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Innovative Concepts for Integrating Mathematics and Modelling Training in Industrial Design Engineering Program*

JOSÉ ANTONIO PÉREZ[1], ÁLVARO DEIBE[2], JOSÉ RAMÓN MÉNDEZ[3], JON SOLOZABAL[3], PABLO FERNÁNDEZ[3], AHITOR REGUEIRO[3] and CRISTINA PRADO[3]

[1] Department of Industrial and Naval Engineering, University of La Coruña. School of Industrial Design, c.\ Dr. Vázquez Cabrera s/n, 15403 Ferrol (La Coruña), Spain. E-mail: japerez@udc.es

[2] Department of Mathematics, University of La Coruña. School of Industrial Design, c.\ Dr. Vázquez Cabrera s/n, 15403 Ferrol (La Coruña), Spain.

[3] Department of Civil Engineering, University of La Coruña. School of Industrial Design, c.\ Dr. Vázquez Cabrera s/n, 15403 Ferrol (La Coruña), Spain.

In order to improve the expertise and skills of students and compensate the growing lack of interest towards mathematics in Industrial Design Engineering, during the last years several innovative teaching experiences have been developed, coordinating academic activities between the areas of Mathematics and Design Projects. These coordinated experiences allowed the introduction of advanced essential contents in parametric representation, numerical analysis and manufacturing in the first course, contents which are barely included in the curriculum of Industrial Design Engineering university degrees. Despite the issues and complexity of their planning and practical implementation, results have been excellent; transforming the perception of mathematics by students from a simple working tool to a stimulating new way of creation and inspiration to explore.

Keywords: industrial design engineering; design education; product design; mathematics learning; STEAM (Science, Technology, Engineering, Arts and Mathematics)

1. Introduction

According to the 29th General Assembly of the World Design Organization, WDO, Industrial Design can be defined as a cross-cutting strategic problem solving process, which seeks to generate innovative solutions at a formal, functional and technical level, questioning the reality, the technology and the available information, through critical, logical and creative reasoning, applicable to products, systems, services and new experiences, whose results leads to innovation, success in business, and definitely in a better world [1, 2].

Consequently, training of Industrial Design Engineers must present a multidisciplinary character, combining intensive training not only in technological and scientific aspects, but also in economic, artistic, social, cultural, environmental and ethical aspects, in order to provide the necessary knowledge for the management of entire product lifecycle, according to the desires and requirements of users and markets [2–5].

Even when traditionally, companies have separated the design process from the rest of activities, complicating the development of new products, as well as limiting the capability of the Design Department to contribute to the growth and continuous improvement of the organization, fortunately, the progressive introduction of new management philosophies based on Total Quality and Project Based Management, where customer satisfaction prevails, are promoting the Design Department to a key role, since it is much easier and efficient to introduce improvements and corrections during the initial stages of the design process, than in the final stages, with complicated designs and extremely complex processes [2, 6].

In this sense, there is a broad consensus regarding the main competences and skills that a training program in Industrial Design Engineering must cover [1, 2]:

- Specific Technical Skills:
  - Understanding the social and historical dimension of Industrial Design as a vehicle for creativity and the search for innovative and effective solutions.
  - Detection and understanding of the values, dynamics and conceptual mechanisms that define the arrival of new trends and desires.
  - Knowledge of advanced production processes, materials and manufacturing technologies.
- Generic Skills:
  - Entrepreneurship and Business and Management Culture.

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- Ability to apply critical, logical and creative thinking.
- Spatial vision and deep knowledge of graphic representation and expression tools.
- Communicative skills, capability to adapt to continuous changes and aptitude to work in multidisciplinary teams.
- Understanding the ethical and social responsibilities derived from professional activity.

These competences are acquired during the training period through a complex combination of subjects and applied knowledge typical of Industrial Design, with theoretical basic subjects, such as Physics and Mathematics, complemented with business administration and quality management, as well as technological and classical engineering subjects, providing a very competitive profile, highly demanded by society [4, 7].

Nevertheless, due to their own nature, there are significant differences between the teaching methods in classical industrial design subjects, where research and practical project-learning strategies prevail, compared to basic subjects, based in theoretical teaching and problem-solving learning [2, 7, 8].

Considering that typically the most fundamental and theoretical subjects are concentrated on the first courses, while the most applied subjects typical of Industrial Design are predominantly disposed in the higher courses, a clear dichotomy between what students really want to study, and what they really must learn is established, just at the beginning of their training, when they still lack the overall necessary vision to understand the nature of the learning process, which can lead to a significant reduction in their motivation and performance [7, 9, 10].

Although it is a generic problem concerning to all engineering degrees, in Industrial Design Engineering it is especially relevant in the case of Mathematics subjects, being a recurring research topic in recent years, including not only the analysis of the causes and the associated issues, but also the proposal and implementation of new methodologies and approaches to provide effective solutions [7–13].

2. Teaching Mathematics in Industrial Design Engineering. Associated Issues

In an increasingly competitive world, innovation and technological development are key aspects to social and economic progress, in such a way that a good professional must continually update their knowledge and skills to satisfy new requirements and expectations, with specific training in their field of expertise, as well as intensive training in theoretical aspects to understand the fundamentals and principles that govern new developments and applications, most of them far beyond the knowledge acquired during academic training [10, 14].

In this sense, a strong preparation in mathematics is strategic, not only as an excellent tool to analyse data and perform calculations and simulations, but fundamentally because contributes to improve organization and planning aptitudes, as well as analysis and logical reasoning capabilities; also providing a common language for knowledge transmission among professionals, skills intrinsic to mathematical reasoning specially interesting for Industrial Design Engineers, since authentic innovation is not based on intuition and spontaneity, but on methodical analysis of the particular issues and existing resources and knowledge, to propose new efficient and technically viable solutions [12, 15, 16].

Although mathematics has always held a relevant place in the training of engineers, in the last years, the perception of what must be learned has changed, moving from a classical approach based on problem solving, to a much broader approach, based on mathematical reasoning and logical analysis [2, 17].

As a reference, on the basis of the existing literature, the European Society for Engineering Education, SEFI, established a minimum set of basic mathematics skills that every engineer should acquire, regardless of their specialty, combining basic competences in numerical calculation with advanced skills related to analysis and logical reasoning [13, 18, 19]:

- Basic competences in numerical calculation:
  - Management of notation, formalisms and mathematical entities.
  - Posing and solving of mathematical problems.
- Advanced skills related to analysis, logical reasoning and knowledge transmission:
  - Mathematical thinking – Knowledge and understanding the potential of mathematics and logical reasoning to solve technological problems.
  - Mathematical reasoning – Ability to formulate complex mathematical arguments and understand their practical implications.
  - Mathematical modelling – Capability to obtain a representative mathematical model of a problem, based on the knowledge and resources available.
  - Analysis and resolution of partially defined complex problems in innovative technological environments.
  - Communication – Aptitude to maintain an effective technical discussion.

This new paradigm suggests interesting challenges from the teaching point of view, regarding how to ensure that students effectively acquire these skills and competences, focusing in two fundamental aspects [11, 13, 17–22]:

- Problems to understand and assimilate the contents and pass the subject, as a consequence of the intrinsic difficulty of mathematics, and deficiencies in the pre-university training.
- Lack of interest in the contents taught, as students are often not able to establish their relationship with real professional practice.

Based on these considerations, in the field of engineering, even when Mathematics typically has been taught in a theoretical way, as a service, by experts from the Mathematics Departments of the Universities, nowadays it is emerging a very interesting innovative tendency to incorporate applied knowledge related to the particular field of specialization, through the collaboration with the Engineering Departments, in order to bring training closer to professional practice [8, 10, 17–19, 23].

3. New Approaches to Integrate Mathematics in Industrial Design Engineering

Inspired on the excellent results derived from project-based teaching active learning approaches based on constructivism in the field of Industrial Design Engineering, in recent years, great efforts have been made to extend this philosophy to other non-applied subjects, taking advantage of new technologies [7, 20, 24–29].

In a general way, the impact of new technologies in teaching is highly positive and motivating, since it allows to develop new forms of learning closer to the habits and interests of the students, bringing an excellent support to effectively address complex problems and practical cases from the first courses, aspects previously reserved for advanced subjects [19, 24, 25, 30–34].

Essentially, this change of paradigm is based on three pillars [30]:

- Fast evolution and democratization of technology, being available at reasonable prices.
- Creation of positive attitudes based on overcoming challenges, replacing theoretical explanations by direct work.
- Autonomous and personalized learning, adapted to the singularities of the students, promoting creativity and decision-making capacity.

Even when this approach allows to bring training and learning closer to real working conditions, significantly reducing the gap between academic training and professional practice, the introduction of new technologies must be controlled, especially in the first courses, as it can generate undesirable dynamics, prioritising the achievement of results by trial and error over the acquisition of an effective working methodology [2, 7, 19, 25, 30].

Based on these considerations, and aligned with this innovative worldwide trend, in the last years, several interesting experiences have been carried out at the School of Industrial Design Engineering, EUDI, of the University of La Coruña (Spain), in order to improve the motivation and training of students, as well as introducing new applied relevant content to their future professional practice [7, 25].

Specifically, a complete integrated teaching experience has been developed in the subject of Mathematics I, where the students work in an applied way several key aspects of the subject related to mathematical modelling and analysis among others, defined on the basis of the professional profile and the specific competencies and skills that Industrial Design Engineers must acquire, in coordination with the subject of Basic Design, an introductory subject in the field of Design Projects, where students analyse the artistic and formal aspects [2, 3].

At the beginning of the course, in the subject of Basic Design students are encouraged to form small groups of 4 or 5 students, establishing an emergent Design Studio, which name must have at least as many different letters as group members, being each student in charge of one of the letters (types) of the name.

The components of each group, starting from a standard OpenType font that adequately represents the essence of their design studio concept, with the help of a 2D vector graphics analysis tool, generate individually the contours of their own letter and modify it, following the criteria established in the subject, generating a coherent corporate identity, as well as other elements representative of the character and spirit of their design studio.

It must be emphasized that in OpenType fonts, the characters are defined by a series of N third-order Bézier polynomials, each one defined by four characteristic points, 2 anchors, which define both extremes of the curve, and 2 handlers, which define the tangent direction in each extreme, that can be easily manipulated with a 2D vector graphics analysis tool [35, 36].

In a complementary way, as a reference, at the beginning of the course, in the subject of Mathematics I students receive an introductory seminar about the significance and the unprecedented development of Industrial Design derived from the development and implementation of Bézier Polynomials in industry, allowing to model and represent any complex design in a compact and easily transmissible and reproducible form, enabling coordinated work between remote teams of designers, like a score in music [35, 36].

Once their own letter has been generated, in the subject of Mathematics I students concentrate on applying mathematical methods and tools to their own type, acquiring the necessary knowledge about modelling, mathematical representation and geometric transformation of curves, among other aspects, working in an applied way the most relevant contents previously studied in the theoretical part.

As a first step, with the help of a 2D vector graphics analysis tool, students extract the coordinates of the four characteristic points of each segment, obtaining a total of 4N points, with two coordinates each one.

From these coordinates, in the first exercise, the students must obtain in a simple spreadsheet the characteristic coefficients of the two third-order Bézier polynomials that define each segment in parametrics, the one related to the x coordinate and the one relative to the y coordinate, generating a total of 2N polynomials.

Evaluating the polynomials in a sufficient number of points, typically between 20 and 50, in the same spreadsheet the students draw the letter, being able to directly validate the exercise comparing the representation obtained mathematically with the starting letter.

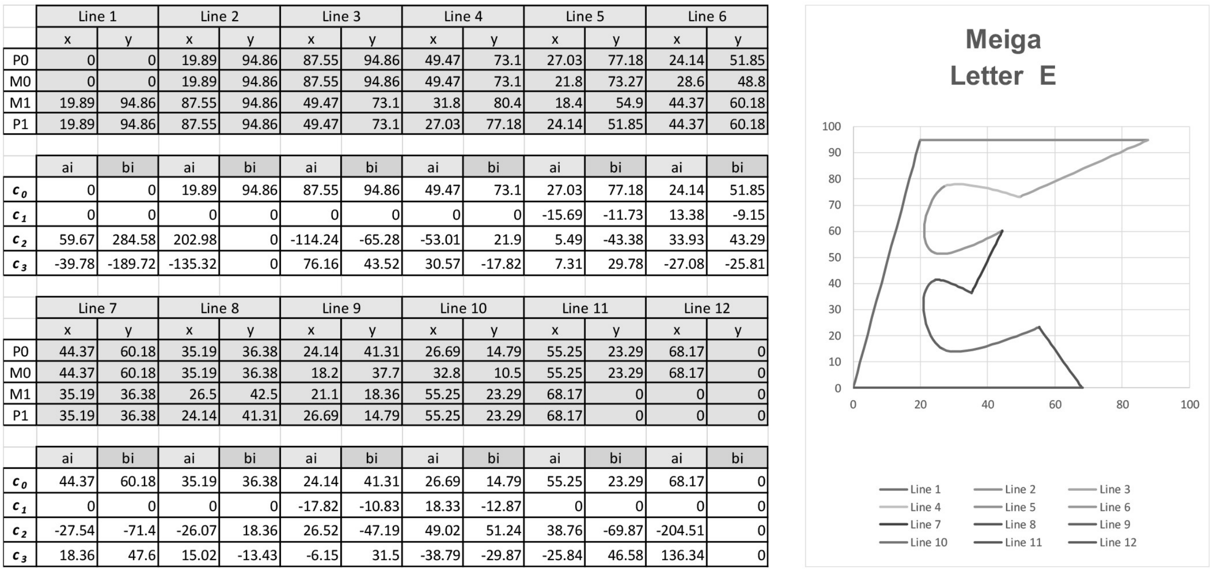
Fig. 1 presents a detail of the final result provided by students in Moodle, showing at the left side the coordinates of the four characteristic points of each segment and behind the four coefficients of each Bézier Polynomial, and at the right the graphical representation of the type.

Once the different Bézier polynomials have been generated and validated, the second activity focuses on their mathematical analysis and treatment, analysing key concepts such as derivation and obtaining relative maximums and minimums, as well as series expansion and the best approximation in a subspace.

In order to rationalize the workload, this activity focuses on one of the 2N polynomials, which, according to the statement of the activity, is chosen by means of a numerical criterion, specifically the one with the greatest difference of ordinates between their relative extremes. To do this, they must previously obtain the first and second derivatives of each of the polynomials and then, setting the first derivative equal to zero, obtain the relative maximums and minimums, and identify the relative extremes using the second derivative sign.

Once the right polynomial has been selected, the students must obtain the first Taylor Series approximations at a variable point a (which can be changed in real time), until reaching the third order, which obviously has to coincide with the original polynomial (a theoretical exercise that students must do as homework during the activity), which allows them to easily check the development of the activity. In a complementary way, the students have to graphically represent the obtained polynomials in a spreadsheet, in order to verify that everything has been developed correctly.

Fig. 2 presents a detail of the final result provided by students in Moodle, showing at the left the coefficients of the selected Bézier Polynomial, and the derivatives in the reference point considered for



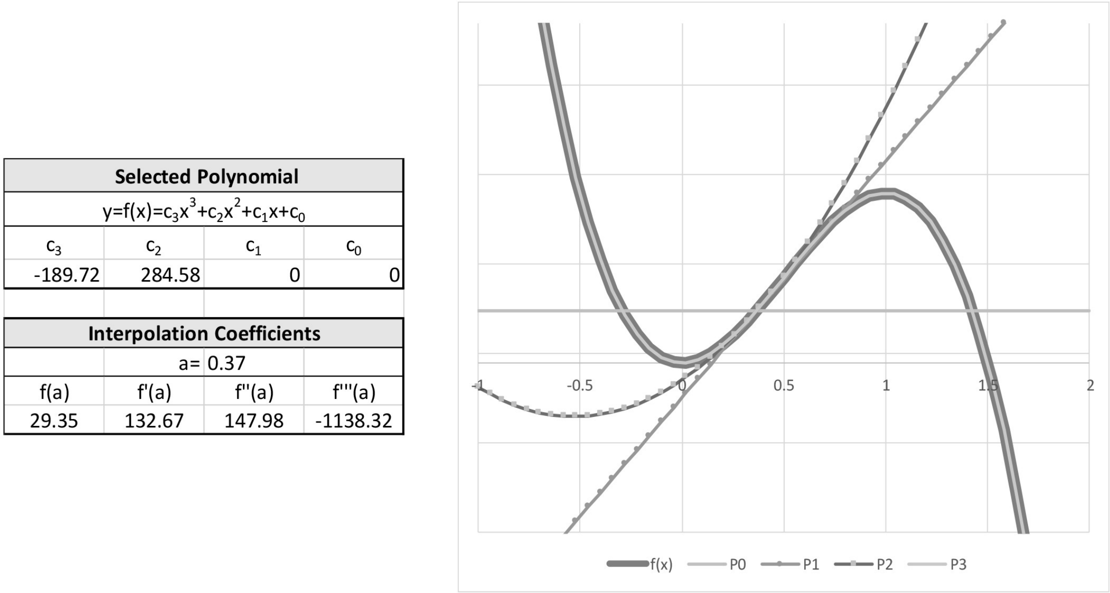
	Line 1		Line 2		Line 3		Line 4		Line 5		Line 6	
	x	y	x	y	x	y	x	y	x	y	x	y
P0	0	0	19.89	94.86	87.55	94.86	49.47	73.1	27.03	77.18	24.14	51.85
M0	0	0	19.89	94.86	87.55	94.86	49.47	73.1	21.8	73.27	28.6	48.8
M1	19.89	94.86	87.55	94.86	49.47	73.1	31.8	80.4	18.4	54.9	44.37	60.18
P1	19.89	94.86	87.55	94.86	49.47	73.1	27.03	77.18	24.14	51.85	44.37	60.18

	ai	bi	ai	bi	ai	bi	ai	bi	ai	bi	ai	bi
c_0	0	0	19.89	94.86	87.55	94.86	49.47	73.1	27.03	77.18	24.14	51.85
c_1	0	0	0	0	0	0	0	0	-15.69	-11.73	13.38	-9.15
c_2	59.67	284.58	202.98	0	-114.24	-65.28	-53.01	21.9	5.49	-43.38	33.93	43.29
c_3	-39.78	-189.72	-135.32	0	76.16	43.52	30.57	-17.82	7.31	29.78	-27.08	-25.81

	Line 7		Line 8		Line 9		Line 10		Line 11		Line 12	
	x	y	x	y	x	y	x	y	x	y	x	y
P0	44.37	60.18	35.19	36.38	24.14	41.31	26.69	14.79	55.25	23.29	68.17	0
M0	44.37	60.18	35.19	36.38	18.2	37.7	32.8	10.5	55.25	23.29	68.17	0
M1	35.19	36.38	26.5	42.5	21.1	18.36	55.25	23.29	68.17	0	0	0
P1	35.19	36.38	24.14	41.31	26.69	14.79	55.25	23.29	68.17	0	0	0

	ai	bi	ai	bi	ai	bi	ai	bi	ai	bi	ai	bi
c_0	44.37	60.18	35.19	36.38	24.14	41.31	26.69	14.79	55.25	23.29	68.17	0
c_1	0	0	0	0	-17.82	-10.83	18.33	-12.87	0	0	0	0
c_2	-27.54	-71.4	-26.07	18.36	26.52	-47.19	49.02	51.24	38.76	-69.87	-204.51	0
c_3	18.36	47.6	15.02	-13.43	-6.15	31.5	-38.79	-29.87	-25.84	46.58	136.34	0

Fig. 1. Exercise 1 – Bézier Polynomials – Final Result Presented in Moodle.



Selected Polynomial			
$y=f(x)=c_3x^3+c_2x^2+c_1x+c_0$			
c_3	c_2	c_1	c_0
-189.72	284.58	0	0

Interpolation Coefficients			
	a=	0.37	
f(a)	f'(a)	f''(a)	f'''(a)
29.35	132.67	147.98	-1138.32

Fig. 2. Exercise 2 – Taylor Approximation – Final Result Presented in Moodle.

the interpolation, and at the right the graphical representation of the original polynomial, and the calculated interpolations, being P0 the approximation of order 0, P1, first order, P2, second order, and P3, third order, which corresponds with the original curve, as can be observed.

The third activity focuses on the geometric transformations necessary to generate the appropriate numerical control code to process the letter on an automatic milling machine, for which, with the help of a spreadsheet, students have to centre the letter at the origin of coordinates, being necessary previously calculate the coordinates of the centroid of the distribution. Once centred, they have to normalize the dimensions of the letter and scale it to the machining area, leaving a safety margin with respect to the border, which is specified in the activity statement.

Once the final points have been obtained, the students proceed to generate the corresponding G code, adding the pertinent control sequences to the coordinates of the reference points obtained, after which they proceed to directly milling the letter under the supervision of the teachers of the subject. The correctness of the code can be directly checked comparing the result obtained with the initial draw of the letter.

Fig. 3 shows a detail of the milling process in the Volume and Shape Laboratory.

In order to guarantee that students acquire the

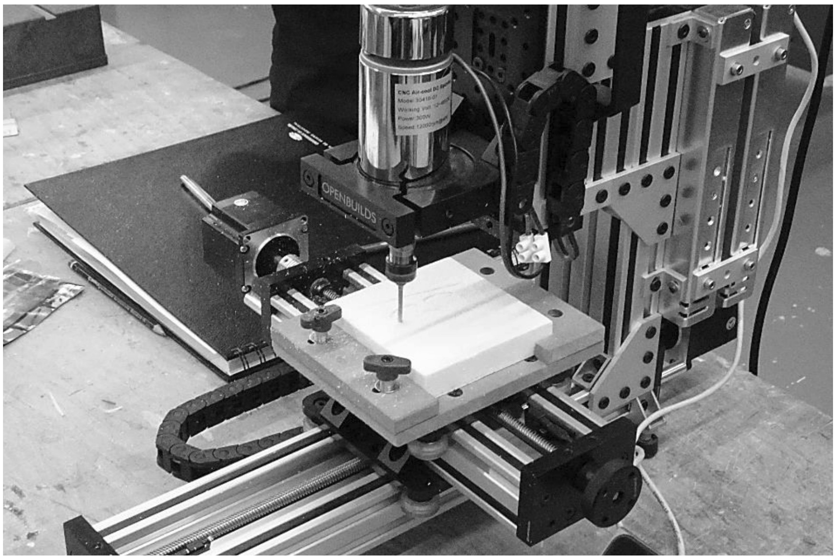


Fig. 3. Exercise 3 – Letter Milling Process.

Fig. 4. Joint Exhibition of Selected Works.

specific knowledge and skills, preceding each task, in addition to conventional master classes, the theoretical foundations and objectives of each activity are detailed in several Introductory Seminars taught in a coordinated mode in both subjects. In a complementary way, at any time prior to delivery, students can consult any doubts or concerns with the teachers of both subjects [11].

Following the schedule, the programmed exercises must be completed and delivered individually on Moodle platform, which allow to reduce the consumption of paper and facilitates its analysis and assessment, establishing also a closer and more natural communication channel with students [29, 37].

Once delivered, each task is evaluated, and seeking a positive feedback, in addition to the qualification using a complete rubric, teachers send to students via Moodle a brief assessment of the results obtained, as well as recommendations for improvement [11].

At the end of the semester, once the works have been evaluated, as an incentive, the best students who have successfully completed the activities programmed in both subjects, are granted with the opportunity to expose their work in the Creative Room in a final joint exhibition, as shown in Fig. 4, where in the foreground the work done in the Mathematics I subject is presented and in the background some related elements developed in Basic Design.

4. Results and Discussion

During the development of the programmed activities, several very interesting substantial changes have been observed, both in the attitude and motivation of the students, as well as in their performance:

- Students are more involved in the development of the course: class attendance has increased around 31.5% since the experience began, as well as they also ask more questions and attend to more tutorials.
- The attendance to final exam has increased significantly, from 65.7% of students enrolled, to 88.3% in the last year.
- Improvement of the academic results, both absolutely, with a greater number of approved students, from 41.4% to 79.7% in the last year, and in a relative way, with an improvement in the success rate, from 63.0%, to 90.3% of evaluated students.

On the other hand, a detailed analysis reveals several issues during its practical implementation:

- The introduction of new activities does not involve an increase in the teaching load of the subject, 6 ECTS, which implies that new activities can detract time to other important contents.
- As a consequence of the increased interest and motivation observed, it has been detected a certain tendency to dedicate a great effort to practical activities, forgetting the theoretical sessions and the final exam.
- Related to their motivation and the difficulties for learning, it must be highlighted the lack of a good basic training prior to their entrance to the University, as well as the limited time available for maturation and assimilation of contents, since the subjects have a quarterly character.
- Possible risk of plagiarism in the practical exercises, since they are presented through Moodle:

> Even when in a Technical School it is not frequent, in order to minimize the risk, in this experience a complete automated footprint control system has been developed, based on the characteristic parameters of the Bézier Polynomials presented by the students.

Consequently, even when the proposed activities are very interesting and motivating, it must be highlighted that requires a great commitment, coordination and hard work from the teachers involved in both subjects, since students work essentially individually, or in small groups, requiring a great effort to control and evaluate the development of activities, considering that due to the own profile of the program, students are more motivated to work on design related activities than on mathematics and the knowhow behind, in such a way that without an adequate control, results may prevail over learning [24].

In this sense, in order to not distort learning process and ensure that students acquire the specific knowledge and skills, in the case of Mathematics I, after several adjustments, the following proportions have been established to evaluate the different aspects [13, 18, 19]:

- Class attendance and participation – 5%.
- Final exam – 30%.
- Directed activities (the analysed experience) – 35%.
- Problem seminars and practices – 30%.

4.1 Students' Opinion

In order to know first-hand opinion about the interest and usefulness of the experience, an anonymous brief survey was conducted at the end of the semester, with a representative participation close to 90% of students enrolled, analysing five key aspects [22, 30]:

1. Interest and utility.
2. Positive aspects.
3. Negative aspects and difficulties.
4. Aspects to add.
5. Influence on motivation towards the study of Mathematics.

These aspects have been evaluated in a quantitative way, where students have to evaluate each aspect in a maximum of 150 words, with a very positive assessment in general terms, which can be summarized that in their opinion, it constitutes an innovative activity, completely different from any previous experience, although it has been an important challenge, not easy and sometimes a bit stressful.

As positive aspects towards their motivation, they highlight the direct practical application of the contents, as well as obtaining a tangible final result (the design and milling of their own type), while the greatest difficulties are focused on the lack of prior training, and the volume of personal work required.

In a more detailed way, as interesting thoughts regarding the contents studied in mathematics, it is worth highlighting the proposal to increase the teaching load in geometry and modelling, and as expected, reduce the time spent on the most arduous and less creative tasks, such as basic calculation and mathematical resolution of problems.

In a complementary way, the following aspects have been evaluated in a quantitative way in a 0 to 5 range:

1. Interest and utility, with a mean of 4.11 and a standard deviation of 1.73
2. Degree of difficulty, with a mean of 3.76 and a standard deviation of 1.51
3. Influence on motivation towards the study of Mathematics, with a mean of 4.35 and a standard deviation of 1.10

As can be observed, these assessments are in agreement with the improvement in the performance of the students in the subject, and the positive evolution of the main quantitative indicators: class attendance and participation, the rate of students that attended to the final exam, and the pass rate, as well as the reduction of the number of repeaters and consequently the total number of students enrolled.

5. Conclusions

The results of the experience have been excellent, with a significant improvement both in the participation and interest of the students, as well as in their performance in the subject of Mathematics, a priori, a less interesting subject considering the profile of the program, where students are more motivated to work on design related activities than on the knowhow behind.

The fact that the activities include both individual and group work, using their own letter, make students consider these activities as personal, incrementing considerably their interest, in clear contrast to the traditional approach in the subjects of mathematics, where impersonal and repetitive activities prevail.

In addition, the innovative nature of the activities and its coordinated design with the Design Projects area, where the creative part is completely carried out, analysing the artistic and formal aspects, while in the subject of Mathematics, the students work in an applied way the most relevant contents previously studied in the theoretical part, has allowed to introduce in a coherent way advanced essential contents in parametric representation, numerical modelling and manufacturing in the first course, fundamental contents which are rarely included in the curriculum of Industrial Design Engineering university degrees.

As a conclusion, the experience has been highly motivating and interesting not only for students, but also for teachers, despite the increase in the workload involved in planning, monitoring and tutoring the different activities, without forgetting the coordination effort necessary to successfully complete the experience.

In this sense, it must be emphasized that during the last 5 years, students have generated more than 100 anagrams and 350 different letters, which means more than 1050 personalized practices to evaluate, in such a way that without an excellent organization and coordination between subjects and teachers, it would be virtually impossible to manage and evaluate that creative capacity.

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José Antonio Pérez is PhD in Industrial Engineering and associate professor at the School of Industrial Design of the University of La Coruña, EUDI. His scholarly research interests are centred on quality promotion in high education institutions, as well as the development and implementation of student-centred innovative learning strategies in industrial design engineering, among others.

Álvaro Deibe is PhD in Industrial Engineering and professor at the School of Industrial Design of the University of La Coruña. Currently, his research interests are focused on the integration of advanced mathematical methods in industrial design engineering studies.

José Ramón Méndez is PhD in Industrial Design Engineering and the director of the School of Industrial Design of the University of La Coruña, and head of Design Projects Area. His research interests are centred on trends research and industrial design and product development, as well as project based learning strategies.

Jon Solozabal is Engineer in Industrial Design, and the coordinator of the subject of Basic Design at the School of Industrial Design of the University of La Coruña. His research interests are centred on industrial design and product development.

Pablo Fernández, Ahitor Regueiro and Cristina Prado are Engineers in Industrial Design and assistant professors in the subject of Basic Design at the School of Industrial Design of the University of La Coruña. Their research interests are centred on industrial design and product development.