Case study based learning using a computational tool to improve the understanding of the jet engine cycle for Aerospace Engineering Degree students

Abstract

In the current paper, a methodology combining a case study with a computational tool for Aerospace Engineering students is presented and discussed. The aim of this methodology is to improve the understanding of jet engine operation through their thermodynamic cycle analysis, particularly focused on the effects of the main boundary conditions for an aircraft engine: altitude and flight velocity, defined in terms of Mach number. Additionally, the organization of the methodology as a case study performed in groups facilitates students' engagement, as well as the development of soft skills such as teamwork ability. The experience of this methodology over the last five years shows that the activity is generally well perceived by the students, and also that there is a correlation between the engagement in this activity and the overall results achieved in the subject, confirming that the methodology improves students' comprehension of the concepts behind engine performance. However, a few points of improvement for the near future are identified.

Keywords

Brayton, Turbojet, Thermodynamics, Thrust, Altitude, Mach, Case study

1. Introduction

The research and development of propulsion systems is one of the main tasks of the aeronautical industry and a core competence for its engineers. Since the development of the first reaction engines based on the gas turbine concept in the early 1940's during the Second World War, significant improvements have been made from architectural and technological perspectives to this day. From the point of view of the thermodynamic cycle, most of these improvements are aimed at achieving the best possible tradeoff between the specific thrust and the specific fuel consumption provided by the engine [1]. Taking into account that this design challenge can be only understood by using as the main tool the analysis of the cycle [2], the curricula of any Engineering degree focused on Aeronautical applications include a subject aimed at propulsion topics where this problem is deeply discussed. In the case of the Aerospace Engineering degree at Universitat Politècnica de València, these contents are taught for the first time in the Propulsion course, which is scheduled during the second semester on the third year [3]. At this stage, the students have already dealt with the fundamentals of the thermodynamic cycles and fluid mechanics during the previous year. Therefore, Propulsion focuses on the implications of the thermodynamic cycle characteristics into the performance of aircraft air-breathing engines, including both reciprocating and jet engine configurations. Within this scope, classroom sessions are devoted to the introduction of the different engine typologies, the definition of the main cycle-based performance parameters and their interrelations, such as specific thrust, thermal efficiency, propulsive efficiency and thrust specific fuel consumption in jet engines [4]. Finally, the calculation of these parameters for specific engine cycles is discussed.

However, the detailed calculation of these cycles in a classroom is time consuming, so that the time for a detailed analysis of the impact of boundary conditions and design parameters is limited. This implies a difficulty in the comprehension of the operation of such cycles by the students. First, while all jet engines are based on the same base thermodynamic cycle (Brayton) the flight conditions (mainly altitude and Mach) impose different conditions for both thermal and propulsive efficiencies, driving for specific engine variants for each range of these parameter aimed at maximizing the overall efficiency. This fact can only be understood after seen the impact of a wide variation of these parameters, which is not possible on hand-made exercises. Second, each engine variant has its own peculiarities from calculation perspective, and not all of them can be seen during the on-site classes. Finally, the usage of parametric studies allows the students to achieve an understanding of the expected order of magnitude of the different parameters involved in jet engine cycle design and calculation.

In addition, the need to incorporate active teaching methodologies as a way to increase the interest and motivation of the students and, therefore, the efficiency of the teaching-learning process, has become evident during the last decades. Thus, there is a shift from a teaching concept focused on the transmission of knowledge by the teacher, to an approach in which the student becomes the main actor [5].

On this concern, the use of specific computational tools makes the thermodynamic cycle analysis more efficient in terms of comprehensiveness of the study, and therefore it is common in the industry especially in the early phases of a new engine design [6]. At the same time, the students feel more attracted by the activity since the stage of analysis becomes easily accessible once the barrier represented by complex and tedious calculations is broken. From a series of boundary conditions mainly depending on the selected application, a wide number of engine architectures can be screened in a reduced amount of time [7]. As a result, a first definition of key parameters in the studied technology, such as the overall pressure ratio, the bypass ratio or the temperature at the turbine inlet can be provided [8] and robustly justified based on cycle analysis.

Considering all these pieces of information, using such kind of software within the scope of the subject can be seen as a double opportunity. On the one hand, it offers the students the possibility to learn a specific tool that is actually used in the aircraft engine industry. It also helps to engage the students since they feel that the effort they put in learning the tool can be useful not only for the subject but also for their future professional careers [9]. On the other hand, from a purely academic perspective, it allows the students to have available a great amount of cycle and performance parameters calculations with a reduced effort. As an immediate learning result, this allows them to go deeper in understanding, specifically concerning better of knowledge of the ranges of variation of performance parameters, and the effects that the different design and/or operational aspects involve. In a second stage, high potential arises for activities guided by reasoning and critical thinking able to bring the student closer to real-life challenges.

Another important aspect of higher education relies on its relationship with the society, which demands that students acquire technical knowledge, with the same depth as in previous times, supported by a series of transversal skills useful for their subsequent performance. The aim is to achieve a harmonious balance between technical knowledge and the capacities, abilities, aptitudes, attitudes, and skills necessary to meet the challenges posed by the professional environment. Competencies such as teamwork abilities, project management or oral communication are usually among the most demanded by companies, many times above the technical knowledge, usually already presupposed. These transversal or non-curricular competencies are key for the students as future engineers since they are needed for their future development in the industry and employers demand them. In this sense, case studies are one of the tools that can be used to help the students in the development of such skills. The fact of working as a group on a project is perceived by the students as a step forward as engineer, enhancing their engagement and satisfaction with the learning experience [10]. Additionally, previous experiences show a positive interaction between case study based-learning and the usage of technological tools [11].

In the current work, a case study learning strategy supported by a software tool for the thermodynamic cycle analysis of aircraft engines is presented. In particular, GasTurb™ [12] platform is selected due to the good tradeoff between easiness and versatility. The proposed methodology revolves around a system-level computational activity that aims to achieve a triple objective consisting of gaining deeper knowledge of jet engine design trends; developing teamwork abilities; and becoming aware of how basic engineering concepts can make them being involved in global challenges such as the Sustainable Development Goals driven by the United Nations [13].

As far as the paper structure is concerned, previous literature works focused on computer-based learning and case-study methodology are reviewed in Section 2. The main features of the software are firstly described in Section 3 as a basis for the definition of the teaching methodology, which is described in Section 4. How the student's activity is structured and guided to reach the learning objectives is discussed in detail. The results achieved in terms of the students' satisfaction, their academic performance and their development in cross-curricular competencies are discussed in Section 5. Finally, the main conclusions of the study are summarized in Section 6, and a proposal of future directions in the implementation of the proposed methodology is discussed in Section 7.

2. Literature review

As stated in the Introduction, one of the most important parts of the methodology proposed consists of the use of a computational tool integrated with the technical contents of the subject. It has been proven in different fields that Computer-Aided Learning can be useful in different ways, since students are more actively involved compared to traditional methods [14]. For instance, Zhu et al. [15] developed a Matlab code for generating compressor and turbine blade geometries to be used in Aerospace Engineering teaching environment. Gamez-Montero et al. [16] combined computer-based learning with flipped-teaching strategies to improve the understanding of turbomachinery working principles, showing an improvement in students' satisfaction. Patterson [17] used machine learning techniques in computational fluid dynamics (CFD) environment, with the aim of helping students to understand how to optimize an aerodynamic profile to reduce drag force. Minichiello et al. [18] presented a mobile-based particle image velocimetry tool, concluding that it helped to increase students' engagement. García-Oliver et al. [19, 20] used Computer-Aided Learning techniques in combustion-related topics, highlighting benefits in the learning processes by the students.

The other core of the current work focuses on case-study based learning. Such methodology aims at discussing open-answer real-life cases using as a foundation the theoretical concepts developed on a certain subject [21], and has been extensively used in several higher education fields such as medical or law education [22]. However, several works have evaluated also the suitability of this method in other fields. Iahad et al. [23] showed a positive effect of the implementation of case studies on students' engagement in Business Management education. Burko [24] discussed different potential applications of case-study based learning in Physics education for undergraduate students, concluding that the versatility of the methodology allows its implementation combined with other tools such as problem-based learning and team activities. Colyer [25] made a similar analysis for chemistry teaching environment, concluding that one of the major challenges is related to making the implementation robust and objective, since the Professor's background and perspective can bias both students' work and its evaluation. Varma and Garg [26] explored the capability of case-study based learning to develop skills related with problem-solving and communication in software engineering education. Anwar and Ford [27] proposed a series of short case-studies focuses on analyzing real-life failures and possible solutions on electro-mechanical engineering field. Zuwala and Sztekler [28] implemented case-study base learning on different subjects related with energy production and alternative fuels at both BSc. and MSc. degrees, concluding a significant gain in technical knowledge and understanding of business impact aspects.

3. Description of the software

As stated in the introduction, GasTurb™ [12] is one of the commercial codes available aimed at the thermodynamic analysis of reaction engines. Such engines, widely used in Aeronautical and Aerospace fields, combine an internal combustion engine, generally based in the gas turbine concept, with a nozzle, which accelerates the exhaust gases to produce thrust force based on the action-reaction mechanism. The code was originally created by Dr. Joachim Kurzke from as part of his work on MTU Aero Engines, as a tool to predict future engine performance during its early design phase. GasTurb™ GmbH based in Aachen (Germany) currently develops the software with orientation to a professional environment. The tool is based on gas turbine performance calculations, but its scope is wide enough to be used by different user profiles such as engineers, researchers or students, depending on the level of calculation scope and design complexity selected.

Figure 1 shows the engine selection window in GasTurb™. As it can be seen, the software allows the evaluation of predefined common aircraft engine architectures based on a gas turbine core, as well as some specific engine concepts derived from them such as the ramjet engine. For each main engine concept, different variations are made available considering standard classification concepts depending on the engine type such as number of spools, the mixing or not of the bypass flow. Although out of the scope of the current work, also gas turbine engines for power generation purposes can be selected.

Once the engine architecture is chosen, the main boundary conditions for the calculation are input (Figure 2). This includes operating parameters such as the flight conditions as well as the design parameters defining the engine cycle, as pressure ratio, burner exit temperature or components efficiencies.

Besides single cycle solution, GasTurb™ includes several tools for customization and numerical optimization purposes. On the one hand, the user can complete the default set of output parameters for each engine type with additional variables included as script in the calculation case, as shown in Figure 3. On the other hand, the most simple of these tools is the "Iterations" option, whose setup window is also presented in Figure 3. When active, it allows screening one design input to achieve a certain target in a operational and performance parameter. Thanks to its simplicity in concept and use, it promotes studies in which the most direct relation between certain design and operational parameters must be found by the students. It enables a better understanding of basic concepts and dependencies since the student is not required to pay excessive attention to the mathematical procedure. For example, this calculation option is used to ensure that the nozzle is always adapted, i.e. that the nozzle performs a complete expansion up to ambient pressure, when a convergent-divergent geometry is used and different boundaries are imposed. For this purpose, the students will set the ratio of the areas between the throat and the nozzle outlet as the parameter to vary to achieve the adapted condition. However, design optimization studies, where the target is unknown and interaction with several variables and design constraints are present, have to be setup through the "Optimization" tool.

Another of GasTurb™'s relevant features consists of the possibility to perform detailed parametric studies. When selecting this calculation option (Figure 4) the software allows exploring the effects of up to 2 design variables on the thermodynamic cycle output. The user must define the initial value, the number of steps to be covered and the step size, and the software will perform all the possible combinations of these factors in a full factorial design. These parametric studies can be complemented with Monte Carlo calculations for a better understanding of the sensitivity of each design or operational parameter on the engine performance.

4. Teaching methodology

This section describes the way in which the commercial software GasTurb™ is used as a key part of the teaching-learning process in the Propulsion course. In particular, the learning objectives expected to be achieved by the usage of this tool are enumerated first, and later on the proposed teaching methodology is detailed.

4.1. Learning objectives and approach

As stated during the introduction, the Propulsion course focuses on the analysis of the thermodynamic cycle of aircraft engines and how its definition impacts on the engine performance parameters. In this sense, flight conditions (mainly altitude and velocity) are known to be critical for the engine operation since they define the total pressure and temperature of the air taken into the engine. In fact, many engine design choices, including the architecture itself, are influenced by these conditions. For this reason, the methodology described in the current paper is designed so that the students can better understand the implications of the flight conditions on the thermodynamic development of each of the engine components and, consequently, on the engine design process. The following specific teaching objectives are considered:

- Study the impact of the altitude on the temperature ratio of the cycle and its consequent effect on the specific thrust and on the thermal and propulsive efficiencies.
- Analyze the impact of the flight velocity on the engine drag, included in the definition of the specific thrust, and on the thermal and propulsive efficiencies.
- Evaluate the impact of the flight Mach on the engine overall pressure ratio and, hence, on the compressor pressure ratio.
- Understand the tradeoff in the optimization of the engine specific thrust and specific fuel consumption.
- Identify the interest for the ramjet engine concept at very high flight Mach.

Through the achievement of these objectives, the students are finally able to relate real-life engine design trends for certain applications, previously identified in other parts of the subject, based on the impact of the boundary conditions characteristic of each application on the engine thermodynamic performance.

Apart from these technical objectives, there are other benefits that should also be considered. On the one hand, GasTurb™ is a software tool that is currently used in the industry in the pre-design phase of an engine. Therefore, its learning can be directly seen as a useful skill for some of the students working for engine manufacturers in the future, while for the rest it helps to understand this pre-design phase with state-of-the-art computational tools. On the other hand, since the activity is performed in groups of five students, it is seen as an opportunity to help them develop soft skills regarding teamwork and organization capabilities, which are strongly demanded by the industry in the recent years [29]. For this purpose, a set of meetings are scheduled at intermediate steps of the work in order to help the students to organize themselves, to focus the work on the most important aspects to be covered and, in general, mentor them along the project development.

4.2. Tool training

Two computer-lab sessions are dedicated to the learning and training of the software GasTurb™, so that the students can then face the final group activity.

The first of these sessions is dedicated to basic aspects of the software. The session starts with two tutorials dedicated to the following aspects:

- Selection of engine configuration and input design/operating parameters.
- Definition of "Composed Values", which are new outputs by user defined formulae from the default calculated parameters.
- Execution of single cases, iterations and parametric studies.
- Data post-processing, including the numerical outputs and thermodynamic cycle diagrams (pressure-volume, temperature-entropy and enthalpy-entropy) for single cases, as well as 2-dimensional contour plots for parametric studies.

Once the students are familiar with the tool and its functionalities, they are asked to team up in pairs and perform a study on a turboshaft engine configuration as the most similar aircraft engine cycle to the basic Brayton cycle studied introduced in previous Thermodynamic subject. In particular, the students have to analyze the effects of the overall pressure ratio and the temperature ratio on the specific power and thermal efficiency of the engine. This study is performed twice: first assuming ideal processes in the compressor, combustion chamber, turbine and power transmission in the shaft; and later introducing realistic efficiencies for these processes. The objective of this study is to confirm that with an almost ideal cycle the thermal efficiency is mostly linked to the overall pressure ratio, while in a real cycle an optimal pressure ratio appears, linked to the particular turbine inlet temperature used for the calculation.

The second practical session is already devoted to the analysis of a jet engine cycle. In particular, the impact of the nozzle design on the performance of a turbojet engine is studied. First, the fundamentals of compressible flow in a nozzle with convergent or convergent-divergent geometry are reviewed. Then, the professors define how to make use of the iteration tool available in the software to ensure that the nozzle geometry is adapted to reach a complete expansion when a convergent-divergent section is selected. Later on, the procedure to activate an afterburning process between the turbine and the nozzle is described. Finally, the students are asked again to work in couples and perform two studies. The first one is focused on the comparison of specific thrust and engine efficiencies (thermal, propulsive and overall) as a function of the kind of nozzle geometry selected: convergent (adapted or chocked nozzle) or convergent-divergent (adapted nozzle). The second is dedicated to the analysis of the afterburning. In this case, the students are asked to evaluate the impact of the afterburning process in two steps: initially, assuming a constant throat section in the nozzle as in the non-afterburning case, and then changing the throat section to maintain the same air flow through the engine. The main objective is for the students to understand that a meaningful increase of the net thrust is only achieved if the throat section is modified, highlighting the need for a variable geometry nozzle in supersonic engines with afterburning and decoupling the design of the cycle (specific thrust) from the sizing (mass flow) as a way to set extensive variables (thrust).

4.3. Case study

As stated before, the main objective of the case study is to analyze the impact of the engine boundary conditions (altitude and flight velocity), which are the main aspects changing between different aircraft applications from the thermodynamic perspective, with real-life design decisions. With that in mind, the study is designed so that students start by performing certain parametric studies in GasTurb, being then guided through the real-life impact of their results in an inductive manner.

In this sense, and once the two aforementioned computer lab sessions are completed, the group project is launched. The complete set of students (around 130 per year) is asked to divide into groups of 5 people. Once the groups are defined, the students are given a common initial set of phases, described in the next lines:

1. *Identify the dependency of the cycle performance parameters of a turbojet engine with respect to altitude and Mach of flight*
    a. *Study as a function of altitude*
    b. *Study as a function of Mach, with additional considerations on the overall pressure ratio.*
2. *Justify (reasoning) the results obtained in terms of the thermodynamic cycle analysis.*

As it can be seen, even if the scope of the work is the same for all the students, the objectives are open enough to allow each group to differentiate in terms of the boundary conditions selected and, more importantly, the analysis performed.

The study is evaluated through a 20 minute presentation where the students have to summarize how they performed the calculations and the main conclusions drawn from them. In this way, the professors will evaluate not only the technical accuracy of the work, but also the capability of the students to synthesize their results and select the most important outcomes from the point of view of engine response as a function of the cycle design.

In order to follow the group development during the weeks dedicated to the activity, each working group is asked to schedule two intermediate meetings with the professors before the delivery of the final presentation. The objective of these two group meetings is to guide the students so that the main learning objectives described in Section 4.1 are achieved. In the first one, after approximately two weeks, the group is asked to describe their organization, detail the simulations they will initially perform and define the tasks to be performed by each member. In this meeting, some difficulties to decide the approach to deal with the detail of each project phase are commonly found. This way, after these phases are identified and discussed for each group, more specific steps, which are summarized in Table 1, are shared with the students as guidelines to facilitate the fulfilment of the objectives. As it can be seen, some of the points included in Table 1 guide the students through the relationship between design and performance parameters for both altitude and Mach parametric studies, which is the core of the discussion to be made at the end of the case study. In the second tutorial, at least one week before the final presentation, the students should discuss the main results achieved and clarify any open points regarding their analysis. In this tutorial, the students are specifically asked to relate the results they achieved up to this point with the design trends identified during the rest of the subject.

5. Main outcomes

5.1. Examples from students' reports

One way to start analyzing the effectiveness of the methodology proposed could be to look at the outcomes obtained from the group project. In this sense, two examples extracted from last academic year's reports are extracted and commented in the next paragraphs.

Figure 5 shows an example regarding the analysis of the altitude effect. As it can be seen, the students focused on the analysis of the impact of the ambient temperature, which is decreased until reaching the tropopause. This reduction of the ambient temperature, with a constant temperature limitation at the turbine inlet, results in a higher expansion potential in the nozzle and reduction of flight speed (constant flight Mach as boundary). Consequently, an increase of specific thrust is obtained with further impacts on propulsive and thermal efficiency as well specific fuel consumption. This can also be seen from the reduction in the compressor specific work induced by the lower initial temperature, also leading to the air-to-fuel ratio decrease. Therefore, the turbine needs to extract less specific work to drive the compressor, reaching a higher temperature at the turbine outlet section, and a higher jet velocity assuming that the nozzle geometry can be adapted to maintain a complete expansion.

Figure 6 shows an extract from another report devoted to the effect of the flight Mach combined with the compressor pressure ratio. As it can be seen, the specific thrust tends to decrease with the flight Mach increase. This rate of decrease is more significant as the flight Mach increases. As a result, the optimum compressor pressure ratio is reduced. By contrast, the overall efficiency of a turbojet engine tends to increase with the flight Mach until reaching the best efficiency pole from where the efficiency drops rapidly. This is related to a reduction of the thermal efficiency as the compressor outlet temperature approaches the temperature limitation at the turbine inlet section despite of the benefit in propulsive efficiency. This situation is found more easily as the pressure ratio in the compressor increases, indicating that this parameter needs to be coupled to the flight Mach number to maintain the desired overall pressure ratio for a given cycle temperature ratio. This way, the thermal efficiency can be maximized and the trade-off between specific thrust and propulsive efficiency optimized.

5.2. Academic results

Figure 7 shows a summary of the results achieved by the students during the last five years of development of the subject. In this graph, the x-axis corresponds to the specific mark achieved during the group activity assessment, while the y-axis shows the average mark obtained in the subject as the result of the different evaluation acts scheduled. In this chart, different colors are defined for each of the academic years under consideration. One of the first conclusions that can be drawn is that most of the data can be found below the bisecting line, which means that better results are generally obtained by the students in the case study activity compared to the rest of the evaluation considered for the subject. However, there is some level of correlation between both results, particularly showing that the students with the best overall marks are, in general, also achieving excellent results in the case study. Given the relatively low weight of the group activity on the final mark achieved (20%), the correlation may be seen as an indication of a deeper learning from the students who have dedicated more effort to the case study. It is also interesting to highlight that despite the low weight of the case study, its average mark corresponds to that of the subject with a small variability within ±0.5 each year.

5.3. Teamwork and leadership assessment

As part of an institutional project, the Universitat Politècnica de València launched a project focused on the development of transversal or non-curricular competences which are general for all the Bachelor Degrees [30]. These competencies were decided based on several studies in the literature [31–33] as well as feedback from employers, and include all the items in Table 2.

For each degree, the corresponding School has selected at least two subjects responsible for evaluating the development of each of these transversal competencies. In the case of Propulsion course, the competency CT-06: Teamwork and leadership was chosen, with focus on the teamwork dimension. Therefore, the objectives and organization of the case of study were defined not only from the point of view of the technical learning objectives, but also to properly evaluate the capability of the students to effectively organize themselves and work as a team. This competency is evaluated by the professors mostly based on the observations from the two scheduled tutorials before the final project presentation, and partially also on the quality and homogeneity of the work performed.

5.4. Students' opinion

As described during the Introduction, ensuring the engagement from the students is crucial to achieve a successful teaching-learning process. Additionally, one of the main difficulties faced during group activities is the task organization between the group members and the resolution of conflicts that may arise. These are important aspects for the evaluation of the Teamwork and Leadership competency previously described. In order to assess both aspects, a specific survey was designed two years ago by the professors and completed by the students. The survey includes the following five statements:

- Q1. The different tasks have been fairly shared between all the team members.
- Q2. Conflicts arisen during the project have been properly addressed and solved.
- Q3. I followed the work performed by other team members and provided ideas to improve it.
- Q4. The group study has helped me to achieve a better understanding of the theoretical and practical aspects of the subject.
- Q5. Overall, I am satisfied with the development of the group activity and its impact on improving my technical knowledge.

As it can be seen, the first three statements are focused on the development of the team from an organizational perspective, while the last two are aimed at assessing the satisfaction of the students with the design and results of the activity. For each of these statements, each student shall indicate his/her level of agreement, in a scale from totally disagree (TD) to totally agree (TA) considering a neutral (N) opinion. Additionally, there is the option for the students to mark a “Don’t know/don’t answer” option in case they do not feel qualify to provide their feedback. The survey is performed anonymously through the online teaching tool PoliformaT, developed by Universitat Politècnica de València, and available only for the students enrolled in the subject.

Figure 8 summarizes the results achieved on the students’ survey during the last two academic year. The answers are coded as previously described. The bars represent the percentage of students (left axis) providing each level of agreement for the five different statements defined (Q1-Q5). As it can be seen, the majority of the students are satisfied with the organization and the methodology proposed, with more than 60% of students providing answers between agree (A) and TA for all of the statements. However, it can be seen that slightly worse results are generally achieved for the statement number 5, which is focused on the general satisfaction about the project. This is particularly clear from the fact it has the minimum number of students providing the best mark of TA (19%). The opinion is mainly moved to A although N and D (disagree) are in the maximum share range with respect to other statements. Instead, the best results are found for the questions regarding the group organization. A quantitative analysis, assigning 5 to TA and 1 to TD is also useful to identify the average satisfaction. This is computed as the mean value of the answers provided for each question. In that case, the lowest value is reached for statement Q5, with an average of 3.75 over a maximum of 5, while the rest of the statements reached average values ranging from 4 to 4.1. Therefore, future efforts should be focused in increasing this overall satisfaction. One option under consideration is to open the scope of the activity, so that each group can decide the aspect of the thermodynamic analysis of reaction engines to evaluate. However, the potential issue of such strategy is related to the fact that each group will develop different technical knowledge and competencies depending on the scope of the work selected. Therefore, a slight redefinition of the rest of the course organization may be needed to ensure that all students reach the minimum set of competencies defined in the scope of the subject.

6. Conclusions

In the current paper, a methodology combining a computational tool (GasTurb™) with case study based learning is proposed in the scope of propulsion topics. The methodology is applied to the understanding of the thermodynamic analysis of reaction engines, as part of the contents developed in the Propulsion subject provided for Aerospace Engineering students. The methodology is divided into two steps: first, two computer-lab sessions are dedicated to introducing the software to the students; then, a project focused on the analysis of the effects of altitude and flight Mach on the performance of reaction engines is proposed.

The following conclusions can be drawn from the study:

- The proposed methodology has been successfully implemented as part of the development and evaluation of Propulsion subject. The reports show that the students reach a high level of understanding of the cycle operation of reaction engines thanks to the use of parametric studies combined with detailed cycle analysis.
- The academic results show that the marks obtained in the group project are generally higher than in other evaluation acts scheduled in the subject, which can be seen as an indication of higher engagement compared to other traditional methods. However, there is correlation between the group project marks and the overall subject marks, especially in the case of the results from the best students.
- Case study based learning has shown to be a good tool to develop and evaluate students' skills in terms of teamwork. This has been assessed through the

monitoring of the groups organization and development by a set of intermediate tutorials scheduled with the professors following the subject.

- A students' survey was designed to evaluate their satisfaction regarding the group project development and the methodology itself. The general satisfaction was high, with the questions regarding organizational aspects achieving the best results (overall satisfaction around 4.1 over a maximum of 5). Slightly worse outcome was achieved in the question focused on the general satisfaction with the methodology, indicating that there is room for improvement to maximize students' engagement and the consequent learning results.

7. **Future directions**

While the overall results of the application of the methodology are satisfactory, a few points of future improvement have been identified and summarized below:

- The Propulsion course is intended to be an introduction to engine design and operation for all Aerospace Engineering students, which should be the foundation for other subjects in the degree, especially for those who enroll into the Aircraft Engine path of the degree. However, the case study presented here was never related to these other subjects, missing an opportunity for further student's engagement. In that sense, there is a new methodology under development which tries to include the case study presented in the current work with other studies performed in Combustion subject (4^{th} year, first semester) and Jet engines and Acoustics (4^{th} year, second semester) into a common portfolio. The objective of these two additional studies is to analyze technology trends that can deal with efficiency, gaseous emissions and noise generation challenges identified on Propulsion case study. In the last subject, students would perform a final discussion including aspects from all three subjects.

- One of the critical aspects observed during the application of the methodology is related to the composition of the groups. Up to this point, the students selected the groups' composition by themselves. However, this implied a few inconveniences. On the one hand, the subject includes a number of people who had different previous experiences than the others. Mainly, this is related to the presence of exchange students from other countries, as well as students who come from other degrees. Since these students have not previously met the rest of the people in the class, they tend to group among themselves, which implies extra difficulties for the Professors involved in the subject to manage their different background. On the other hand, since students are teaming with their friends, the few conflicts that appear are typically not raised until the situation becomes critical for the group development. Therefore, a different strategy with groups organization guided by the Professors, assigning each team member a specific responsibility in the activity, is being set up for the upcoming academic year.

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