competencias-especificas>).

In order to design the collection data form, a list of 36 mathematical topics and tools were established. During the last few years, some teachers of the School are pointing out that the mathematical training of the newly arrived students is increasingly poor. So, some mathematical concepts and tools from pre-university studies were also incorporated. The list was reviewed by all project members to ensure that it was complete, understandable and balanced between enough detail and not excessive length. The option to specify that a subject does not require any mathematical background was also included. Finally, teachers could also refer to not listed identified requirements or gaps and indicate the availability of simple exercises in the context of their subjects, related with the listed requirements.

The link to the form was sent to the coordinators of the nine degrees of the School, requesting its distribution among the corresponding degree professors. The link was accompanied by an email highlighting that the aim of the project was to provide students with the opportunity to acquire the specific skills of the corresponding curriculum. It was also announced that, once the information had been analyzed, a meeting would be scheduled to share the conclusions and to discuss possible needs and opportunities for improvement.

All submitted information was automatically downloaded into an Excel spreadsheet.

### **Phase III: Organization of the information collected.**

During this phase, the project focused on defining an efficient strategy to organise the vast amount of information gathered. In order to analyse, illustrate and draw conclusions, four templates were designed.

*Template 1* was devoted to processing general information for each degree, in terms of percentages of received responses per course and per semester, percentages of subjects that do not require mathematical training and, finally, percentages of subjects in which some gaps or deficiencies had been detected. This template also included the list of subjects for which a response to the form had or had not been received.

*Template 2* was devoted to processing the information collected on mathematical requirements by subject and semester. A table was included in the model with columns representing the various semesters of the curriculum ( $S_j$ ,  $j=1, \dots, 8$ , for the Engineering degrees and  $S_j$ ,  $j=1, \dots, 10$ , for the Architecture Studies degree). The rows were aligned with the different requirements. In particular, the first row was reserved for subjects with no mathematical requirements. The following rows matched the requirements ( $R_i$ ,  $i=1, \dots, 36$ ) included in the form. Note that, in many cases, several  $R_{ik}$  rows were needed for the same requirement  $R_i$ . In the cell ( $R_{ik}, S_j$ ), the administrative code of the subject  $k$  in semester  $S_j$ , in which requirement  $R_i$  had been indicated, was introduced. Finally, the last rows contained those requirements that had been additionally stated in the answers to the form by the teachers. This kind of information representation made the temporal analysis of mathematical requirements easier in all the degrees.

*Template 3* was devoted to processing information on detected mathematical deficiencies and analysing their possible causes. A table similar to template 2 was created. Its rows and columns indicated the unacquired requirements  $R_i$  and the semesters  $S_j$ , respectively. However, in each cell ( $R_{ik}, S_j$ ) the code of the subjects was accompanied by a key (1, 2 or 3) encoding the reason for the reported deficiency:

- Key = 1 meant that  $R_i$  had been explained but forgotten,
- Key = 2 meant that  $R_i$  was not included in the study plan,
- Key = 3 meant that  $R_i$  was introduced and studied later in the study plan.

The maths teachers of the DT settled these keys by reviewing the content of the degree subjects.

*Template 4* was devoted to elaborating the list of professors indicating the availability of simple examples for the illustration of the utility of a requirement  $R_i$ . In this template, a table was also created to show in each row the information concerning the teaching staff and the corresponding subject: name, email, knowledge area, subject administrative code, subject name, degree, course and semester. In the next columns, rows showed all the mathematical requirements  $R_i$  identified by the teachers. All this information was easily obtained from the Excel spreadsheet provided by the Drupal form. Finally, in the last columns, some information tracking was also introduced: teacher contacted (yes or no / person who has contacted), permission to use the material provided by the teacher (yes or no), received material (yes or no).

From the information collected in the Drupal form, each DT filled out the four above-mentioned templates.

#### **Phase IV: Analysis of the information and preliminary conclusions.**

In this phase, each DT analysed the data collected in the form (phase II) and organised it in the templates (phase III). Subsequently, all DT's analysis were shared and discussed in a round table. A report format document was designed to capture conclusions in all the degrees.

In addition to these conclusions, some proposals for improving the corresponding degrees curriculum were suggested. In this sense, some non-required mathematical concepts were detected. In some subjects, some changes in the temporal order of the teaching were proposed

for the refinement of the sequencing of contents. Furthermore, it was also considered a possible inclusion of more mathematical credits to accomplish the identified deficiencies in some degrees.

An important goal of the project was to enable communication mechanisms between mathematicians and non-mathematicians teachers. For this reason, a meeting with the whole teaching staff of each degree was scheduled. Using template 4, a personalised invitation was sent to the teachers who had indicated the availability of simple examples to illustrate the use of mathematical tools in the context of their subjects. During these meetings, each DT presented the conducted analysis, as well as the conclusions drawn, explaining the appropriate format of the requested examples in order to make them as useful as possible. Finally, a time period was established to ask for clarifications, provide new information and nuance some conclusions. In this way, an interesting communication channel was initiated. It will be maintained over time while serving as a triangulation instrument, adding more rigour to the research carried out (Rodríguez et al., 1996).

### **Experience and results**

The initial number of project members was 24 and after the first meetings (Phase I) 2 more professors joined the project. In particular, 14 participants were involved in mathematical teaching and 12 in non-mathematical teaching. At Phase II, 36 mathematical requirements were listed in the form: 3 corresponding to mathematical knowledge that should be acquired before university, 8 from Calculus, 5 from Differential Equations, 9 from Algebra and, 7 from numerical methods, finally, 4 from Statistics and Optimization.

The form was available for two weeks and was sent to all the School's faculty. A total of 370 responses were received. Table 1 displays, for each degree, the total numbers of subjects and semesters of the corresponding study plan, as well as information collected in Template 1: the numbers of received responses, subjects with provided information (sometimes, professors in different teaching groups sent information of the same subject) and, finally, subjects reporting no maths requirements. Table 1 highlights this information in light pink.

<i>Degree in</i>	# Subjects	# Sem.	# Responses	# Subjects with info (%)	# Subjects with no requirements reported
Architecture studies	50	10	30	29 (55%)	8
Chemical Eng.	41	8	50	38 (92.6%)	4
Computer Eng.	63	8	52	47 (74.6%)	16
Electrical Eng.	42	8	31	28 (66.7%)	0
Electronic and Automatic Eng.	43	8	34	28 (65.1%)	0
Industrial Design Eng. and Product Development	52	8	36	32 (61.5%)	16
Industrial Technology Eng.	53	8	62	38 (71.7%)	1
Mechanical Eng.	51	8	35	32 (62.7%)	1
Telecommunication and Services Eng.	60	8	40	37 (61.7%)	1
<b>Total</b>	<b>455</b>	<b>8 or 10</b>	<b>370</b>	<b>309 (68%)</b>	<b>47</b>

Table 1: General information and collected data about degree subjects (Template 1).

Analysing Table 1, significant differences on the participation in the different degrees can be observed. Figure 2 displays the number and percentage of responses collected in each degree over the absolute number of collected responses. Let us observe that the Industrial Technology Engineering degree provides the greatest number of responses, 16.8% of the data collected. On the contrary, the degree in Architecture studies only supposes an 8.1% of the data.

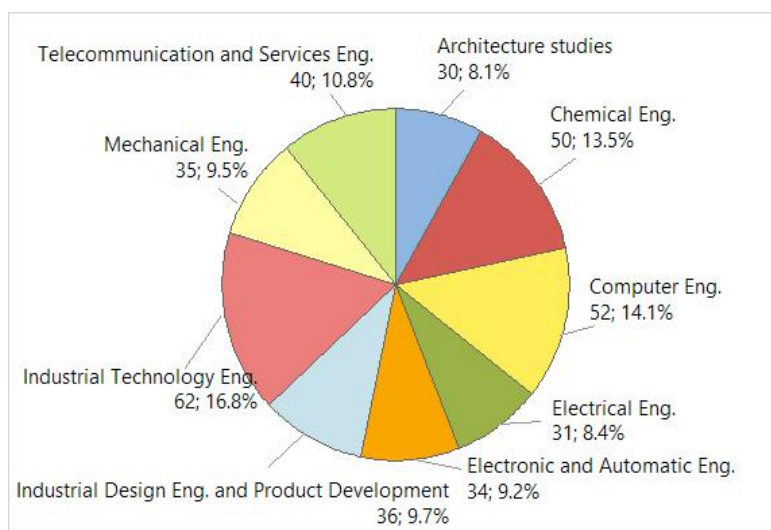


Figure 2: Number of responses and percentage of participation per degree.



A temporary participation analysis is shown in Figure 3, where the total number of responses for all the subjects at each semester is represented. The number of responses collected in semesters 9 and 10 corresponds to the degree in Architecture studies, which is the unique degree with 10 semesters instead of 8, as all the others. For this reason, from now on, only information of the first 8 semesters will be considered in order to simplify the illustration of the performed analysis.

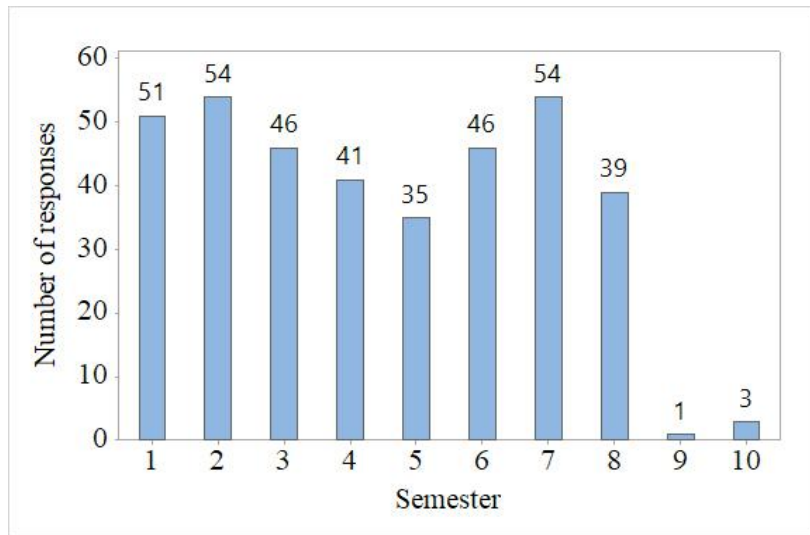


Figure 3: Total number of collected responses in each semester.

Next, Figure 4 illustrates, for each degree and semester, the percentage of subjects in which at least a response to the form has been received. The red line provides a reference at 50%. It can be easily checked that, in all the degrees, a response rate over 50% has been obtained in almost all semesters. Let us also observe that semester 8 presents the lowest participation rate. This coincides with the fact that, mainly, optative subjects and the final undergraduate project are offered to students in this semester.

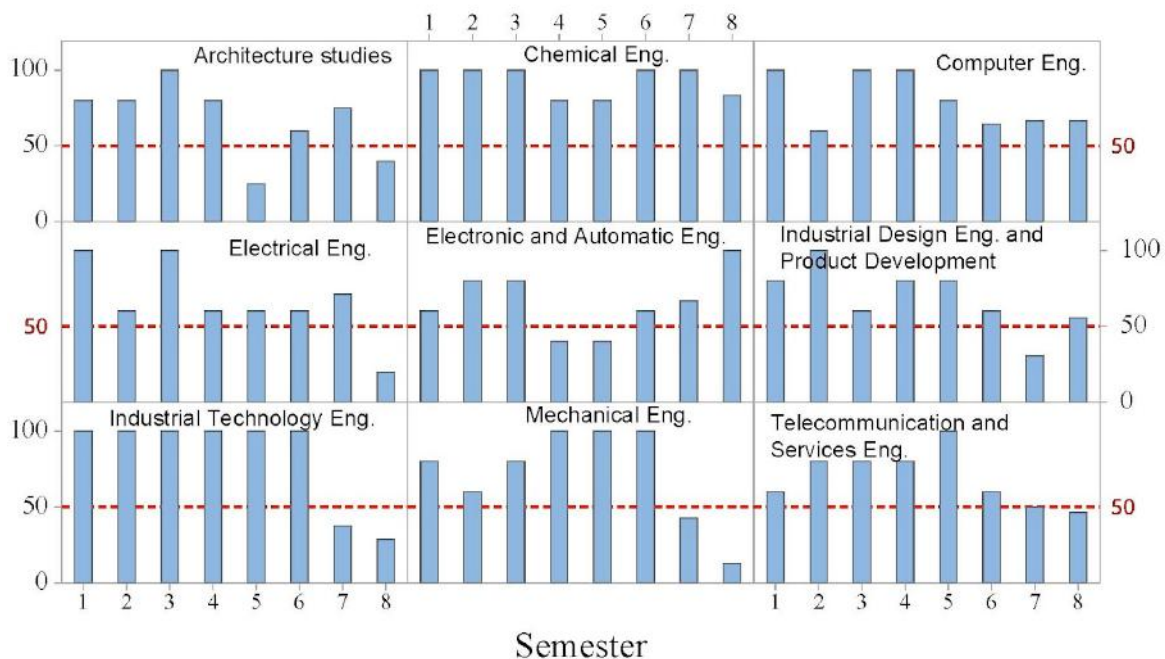


Figure 4: Percentage of subjects with at least a response per semester and degree.

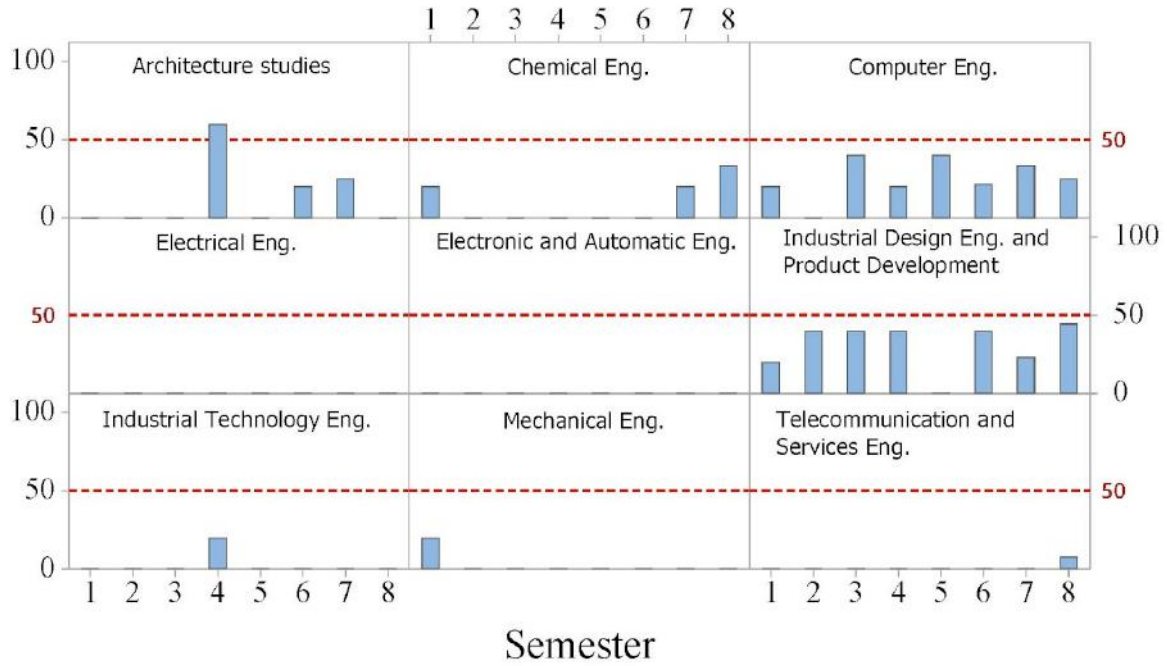


Figure 5: Percentage of subjects with no mathematical needs reported per semester and degree.

Figures 5 and 6 provide detailed information on the number and the percentage of subjects for which no mathematical needs have been reported. As illustrated in Table 1, there are 47 over 309 subjects with response. The pie chart in Figure 6 compares among degrees the corresponding number and percentage in the total set of 47 subjects. It can be observed that 85% of these subjects are distributed in only three degrees: in Industrial Design Engineering and Product Development, in Computer Engineering and in Architecture Studies. For the rest of degrees, the corresponding percentage is very low. In fact, in Figure 5 we can check that there are two degrees (in Electrical and in Electronic and Automatic Engineering) in which at least a response has been received requiring mathematical knowledge in all the subjects, so they do not appear in Figure 6.

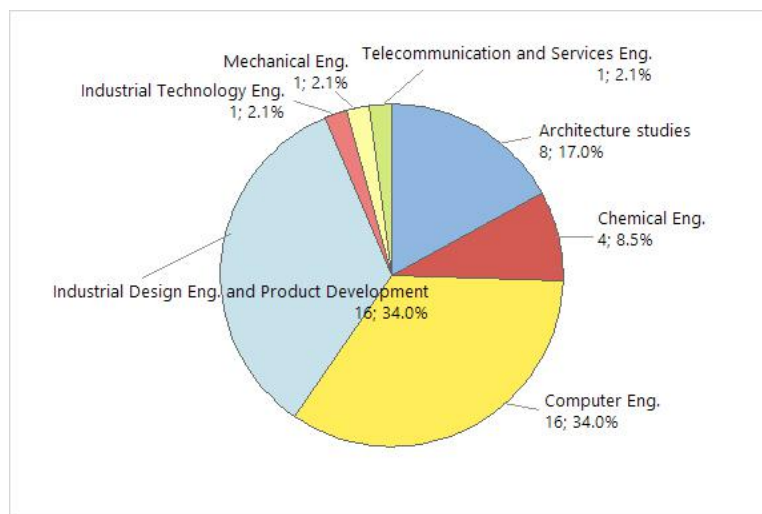


Figure 6: Number and percentage of subjects with no mathematical needs reported.

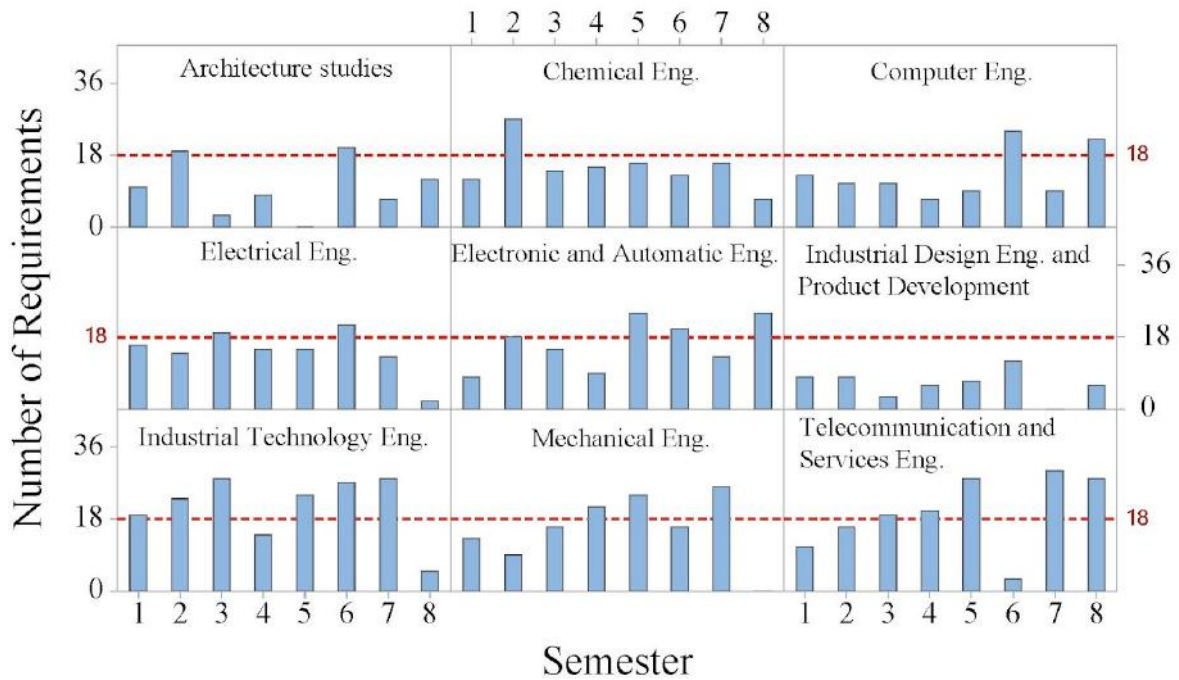


Figure 7: Number of mathematical requirements for each degree and semester.

Figure 7 shows in each degree, for each semester, the number of mathematical requirements out of the total set of 36 requirements. Those requirements that were reported in more than one subject have been considered only once. Furthermore, Figure 8 shows the number of requirements per semester counted as many times as they have been reported in the forms related to each semester. For instance, the maximum is achieved in semester 7 of the degree Telecommunication and Services Engineering, in which a total of 96 mathematical requirements were marked among the forms corresponding to the 19 subjects implied in this semester.

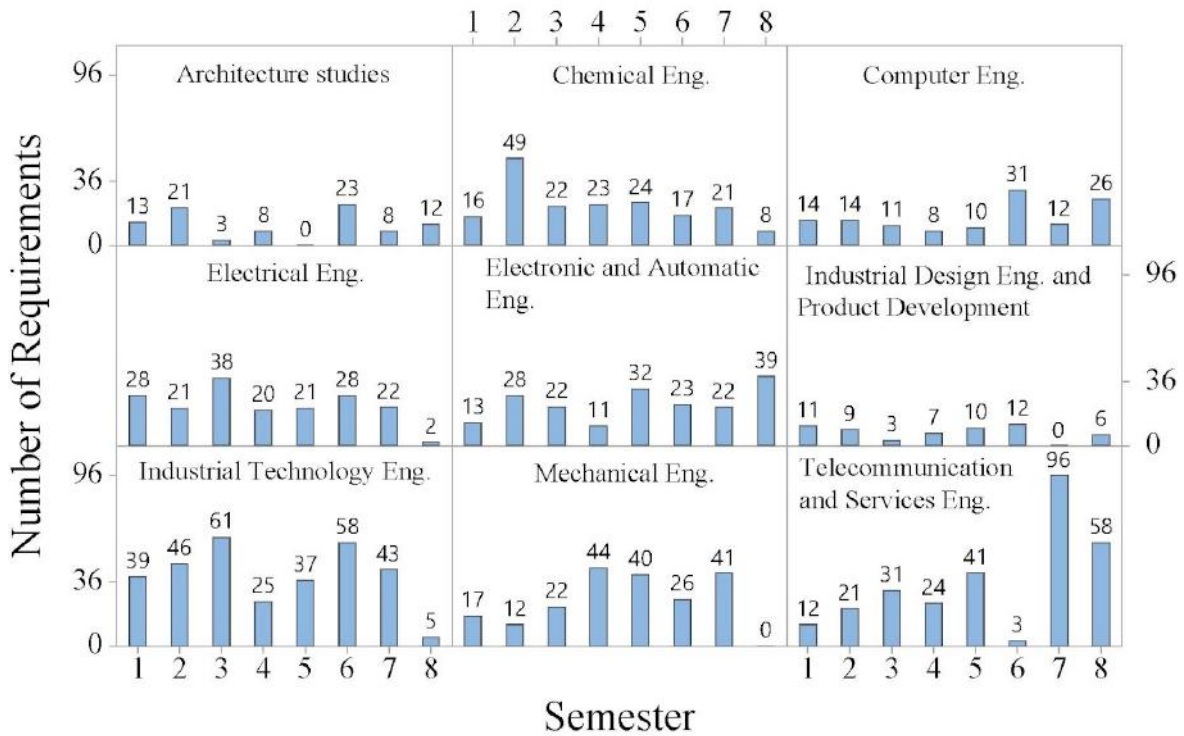


Figure 8: Number of the mathematical requirements (counting repetitions) for each degree and semester.

A similar representation is shown in Figures 9 and 10 to analyse the number of mathematical deficiencies reported. From the total set of 309 subjects with at least one response to the form, some deficiencies are detected in 119 subjects. As it can be seen in Figure 9, deficiencies are usually detected in subjects in the first years of the program. Let us observe that mathematical gaps have been reported for more than a half of the subjects in five (of eight) semesters of the degree in Industrial Technology Engineering.

It is also observed that even the degrees that previously had fewer requirements have detected deficiencies in Mathematics. A reason may be that the subjects that did mark mathematical requirements also detected deficiencies in those requirements. This is not as surprising as it may seem, since the mathematical training in the degrees in Architecture Studies and in Industrial Design and Product Development Engineering is less than in the rest of the degrees of the School. On the other hand, in the Telecommunications Services Engineering degree, from the fourth semester onwards, no deficiencies are detected. It should be noted that the study plan of this degree provides 6 more credits than the rest of the degrees in Engineering. This fact can explain that in the distribution of the 119 subjects in the degrees displayed in Figure 10, only 5.9% of the subjects correspond to Telecommunications Services Engineering degree.

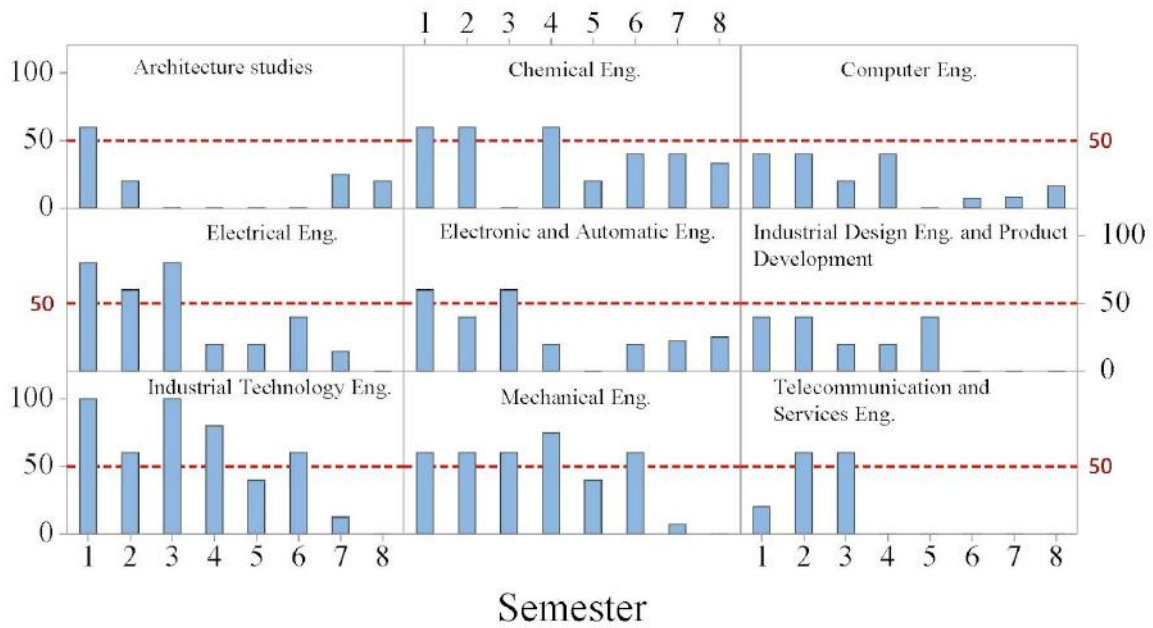


Figure 9: Percentage of subjects with mathematical deficiencies detected per semester and degree.

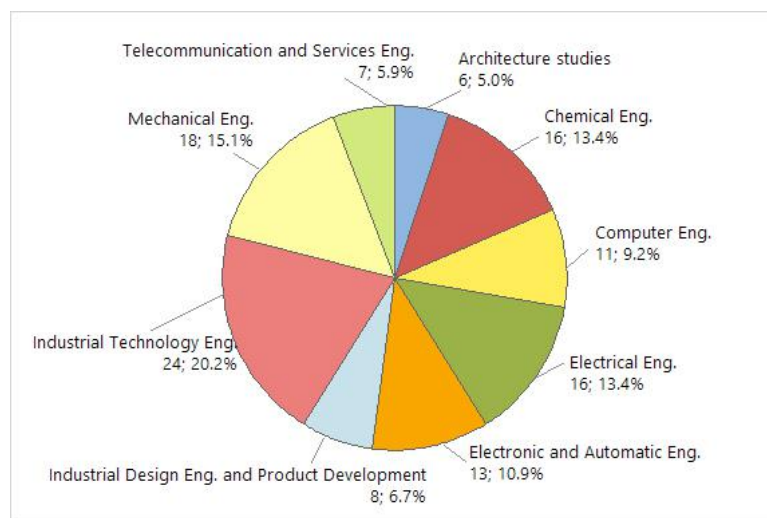


Figure 10: Number and percentage of subjects with mathematical deficiencies detected.

On the other hand, Figures 11 and 12 illustrate, for each degree, the frequency of each requirement and deficiency, respectively, that is, the number of times (counting repetitions) they have been reported in the different subjects of the degree. In these figures, degrees have been denoted by  $D_i$ ,  $i=1, \dots, 9$ , and identified by colours. Moreover, Rows  $R_j$  and  $DF_j$ ,  $j=1, \dots, 36$ , identify the listed requirements and those reported as deficiencies, respectively. Let us notice that they have been listed by knowledge groups. The sum of the frequencies for all requirements and degrees is 1638. As far as deficiencies are concerned, the sum of the frequencies is 291.

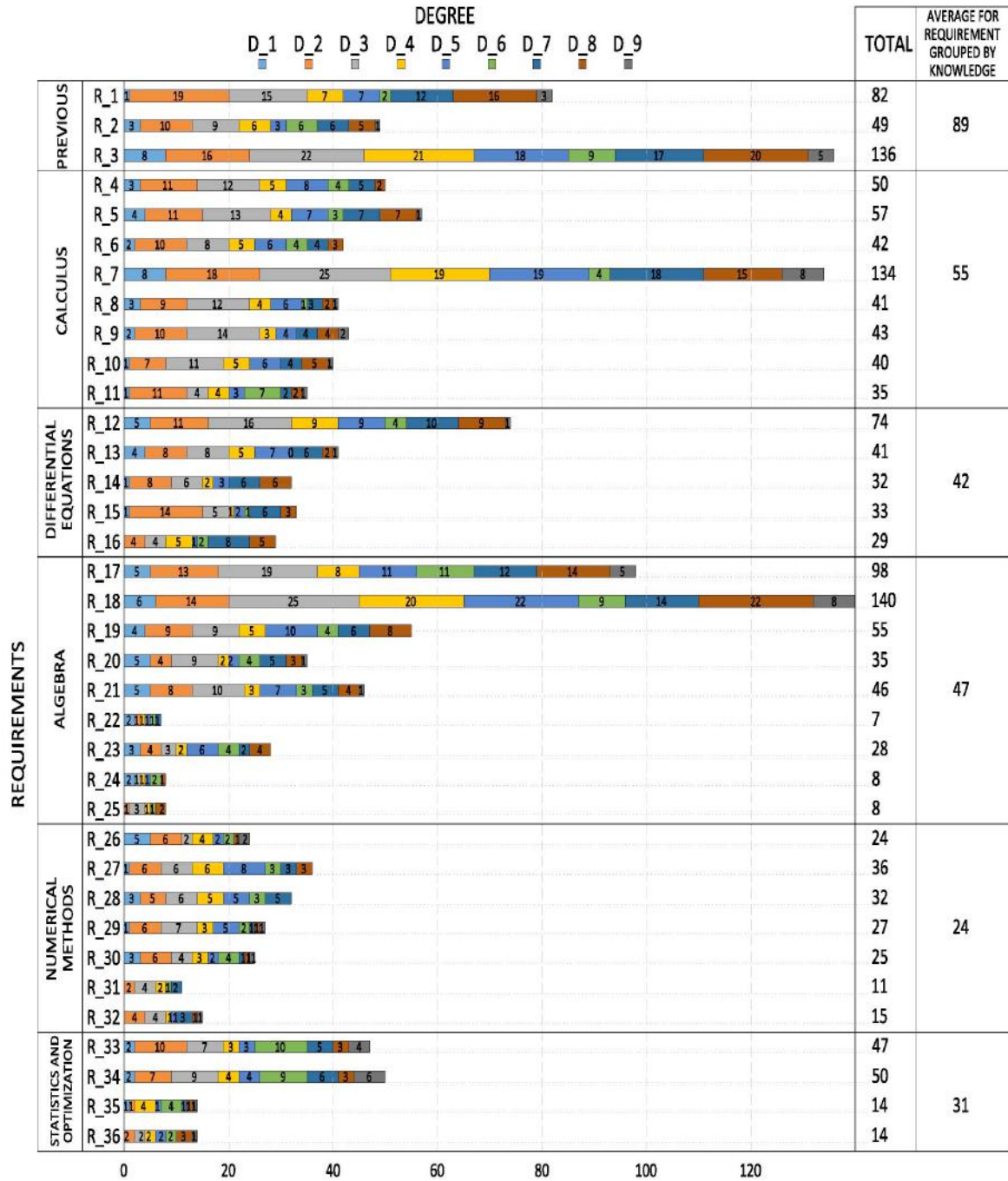


Figure 11: Mathematical requirements for degree (D\_1: Architecture studies, D\_2: Telecommunications and Services Engineering, D\_3: Industrial Technology Engineering, D\_4: Chemical Engineering, D\_5: Mechanical Engineering, D\_6: Computer Engineering, D\_7: Electronic and Automatic Engineering, D\_8: Electrical Engineering, D\_9: Industrial Design Engineering and Product Development).

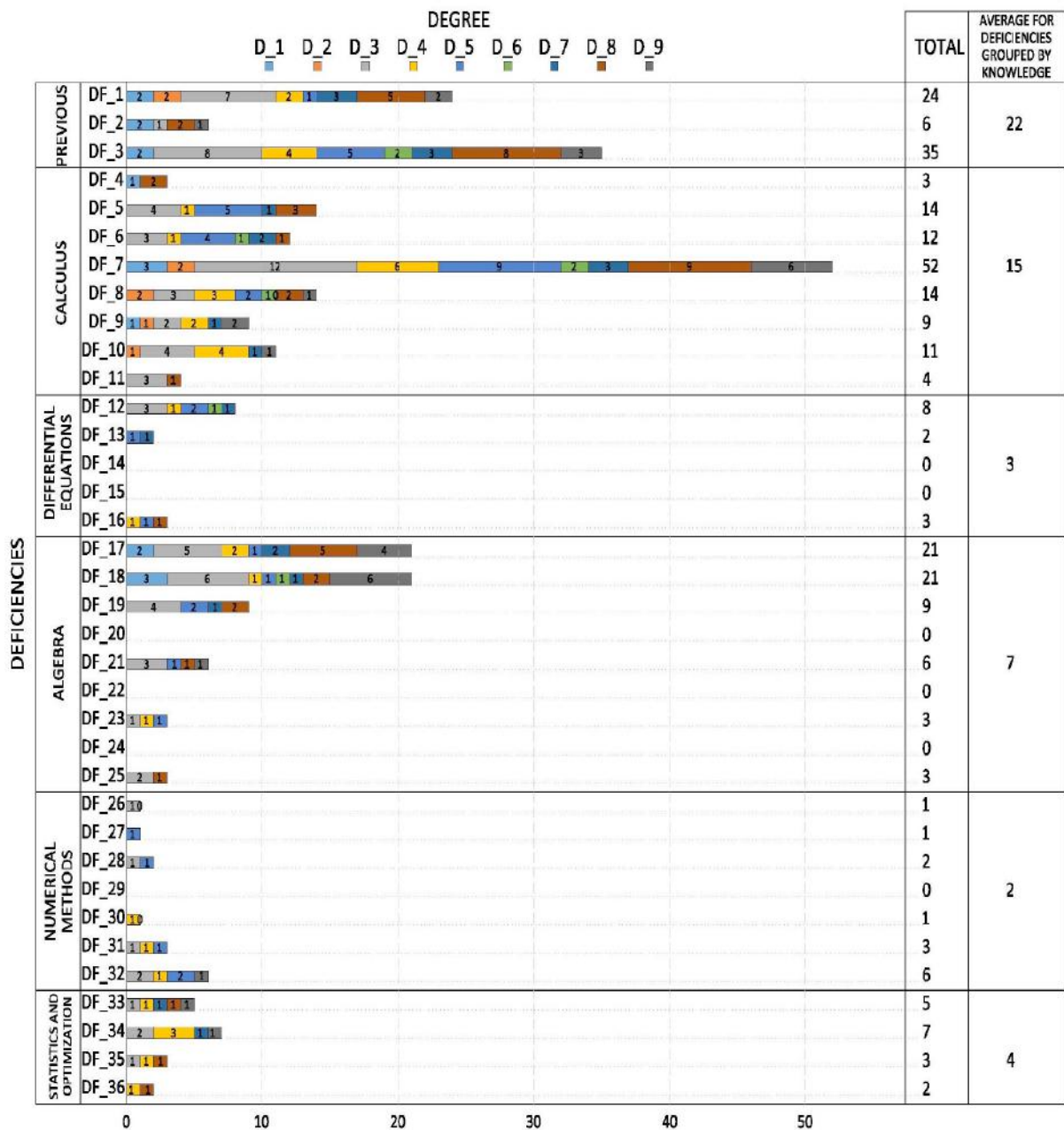


Figure 12: Mathematical deficiencies grouped by knowledge for each degree (D\_1: Architecture studies, D\_2: Telecommunications and Services Engineering, D\_3: Industrial Technology Engineering, D\_4: Chemical Engineering, D\_5: Mechanical Engineering, D\_6: Computer Engineering, D\_7: Electronic and Automatic Engineering, D\_8: Electrical Engineering, D\_9: Industrial Design Engineering and Product Development).

Figures 13 and 14 display the average values obtained as the ratio of the sum of all item frequencies divided by the total number of items in each knowledge group. From Figure 13, we can see that the bar charts corresponding to the degrees in Architecture Studies, in Industrial Design and Product Development Engineering and in Computer Engineering present a different pattern from the rest of degrees, illustrating the fact that they require a different mathematical knowledge. On the other hand, the bar charts corresponding to the degrees in Industrial Technology Engineering and Telecommunications and Services Engineering reveal the highest level of reported requirements.

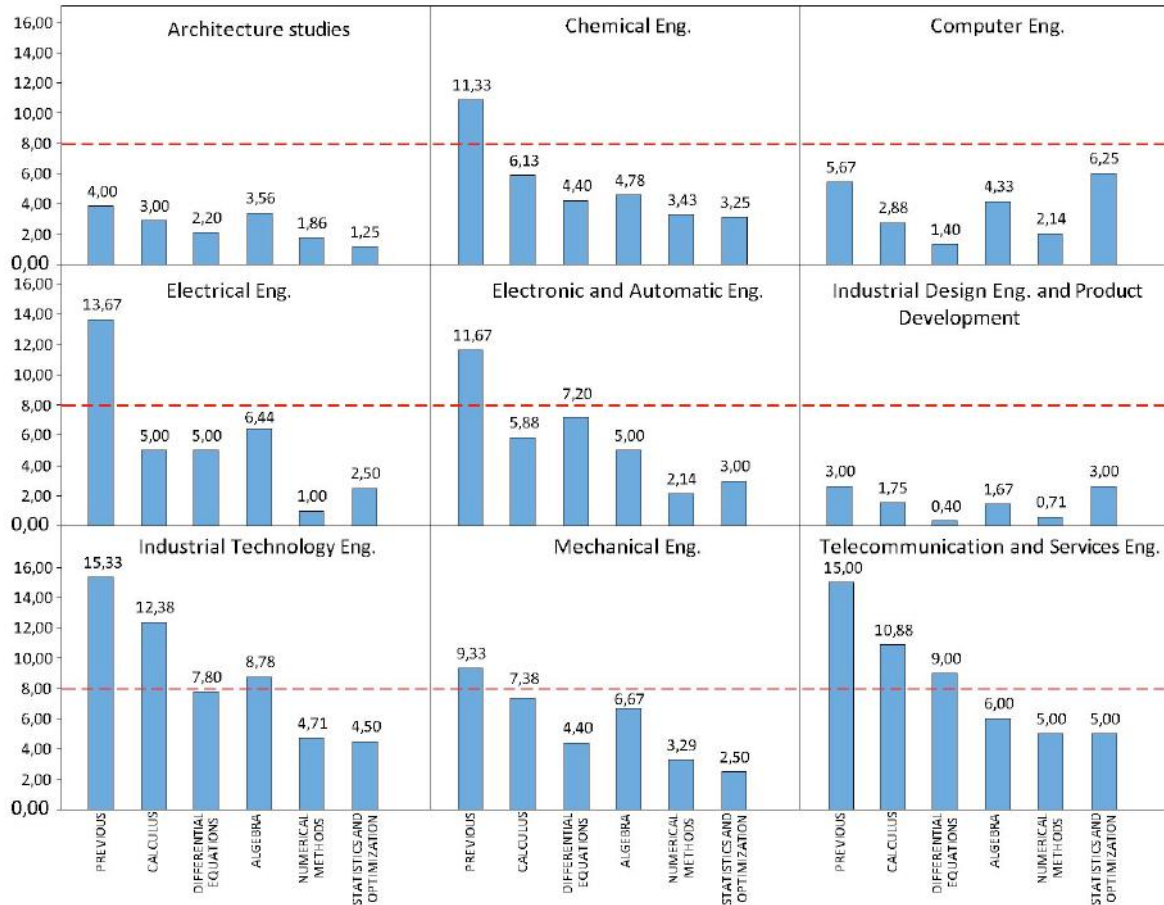


Figure 13: Average value of total requirements marked per knowledge group and degree.

With respect to deficiencies, Figure 14 shows that the degrees in Electrical Engineering and in Industrial Technology Engineering share a pattern representing a high level of detected deficiencies. In contrast, the degree in Telecommunications Technologies and Services is the degree with the lowest number of deficiencies, being concentrated in two groups: Previous and Calculus.

Moreover, in Figure 15 the average values of total deficiencies and total requirements for each degree are also provided. The position of each knowledge group in the graph, represented by a dot, shows a different profile for each degree; although some similarities can be also observed, as discussed before. For instance, in all the degrees, mathematical concepts and tools to be acquired in pre-university studies are the requirements and deficiencies most identified. This fact is going to be analysed in a second edition of the CEIP.



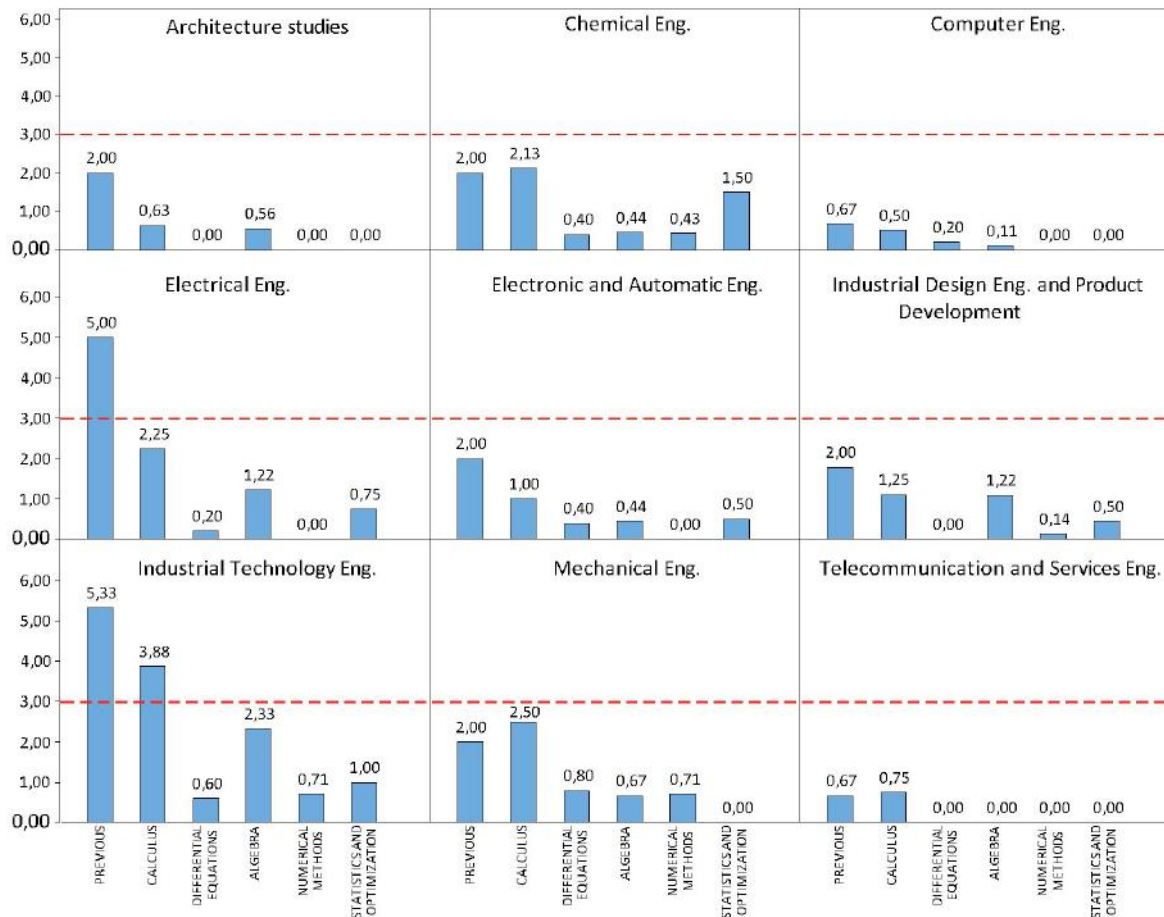


Figure 14: Average value of total deficiencies marked per knowledge group and degree.

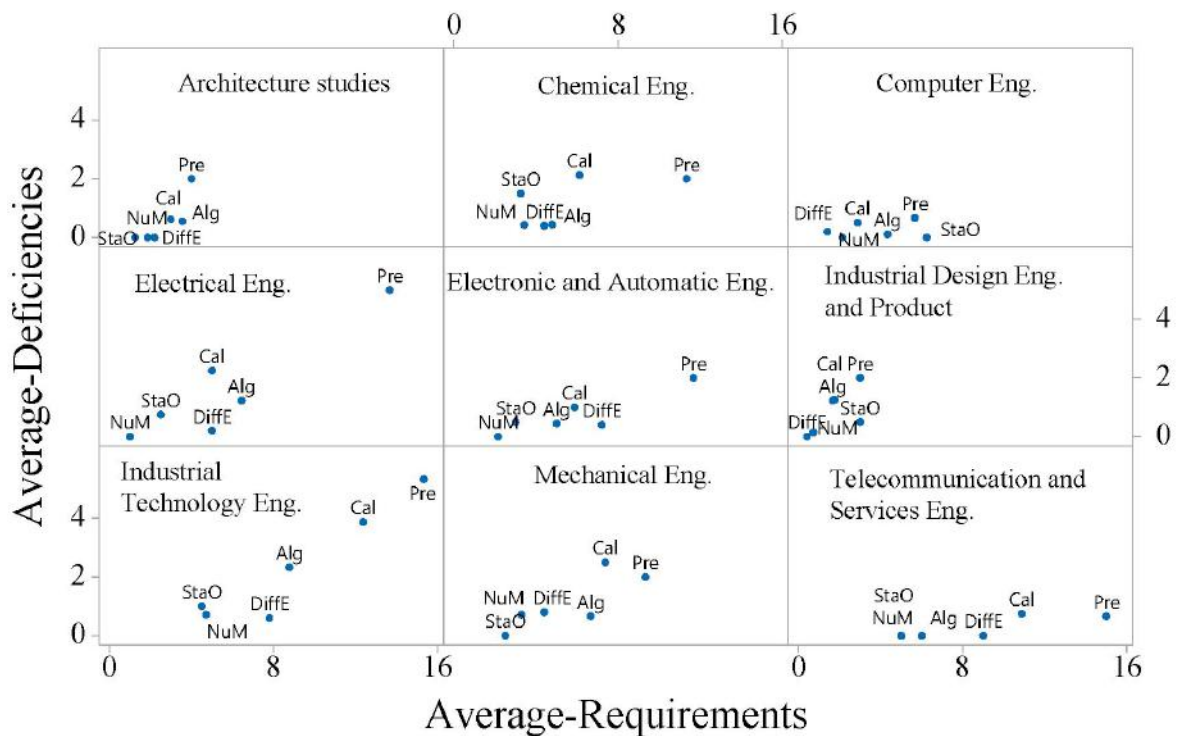


Figure 15: Average value of total requirements versus average value of total deficiencies per degree.

Finally, Figures 16 and 17 reflect the information collected in Template 4 (Phase III) about the availability of simple examples illustrating the application of the requirements in the context of non-mathematical subjects. A total of 161 professors indicated in the form their interest in providing this kind of examples. From Figures 16 and 17, we can see the distribution of these professors in the different degrees. It can be said that, in general, there has been a positive response to this initiative.

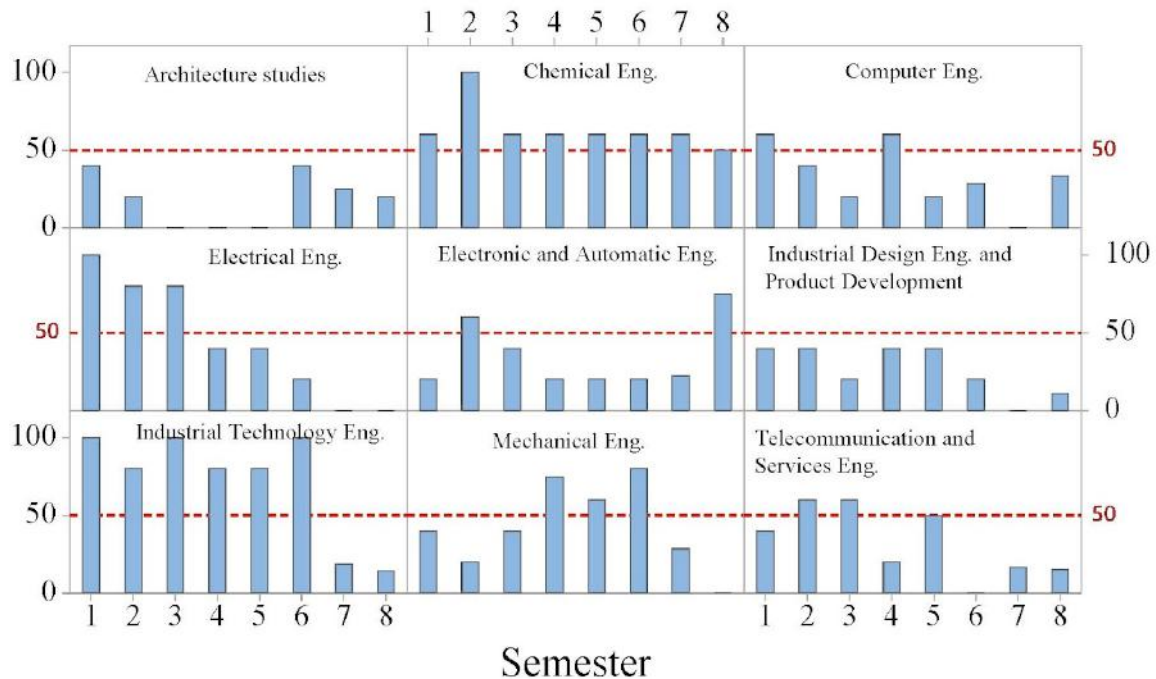


Figure 16: Percentage in the set of subjects in each semester and degree providing illustrative examples.

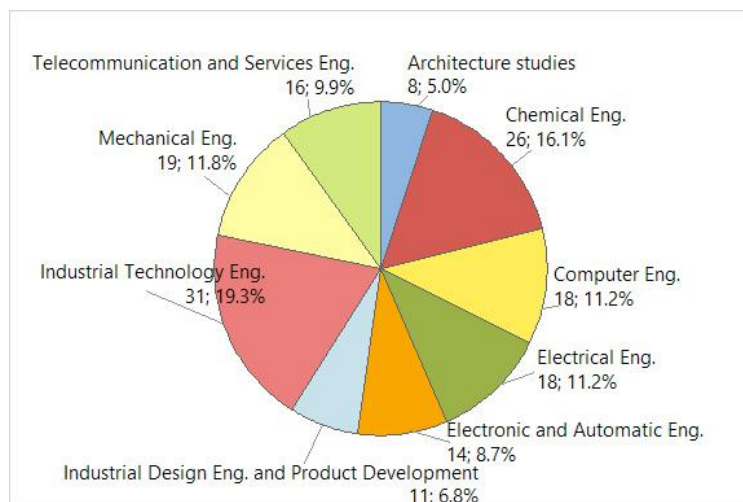


Figure 17: Number and percentage of subjects with illustrative examples.

## Conclusions

An efficient, active and collaborative methodology has been described to analyse the mathematical requirements that should be included in study plans of the undergraduate degrees of the School of Engineering and Architecture at the University of Zaragoza. The methodology applied is based on the activation of communication mechanisms between the

teaching staff of mathematical subjects and those of higher courses, in which the students must acquire the specific skills of each degree.

A number of activities have been described, such as meetings, discussions, round tables, digital document exchange, form design and completion. A great deal of information has been gathered about the mathematical knowledge required and its appropriate scheduling in all the degree programs analysed. All the information has been processed at two levels: global by degrees and sequential per semester in each degree. Some mathematical deficiencies that should be addressed in the initial training have also been identified.

The total number of subjects involved in the study is 455, corresponding to nine different degrees in Architecture and Engineering by the University of Zaragoza. 370 teachers have participated providing detailed data on 309 subjects, that is to say 68%. This percentage illustrates that the strategy applied is effective.

The strategy followed has facilitated the analysis of all the collected information and, consequently, the drawing of conclusions and proposals to improve the corresponding curricula as far as mathematical training is concerned. In addition, it has allowed teachers to collect material to contextualise the mathematical formation in different disciplines and to help the students to understand the relevance of the mathematical formation, motivating them in their study.

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