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A COMPREHENSIVE EDUCATIONAL APP FOR PROPULSION SYSTEMS

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ABSTRACT

This paper presents the development of a multi-platform application for rapid aeroengine performance simulation which aims to reshape conventional educational processes in aerospace propulsion taught courses. This is facilitated by enhancing students' interaction with a broad spectrum of propulsion concepts, ranging from subsonic to hypersonic regimes. The motivation of this app draws upon the ever-increasing use of smartphone apps among the student community. It is envisaged that this phenomenon could be beneficial to widen students' knowledge. The user of the app can rapidly extract the thermodynamic and performance parameters at different operating conditions for several propulsion concepts, including conventional turbojets and turbofans, as well as ramjets, turboramjets and advanced, pre-cooled, combined cycle engines. The development process of the application as well as the built-in models are described in detail herein. The app is employed in an aeroengine technology course in Greece and used by the students to investigate the fundamental operating principles of advanced propulsion systems. These include a turboramjet, a hydrogen-powered ramjet as well as a hybrid, pre-cooled, air-breathing rocket-cycle concept. This is facilitated through the use of the app for the performance modeling of each one of the propulsive architectures. Results show that the impact of the app on the educational process is beneficial, with the vast majority of the students providing positive feedback. It is found that the app has far increased their interest and level of knowledge related to propulsion systems, in comparison to traditional teaching techniques. This would have been impossible in the time frame of an academic semester without the implementation of the app.

Keywords: Aeroengines, Propulsion, Education, Smartphone applications

NOMENCLATURE

Roman letters

F_G	Gauge stream force [N]
p	Static pressure [Pa]
T	Static temperature [K]

Greek letters

θ, ϕ	Fluid force in thrust and drag domain [N]
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Subscripts

s	Standard
∞	Free stream conditions
0	Total conditions

Acronyms

GPF	Gross Propulsive Force
$SSTO$	Single Stage to Orbit
TET	Turbine Entry Temperature

1. INTRODUCTION

Since the beginning of human flight, propulsion has been the cornerstone of air and space transportation systems, and great effort has been devoted ever since towards improving propulsive capabilities [1, 2]. As a result of this continuing effort, significant, step-change technologies have been developed, the most important one being by far the jet engine, which has certainly shaped the way industry and academia road the future map of propulsion architectures. The motives driving research and development of air and space propulsion are numerous and range all the way from improving environmental conditions to achieving sustained hypersonic flight. These include reaching zero-emission flight through higher engine efficiency [3] and electrification [4, 5] and increased flight speeds through design optimization and novel engine cycles [6, 7].

While aeroengine related technology is getting more and more advanced, the fundamental principles governing propulsion systems still need to be thoroughly communicated and well taught to the next generation of engineering students. This is an essential step for an in-depth understanding of the field that will

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facilitate them to proceed to more advanced concepts with significantly increased complexity [8]. In fact, one is usually quite familiar with the fundamentals of a specific field before he can contribute to its development. However, it is envisaged that significantly more complex propulsion concepts, or a combination of them, will provide step-changing technologies in the upcoming decades and will revolutionize contemporary air and space transportation systems. These concepts include, but are not limited to, Ultra High Bypass Ratio (UHBR) engines [3, 9], hybrid-electric architectures [10], combined cycle engines [11, 12] and precooled concepts [9, 13].

As such, it becomes evident that students would highly benefit from the opportunity to become familiar with the major similarities and differences between the principles of conventional aeroengines and advanced concepts, which are currently under development. Unfortunately, this is something that rarely happens in most under- or even post-graduate curriculums for several reasons, including time and structure limitations. Therefore, future education in aeroengine technology related courses should be carefully designed to ensure that students learn and understand the fundamental operating principles of propulsion concepts while at the same time they are being exposed to as much novelty as possible to increase their scientific knowledge and interest on the topic. Nevertheless, explaining in detail and breaking down of such advanced systems to their fundamental constituent components requires tailored lectures and would inevitably occupy an important percentage of most traditional taught courses.

Problem-based learning has been the focus of numerous studies and proven to be a reliable teaching technique, especially for more advanced courses such as gas turbine theory [14, 15]. Another approach towards improving learning, is introducing computer software to enhance students understanding on the corresponding subject. However, this is not always possible for undergraduate courses, due to complexity build-up, funding and software being proprietary, with no access allowed to the students. Technological advancements in the field of computer science can help alleviate some of these problems. For example, open-source, web or mobile-based applications are now an integral part of human lives and could play an important role in enhancing education. Several studies have reported results supporting this statement, and as smartphones technology further advances, this phenomenon is expected to enhance [16, 17]. While technology has been introduced so widely in students' everyday life, its use remains quite limited when it comes to the educational process. Institutes are usually restricted to the traditional way of teaching (i.e., blackboard) and the use of computers for problem-based learning, making the overall procedure non-interactive and sometimes potentially tedious. However, numerous ways have been employed in the past to increase students' interaction in education as well as to enable a more flexible learning process. Besem et al. [18] introduced a series of podcasted lectures in engineering courses, thus allowing for a learning pace, tailored to each individual student through the capability to pause and re-watch the recorded video. Most students considered recorded lectures a very useful addition that could complement traditional teaching. This approach proved to be extremely useful especially during COVID-19 lockdown. Aslanidou et al. [19, 20] implemented an

earlier version of the multi-platform app AeroEngineS, discussed in this study, into an under-graduate gas turbine technology course in Sweden. Two academic years with and without the use of the app were compared and results showed that the use of the app made the course more appealing and helped the students further understand the fundamental principles of gas turbine theory, while providing a gamification factor at the same time.

Introducing a mobile app into the traditional educational process is expected to be very advantageous for the students in terms of increasing their interaction with the subject and enhancing their interest [16–20]. In addition to this, mobile apps have also been developed and implemented for teaching purposes in fundamental fluid mechanics courses. Minichiello et al. [21] introduced a mobile instructional Particle Image Velocimetry (PIV) educational tool for Android-based smartphones and tablets to an undergraduate course. This tool was designed both to increase students' interest and to provide hands-on experience in the fundamentals of fluid mechanics. The reported findings suggested that students showed an increased interest on the topic which could potentially lead to further studies on fluid flows. Therefore, it is well established that 21st century technologies, such as mobile-based applications, could be very beneficial for education, if designed and implemented properly in the course structure.

This paper presents a novel multi-platform app, which serves as a rapid simulation tool for propulsion systems, tailored primarily for educational purposes [22]. The development process of the app itself, as well as the mathematical formulation implemented in its embedded models, are provided in detail. A systematic approach is proposed to integrate the use of the app into the structure of an undergraduate course, related to aeroengine technology in Greece. This is facilitated through careful design of three assignments which require the extended use of the app, coupled with post processing of results, to obtain trend graphs of the leading performance metrics of several propulsion systems. Theoretical questions are then employed regarding key features of the investigated engines. The propulsive architectures employed in the proposed approach include a ramjet engine [23], a turboramjet engine [11] and a novel pre-cooled hybrid air-breathing rocket-cycle concept [24]. Such propulsion systems are rarely included in the curriculum of most under- or postgraduate courses, due to time limitation reasons or even complexity. The assignments are handed to the students after detailed explanation of fundamental principles of propulsion as well as extensive assignments on the performance of conventional 2 and 3-spool turbofans have been concluded. Therefore, the students can appreciate the complexity of more advanced concepts and understand the limitation of contemporary aeroengines through a direct comparison. Students were kindly asked to voluntarily provide their feedback, shortly after the termination of the course. Results are recorded and presented in this study. Based on students' feedback and the overall enabling potential of the app, conclusions are drawn regarding the benefits of its employment in the course structure.

2. METHODOLOGY

2.1 AeroEngineS Background

The multi-platform app AeroEngineS, which stands for Aero Engine Simulation, is a performance analysis tool, originally de-

veloped by undergraduate students at the Aristotle University of Thessaloniki in Greece [25]. Its main aim is to provide a rapid, easily accessible, yet accurate enough tool which can be utilized to analyze, quantify and compare the performance capabilities of various propulsion systems. This is facilitated through the direct thermodynamic calculation of the operating conditions at each station of the corresponding apparatus under investigation. Critical performance parameters are derived such as the specific fuel consumption (SFC), specific impulse, engine's efficiencies as well as the produced thrust. These are also a function of the user's input values which are required to fully define the operating conditions of each propulsive architecture (e.g., flight altitude, flight Mach number, etc.). AeroEngineS is being thoroughly maintained and updated ever since its original development and new templates are being added frequently. These additions aim at increasing the app's simulation capabilities to a wider range of operating conditions and propulsion systems. Currently the app has a simulation domain ranging from subsonic/supersonic 1-spool turbojets and subsonic 2-spool and 3-spool turbofans to advanced concepts of supersonic and hypersonic propulsion. However, the app features additional templates for the calculation of civil engine's emissions, the prediction of compressor map operating points, as well as the calculation of the distance between any two airports. Hence, the app approaches a variety of topics concerning aviation and it is not limited to the performance simulation of propulsion systems, despite this being its main objective. AeroEngineS is available online as a web-based tool [22] and also as a mobile application for both Android [26] and iOS software [27], thus providing at hand simulation capabilities readily available with or without internet access. The details of the development process of the application, as well as the different templates currently available, will be presented in the following sections.

2.2 Evolution over time

Over the years, AeroEngineS app has been through a number of minor updates focused at various bug fixes, appearance modifications and overall design improvements, as well as some major ones, which introduced additional capabilities (i.e., templates) to the app. Figure 1, demonstrates the evolution process of AeroEngineS starting from its original version (V.01) to its current one (V.05), in terms of interactive templates added. An overall number of 7 additional templates have been introduced to the app to date, compared to its original version. These are highlighted in each version update box (Fig. 1), and the most important ones include the introduction of advanced pre-cooled hybrid air-breathing rocket engine, hydrogen-fueled ramjet engine as well as a turboramjet cycle engine. These additions, in tandem with the already existing turbojet and turbofan engines, provide a complete range of propulsion systems, which is suitable for rapid comparisons between the different propulsive approaches. This is the key feature that makes the AeroEngineS app quite beneficial especially for educational purposes, among others.

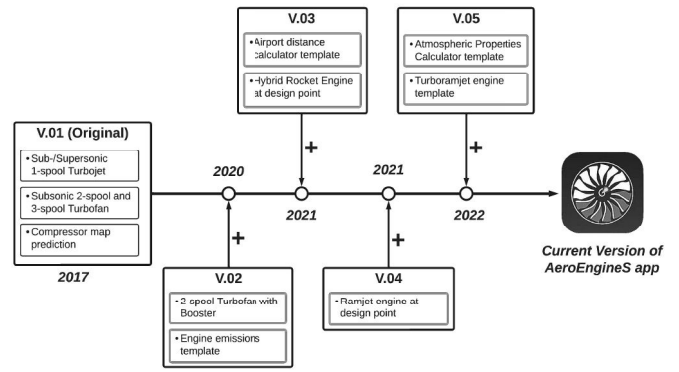


FIGURE 1: AEROENGINES APP EVOLUTION PROCESS THROUGH MAJOR VERSION UPDATES

2.3 App development process

The overall development process of the AeroEngineS app is depicted in the simplified flowchart of Fig. 2 for any number N, of built in functions. As seen in the figure, all original source codes of the embedded functions are initially developed in proprietary (Matlab) or open-source (Python) programming environments, and constitute the core of the app, since they are the result of intense and time consuming technical research related, but not limited to the performance modeling of propulsion systems. Due to the nature of the app development process, source codes must first be properly translated (i.e., into JavaScript codes) before they can be integrated into the overall framework. The interface pages, namely, the app's main page, the user's inputs pages as well as the app's results pages, are developed using the standard language for documents which are designed to be displayed in a web browser (i.e., the HyperText Markup Language or HTML). A style sheet language (i.e., Cascading Style Sheet or CSS) is used for the editing and presentation of the documents written in the markup language. The integration of the interface pages structure (HTML files) and style (CSS files) along with their corresponding functions (JavaScript files) is facilitated via a code editor, which is optimized for building web and cloud applications (i.e., VSCode), while in previous versions of the app, a different Integrated Development Environment (IDE) was used (i.e., Net-Beans). Finally, the application is converted to hybrid mobile apps (for iOS and Android) using a cloud converter. Through the process briefly described above, the app becomes available online as a web-based tool [22], in the Google Play Store as an Android app [26] as well as in the App Store as an iOS app [27].

The built-in functions are displayed to the user at the app's main page, once it is opened in a smartphone or accessed through a web browser. The main page is shown in Fig. 3, where three major sections are highlighted and the featured functions are numbered from 1 to 8 to facilitate the detailed breakdown and description of the app's functionality. At its current version, the app consists of three main sections, namely "quick calculations", "engine performance modeling" and "extra characteristics". This study is focused on the engine performance modeling functionalities of the app and its educational benefits. Therefore, details on the first and last section of the app as shown in Fig. 3 will not

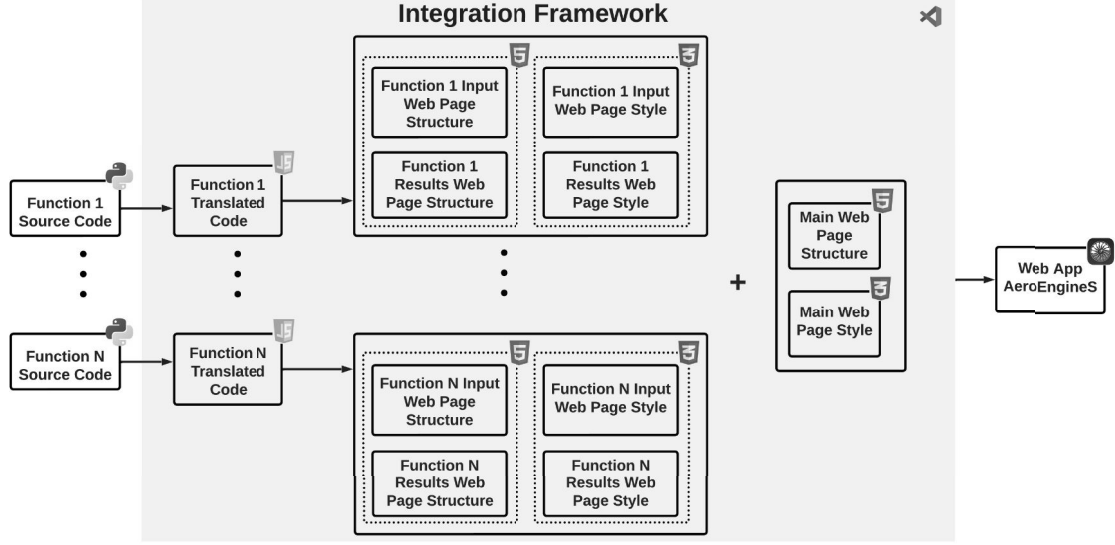


FIGURE 2: SIMPLIFIED FLOWCHART OF THE DEVELOPMENT PROCESS OF THE AEROENGINES APP

be provided herein, but a brief overview of their features will be presented.

2.4 Engine performance modeling

All engine performance models found within the app employ a component-level modeling approach, where most engine components are treated in a black-box manner. In other words, it is only the inlet and outlet conditions that are of interest, while losses due to irreversibility effects are assumed where deemed necessary. Consequently, a fundamental thermodynamic calculation approach is shared among all four featured models (i.e., templates 3, 4, 5 and 6 in Fig. 3). The commonality found within different templates or models is a direct result of the common thermodynamic aspects featured in most air-breathing propulsion systems, which operating principle is based on the well-known Brayton cycle. These components include turbomachines, combustion chambers, air intakes as well as exhausts.

2.4.1 Component-level modeling. The featured models make use of the U.S. Standard Atmosphere model [28] to calculate the engine inlet conditions based on the corresponding altitude, for values up to 25 km. The conditions downstream of the inlet section of each system are derived using isentropic flow assumption for sub-sonic inlet configurations, while shock-expansion theory is employed for supersonic inlets [29]. The well-known isentropic relation is employed for the calculation of the outlet temperature conditions at the compressors. The isentropic efficiency is used to account for losses [30] and is calculated on the basis of the polytropic efficiency η_{pol}^C , and corresponding compressor pressure ratio (PR) (Eq. (1)).

$$\eta_{is}^C = \frac{\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma \eta_{pol}^C}} - 1} \quad (1)$$

Both η_{pol}^C and PR are specified as inputs by the user for typical

aircraft engines such as 2-spool and 3-spool turbofans (i.e., all functionalities included in template 3 of Fig. 3). In the models referring to high speed propulsion, namely, templates 4, 5 and 6 of Fig. 3, the compressor pressure ratio is fixed because of the application being specific, or not involving moving parts at all (i.e., in the ramjet model). Additionally, for models where accuracy is desired over lower complexity, variable gas properties (i.e., C_p , γ , R) are accounted for through the implementation of the formulae proposed by Walsh and Fletcher [31]. This approach requires an implicit scheme until convergence between an initial guess temperature and the actual exit temperature is reached, and is adopted in all functionalities found in template 3 [25]. This increased accuracy method is not included in templates 4, 5 and 6 (Fig. 3), where the gas properties are calculated at mean temperature values between inlet and outlet boundaries. The error induced in the leading performance metrics when calculating specific heat based on mean temperature values of inlet and exit boundaries could be up to 1.5% [31]. This is acceptable for the high-speed application templates (i.e., 4, 5 and 6), where the objective is to demonstrate the fundamental operating principles of the cycle under investigation, from an educational perspective. The mechanical efficiency of the compressor-turbine coupling is set either as a user-specified parameter with a default value of 0.99 (in models of template 3) or employed internally in each model using the same value (i.e., in templates 4, 5 and 6). A similar approach to the one presented above for the compressors is also used for the turbines, not repeated here for brevity.

In the treatment of the combustion process for the typical aircraft engines found in template 3, fuel to air ratio (FAR) is obtained by solving the enthalpic equilibrium (Eq. (2)) at the combustion chamber, utilising the iterative approach found in Ref. [31].

$$FAR = \frac{h_{out} - h_{in}}{LHV \cdot \eta_{comb}} \quad (2)$$

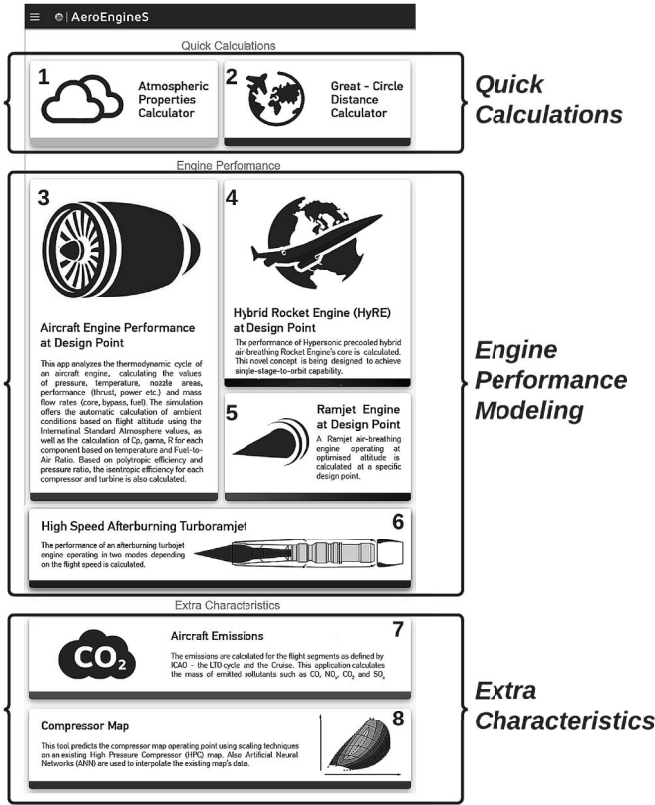


FIGURE 3: APP'S MAIN PAGE AS DISPLAYED IN A WEB BROWSER WITH SECTIONS HIGHLIGHTED AND TEMPLATES NUMBERED

In Eq. (2), h denotes the enthalpy per unit mass, LHV is the lower heating value of the fuel and η_{comb} is the combustion efficiency. Both LHV and η_{comb} are user-specified values in the models of template 3. More details can be found in [25]. In the templates 4 and 6, FAR is calculated through Eq. (2) on the basis of a mean temperature value at the inlet and outlet of the combustor, and no iterative approach is implemented to reduce complexity. In the ramjet model (i.e., template 5), FAR is set to stoichiometric values, since there is no downstream turbomachinery and therefore, high temperature of combustion products exiting the chamber, does not pose a limitation [23, 31].

Exhaust nozzles are modeled based on isentropic flow assumption. Critical pressure ratio is calculated to assess choked flow operation. The conditions at the exit plane of the propulsive nozzle are thus obtained, using Eqs. (3) and 4 for the ideal exit velocity and static temperature, respectively:

$$V_{ideal} = \sqrt{\frac{2\gamma RT_0}{(\gamma - 1)} \left(1 - \left(\frac{1}{NPR} \right)^{\frac{\gamma-1}{\gamma}} \right)} \quad (3)$$

$$T_e = \frac{T_0}{1 + \left(\frac{\gamma-1}{2} \right) \cdot M_e^2} \quad (4)$$

In Eq. (3), NPR is the nozzle pressure ratio, defined as the ra-

tio of the nozzle inlet total to ambient static pressure, R is the gas constant, γ is the ratio of specific heats, and T_0 is the total temperature. The exit Mach number M_e in Eq. (4), is calculated through the ideal jet exit velocity (Eq. (3)), that being the velocity that would be achieved under fully isentropic flow expansion to the ambient static pressure, and the local speed of sound.

2.4.2 Performance accounting. Each model provides the user with some key performance metrics for the corresponding propulsion system, which include SFC, thrust, and engine's efficiencies (thermal, propulsive and overall), among others. The aim of this section is to present the definition of these parameters as provided by the app, to eliminate any potential ambiguities that may occur to the users when reading the results, and to ensure that the interpretation of the latter, is properly done. The thrust of an air-breathing propulsion system is defined as the change in the gauge stream force between the inlet and outlet stations [32]. The force at the outlet station, refers to the standard gauge stream force produced at the exit plane of the nozzle, which is commonly referred to as standard gross thrust, and evaluated for a single stream engine by integration of the momentum flux and pressure terms. Thus can be expressed as follows:

$$F_{G,out} = \iint_{Area} \rho u_x^2 dA + \iint_{Area} (p - p_\infty) dA \quad (5)$$

Assuming a uniform, single-valued profile of the field variables at the exit station, Eq. (5) reduces to:

$$F_{G,out} = \rho_e \cdot V_e^2 \cdot A_e + (p_e - p_\infty) \cdot A_e \quad (6)$$

The standard net thrust F_N can be then obtained from Eq. (7):

$$F_N = F_{G,out} - F_{G0} = F_{G,out} - \dot{m}_{in} \cdot V_\infty \quad (7)$$

For an engine featuring a bypass duct, the standard net thrust needs to account for the second stream and is modified to:

$$F_N^{ds} = F_{G,out}^{core} + F_{G,out}^{bp} - F_{G0} \quad (8)$$

In the equation above (Eq. (8)), the superscript ds refers to double stream engine, while the standard gross thrust terms for the core and bypass are obtained through application of Eq. (6) for each stream respectively. The forces defined in Eqs. (7) and (8), namely the standard net thrust, correspond to the force that is displayed to the user of the AeroEngineS app, depending on whether the propulsion system features a bypass duct or is a single stream engine (e.g., the ramjet). The well-established definition of leading performance metrics such as the SFC and engine's efficiencies, is based on the calculated net thrust, and can be found in Ref. [30].

2.5 Educational integration and use

The app has been employed in aeroengine technology courses at universities both in Greece and Sweden in the past, through several assignments as well as through direct use in the final exams of the corresponding semester [19, 20]. Additionally, the

effect of the app on students' learning process was analyzed and clearly reviewed as positive. However, the version used was limited to simulating the performance of contemporary turbojet and turbofan only. In order to fully exploit the new potential provided by the latest updates of the app, three new assignments were designed and handed to the students sequentially, at the Aristotle University of Thessaloniki, Greece, within the course of "Aeroengine Technology". The course is undertaken during the last semester of studies (5th year), in five-hour lectures per week (split into two-hour and three-hour lectures). Details on the course organization and workload distribution in corresponding activities can be found in [20]. The course credit level according to the European Credit Transfer and Accumulation System (ECTS) is 5.

The assignments focused on the employment of the Aero-EngineS app, to investigate the fundamental operating principles of three propulsion systems: a hydrogen-powered ramjet engine cycle (1), a high-speed afterburning turboramjet cycle (2) and finally a hybrid, pre-cooled, air-breathing rocket cycle (3). This was done towards approximately the final quarter of the semester, when the students had already undertaken advanced assignments requiring them to develop numerical codes for the performance evaluation of high bypass ratio (BPR), 3-spool turbofan, and compare it to real data. Also, the students were already taught the fundamental principles of propulsion, including turbomachines, intakes and exhaust nozzles at the time when the assignments were introduced. The aim of the assignments was to facilitate the understanding of the performance and operating principles of advanced propulsion systems, and how they differ or not, compared to more conventional turbofan and turbojet engines, which the students have investigated in detail previously. The app provided a means to undertake the aforementioned analysis in a fast and efficient way.

2.5.1 Assignments description. The structure of the three different assignments that were handed to the students was identical. Initially, a brief introduction was included, providing critical information related to the corresponding propulsion system under investigation, as well as a simplified schematic, with numbered stations. The numbering system corresponded exactly to the results format provided by the AeroEngineS app, so that the possibility of misinterpretation of the app's results was eliminated. Following the introduction, the main body of the assignments was given. This was divided in two sections, namely the numerical and the theoretical part. In the numerical part, the students were required to utilize the app and run several performance simulations for a number of given scenarios or design points, for each one of the propulsion systems. The cycle operating conditions as well as leading performance parameters were extracted from the app's results page. Once all of the operating parameters, including temperature and pressure for every numbered station were collected, students were required to produce several graphs to capture fundamental trends, by post processing of the results using either a programming language or MS excel. These graphs included the combined enthalpy-entropy diagram for each engine superimposed for all different operating conditions, as well as a number of graphs demonstrating the impact of several parameters (e.g., altitude, flight Mach number, FAR, etc.) on

the performance metrics of the corresponding propulsion system (e.g., standard net thrust, SFC, efficiencies, inlet pressure and temperature ratio, etc.).

Once the results were collected and visualized in the requested diagrams, students were required to briefly answer a number of theoretical questions, related to the produced charts as well as to the general understanding of the propulsion system under investigation. The assignments were submitted by the students in the form of reports and were graded from 1 to 5, 5 being the highest grade. Some of the theoretical questions of the assignments focused, among others, on the limitations posed upon the engine's Mach range due to shock-induced temperature build-up at the intake [12], and how this can be mitigated through pre-cooling technologies [13]. In the last assignment (i.e., investigating the HyRE concept), the students were also requested to produce combined charts, showing the behavior of propulsive efficiency, thermal efficiency and SFC, with flight Mach number, for each one of the propulsive systems examined, including the previously investigated turbofan. Therefore, at the end of the assignments the student had produced a map, demonstrating the performance metrics of four totally different concepts, namely, a contemporary 3-spool turbofan, a ramjet, a turboramjet as well as a pre-cooled hybrid air-breathing rocket-cycle concept. This facilitated the direct comparison of the performance and fundamental operating principles for each one of the aforementioned propulsion systems.

3. RESULTS AND DISCUSSION

3.1 Performance models

Figure 4 depicts the input parameters page for each of the featured performance models (templates 3, 4, 5 and 6 in Fig. 3), as is displayed to the user of a smartphone. As can be seen, each model requires some mission data as input, such as the flight altitude or speed (i.e., M_∞). Efficiency parameters for combustion as well as polytropic efficiencies of turbomachinery components can also be set, but have default values which are typically found in such systems. Additionally, some geometrical aspects can be set in the template for contemporary civil aeroengines, such as the fan diameter, the bypass ratio and the hub/tip ratio of the fan blades, in the case of a turbofan. In this template, compressors pressure ratio and turbine entry temperature (TET) can also be modified by the user, to match the target engine's specifications. This is not available for the high-speed systems, since the model is designed on the basis of a specific engine concept, imposing several operational parameters, such as the pressure ratio, among others. For each one of the models, a schematic of the propulsive configuration is provided in the inputs page, with stations numbered in consistence with the results format. Once the required inputs are set, the user can click the "calculate" button to obtain the results.

3.2 Scope and validation

The accuracy of all of the performance models of the Aero-EngineS app, has been validated against publicly available data. The models for civil aeroengines found in the template number 3 of Fig. 3, have been originally developed by Pontika et al. [25], along with the model for the compressor map operating point

FIGURE 4: USER INPUTS PAGE FOR ENGINE PERFORMANCE MODELS; FROM LEFT TO RIGHT: 3-SPOOL TURBOFAN, TURBORAMJET, HYBRID AIR-BREATHING ROCKET CYCLE, RAMJET

The HyRE and ramjet templates were developed and integrated into the app as standalone performance simulation models by Tsentis et al. [33]. The ramjet template was the result of the need for a ramjet-like operation in the bypass duct of the concept featured under the HyRE template. This template aims at design point performance analysis of a novel, pre-cooled propulsion concept utilizing both air-breathing and rocket cycle characteristics. This engine concept, which is currently under development [34], could revolutionize the jet engine era and provide a step-change technology. It aims at achieving Single-Stage-To-Orbit (SSTO) capabilities, serving as the propulsion unit for a spacecraft launcher which could take-off like a conventional aircraft, deliver some payload to a specific orbit and then perform an aircraft-like horizontal landing [24]. This would dramatically reduce the cost and turnaround time of the mission, thus increasing exponentially the number of launches per year [35, 36]. It should

Template number 6 refers to the simulation of a high-speed turbojet concept which features ramjet-like characteristics. It is inspired by the well-known Pratt and Whitney J58 engine [40],

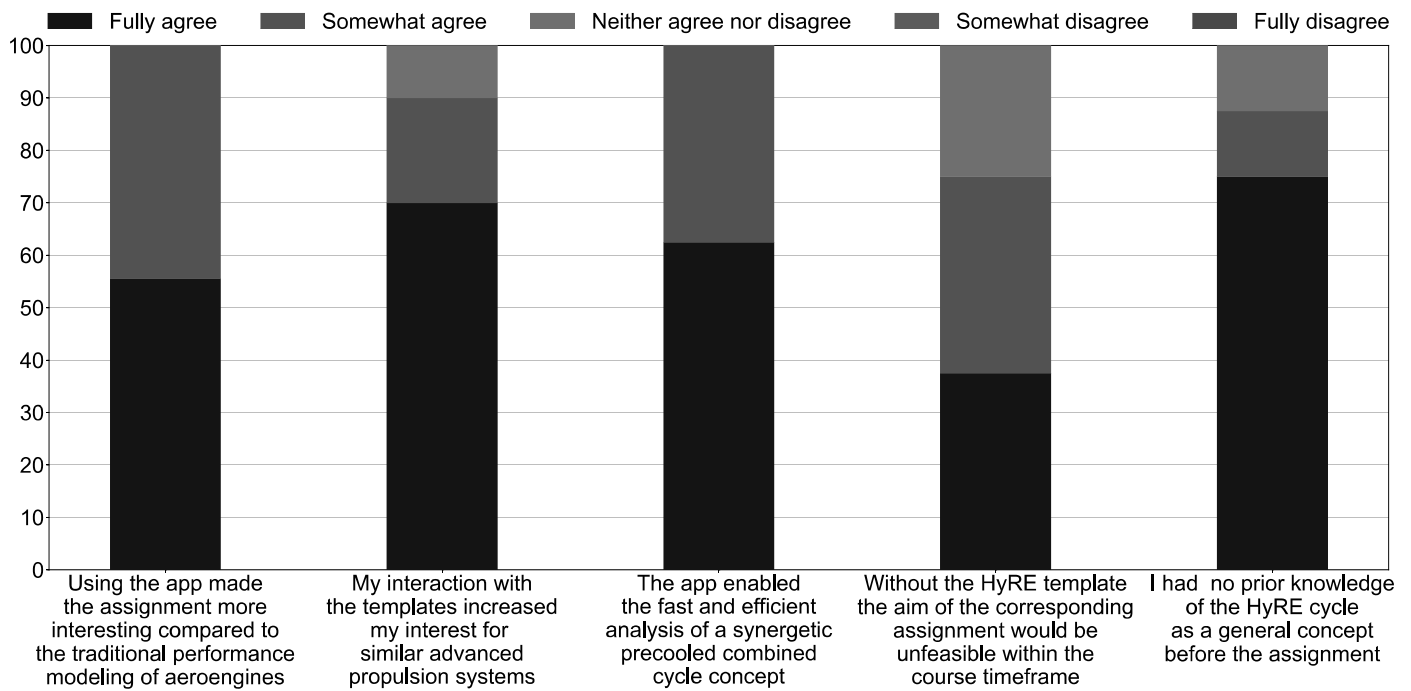


FIGURE 6: STUDENT REPLIES TO THE QUESTIONNAIRE ABOUT THE ROLE OF THE THREE ASSIGNMENTS IN THE COURSE

them. As such, and in order to evaluate the impact of the extended integration of the app into the aeroengine technology course, the students were kindly asked to provide their feedback by answering a short questionnaire shortly after the termination of the course and final grading. The questionnaire included questions related to the role of the app in the educational process for each one of the propulsion systems of the assignments (i.e., for each one of the templates number 4, 5 and 6 of Fig. 3), as well as generic questions about students' overall opinion on the employment of AeroEngineS in the course. Students were strongly encouraged to make suggestions on the improvement of the app in any potential way, as well as, to highlight its drawbacks. It should be noted that the students that voluntarily answered the questionnaire were approximately 73% of the total students enrolled in the course (i.e., 16 out of 22). There were the students that showed interest in the course and attended consistently all lectures, while there was a small minority (about 18%) of students that did not participate in the course from the beginning, and therefore not in a position to answer at all. A small percentage of students (approximately the rest 9% or 2 students) did not answer the questionnaire, while still attending the lectures and submitting the assignments. The reason for this may lie in the fact that the questionnaire was not mandatory, and students had exams for other courses running at the same time, each student having a totally different schedule in terms of study load. However, the amount of students participated in the questionnaire is still considered enough to provide statistically confident results, which could then be taken into account to draw conclusions on the app's educational impact.

Figure 6 illustrates the replies of the students to selected questions related to the role and impact of the three assignments on their understanding of the fundamental operating principles

of the propulsion systems investigated. The majority of the students (above 80%) fully or somewhat agreed that the assignments were indeed helpful to understand key principles of the examined systems (dark and light blue colors respectively in Fig. 5). Regarding the first assignment (i.e., the ramjet engine), all of the students agreed that it helped them to grasp what is the working Mach range of a ramjet and why it exists, meaning, why it is not possible for ramjet engines to operate above or below certain Mach numbers. Additionally, almost 90% of the students agreed to some degree that the assignments highlighted the significance of shock waves for the operation of high speed propulsion systems, as well as helped them understand the operating principles of the novel pre-cooled combined cycle. This is also depicted in the responses to the question related to the impact of pre-cooling the air upstream of the compressor, in which, only a small minority (slightly above 10%) thought that the assignment did not contribute in establishing this point. All students declared that by learning the rationale of advanced propulsion concepts, through the assignments, the limitations of contemporary aeroengines, such as turbofans and turbojets, were made apparent (last column of Fig. 6).

The aforementioned assignments were facilitated by the use of the corresponding three templates of the app. Therefore, it is important to examine, to what extent the students think that the app was helpful in conducting the assignments, as well as, whether its employment in the course is welcomed or not. These are demonstrated in Fig. 7. As seen in this figure, the entirety of the students who responded to the questionnaire, agreed to some extent, that using the app for the performance analysis of propulsion systems is more interesting compared to the traditional way of aeroengine modeling (i.e., developing a computational code

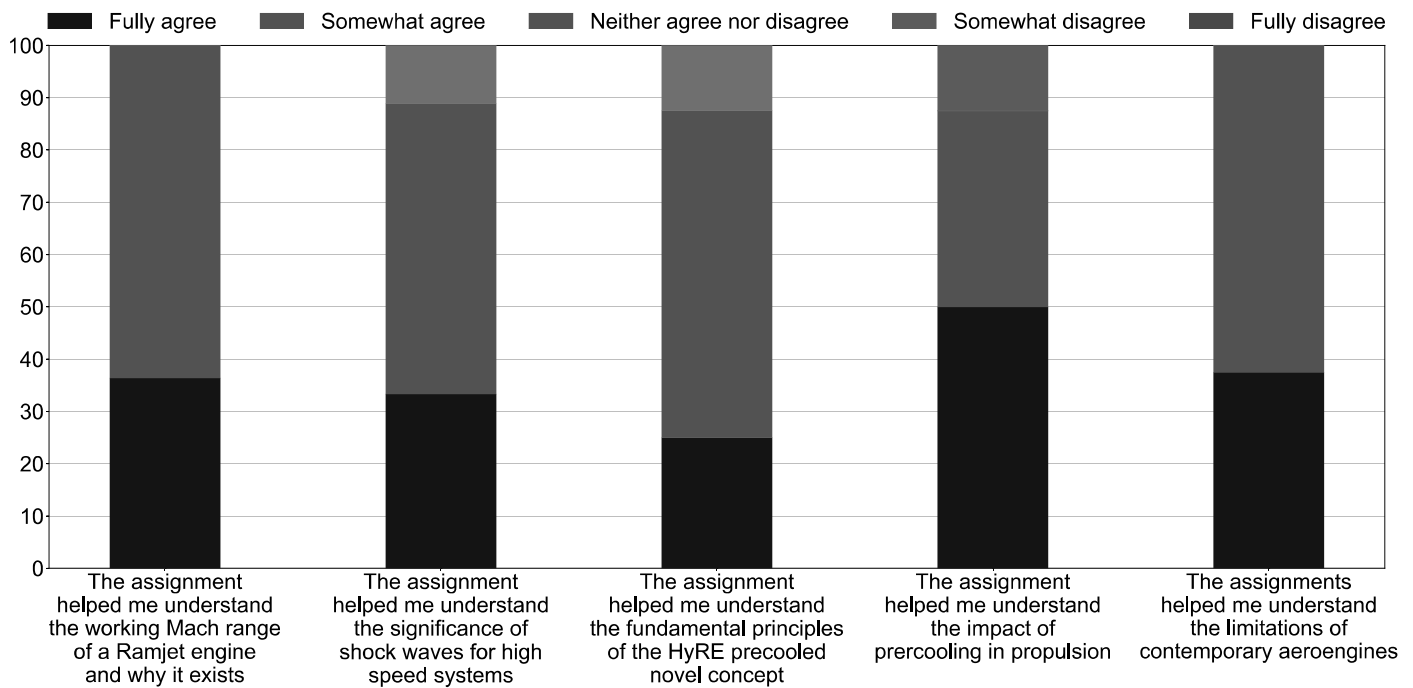


FIGURE 7: STUDENT REPLIES TO THE QUESTIONNAIRE ABOUT THE ROLE OF THE APP IN THE ASSIGNMENTS

in a personal computer). However, these results may be connected with the fact that the students had already performed a traditional performance modeling for a 3-spool turbofan by developing their own code in a programming language, earlier in the course. Therefore, having obtained this experience, they might only focused on what is more enjoyable, rather than both enjoyable and beneficial, when answering this question. It is the authors' belief that both methods should be employed, since each one has different advantages to offer to the students. Furthermore, approximately 90% of the students thought that the interaction with the app's templates as required for these assignments, increased their interest for similar advanced propulsion systems. This is a very encouraging result, in terms that these are technologies that are envisaged to revolutionize air and space propulsion in the years to come, and thus where research should be guided towards in the future.

All students agreed that AeroEngineS, and the HyRE template in specific, enabled the fast and more efficient performance analysis of a complex synergetic concept. Additionally, approximately 75% of them, thought that the assignment would be impossible to achieve its aim in the timeframe of this course without the use of the HyRE template, while the rest 25% of the students were neutral to this statement. Finally, it should be noted, that almost 9 out of 10 students had no prior knowledge at all, related to the pre-cooled, combined cycle concept. This demonstrates the significant impact that the utilization of this app had on the content of the course and the learning outcomes of the students.

Student feedback of their opinion on the overall impact of the AeroEngineS app on the course, is shown in Fig. 8. Six questions (questions A to F), as posed to the students in the questionnaire, along with their corresponding replies are depicted. A remarkable

90% of the students, fully agrees that the overall contribution of the app to the course is positive, while the rest 10% agrees as well, but probably to a lower degree (question A). All students declared their agreement when asked whether the introduction of this app to the course constitutes a novelty/initiative towards the right direction, in terms of future education, with 70% of them fully agreeing to this statement and the rest 30% agreeing to a lower extend (question B).

Additionally, the entirety of the involved students, considers the interaction with the app during the course to be interesting (question C). This is something that was not self-evident beforehand, since utilization of the app includes no self-developed coding or other advanced methods for performance modeling, and as such, there was the potential of the students losing interest on the subject. Again, this may be connected to the fact that the students had already obtained the experience of developing their own code for performance simulation of aeroengines, and thus the results should be interpreted carefully. Focus should be given on the replies of question D, where it can be seen that all students agreed, that the introduction of the app in the course, expanded their knowledge further, compared to the traditional curriculum. This outcome, is entirely based on the employment of the AeroEngineS app in the course. Furthermore, the majority of the students (80%), thought that the interaction with the app through the process described herein, increased their interest for propulsion systems in general (question F). This is expected to lead to an increased number of propulsion-related master theses, which usually constitute the first step of an individual's career, the latter being frequently closely connected to the original topic of the master thesis. Of course, this is only one component which is related to an individual's subsequent career choices, and therefore,

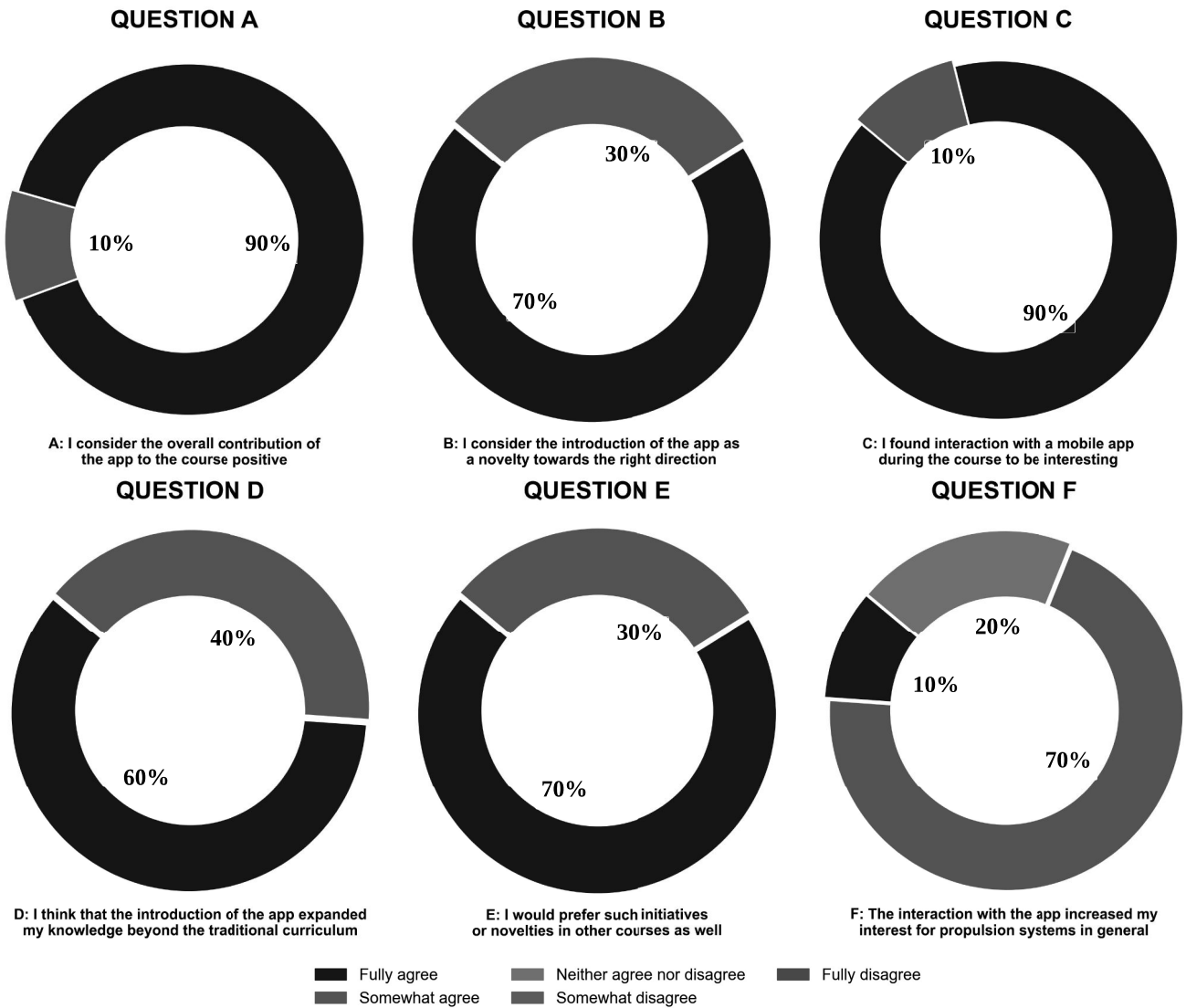


FIGURE 8: STUDENT REPLIES TO THE QUESTIONNAIRE ABOUT THE OVERALL IMPACT OF THE APP ON THE COURSE

should not be regarded as a cause and effect phenomenon.

Probably the most reliable metric to judge whether the experimental transition towards a more digital era in education, as presented in this study, was successful or not, is depicted in the responses to question E (Fig. 8). It can be seen that 70% of the students would strongly prefer similar initiatives in other courses as well, while the rest 30% would also be in favor of this, but probably to a lower degree. In any case, there was no student to declare his disagreement with this statement overall. This does not mean that every course should involve a similar mobile or web-based application, but rather that novel ways of teaching should be considered in other engineering courses as well, according to the students.

As presented in this section, the students provided quite positive feedback on the employment of the app in the course. They were satisfied with the way the course unfolded, and with the knowledge they obtained. They were also asked what is the most

interesting or important information they obtained through this process, as well as, to briefly describe their overall impression from using the AeroEngineS app within the course. Some of their own thoughts, as submitted in the questionnaire, are presented next.

- “This is a very useful app. Its use in the course should continue in the future since it enables the rapid evaluation of known concepts (turbofan engines), as well as the familiarization and analysis of relatively unknown and novel ones (turboramjet and HyRE).”
- “An amazing experience, in which the app has a pivotal role. Without the app’s HyRE model it would be very difficult to study such an interesting and novel engine.”
- “My engagement with such engine concepts would be almost impossible without the app. Its simplicity and rapid calculations make it really interesting. Additionally, the simplified

schematics of the propulsion systems provided in the app, were very useful.”

- “The app is exceptional. It allows within seconds, the calculation of operating characteristics for such a complex engine (HyRE)”.

It is very important to highlight that the majority of the students’ responses are stated in a manner that indicates no tedious feelings involved, which can be frequent in filling voluntary questionnaires. On the contrary, their responses seem to include excitement about getting familiar with novel concepts, far beyond the traditional curriculums. Furthermore, they seem to understand, the role of the app in these assignments, which widened their field of knowledge in propulsion. Students were also asked to make suggestive comments, towards improving the app or the way it is implemented in the course structure. Some of their suggestions were as follows:

- “Further technical details on the development of the pre-cooler featured in the HyRE concept, since this is the most novel component of this cycle, would be interesting”.
- “It would be nice if the app could produce trend charts as well, like the ones that we manually extracted in the assignments”.
- “I think it would be a nice idea if there was the potential of extracting the results in a file directly from the app to make the analysis even more efficient, and for better visualization”.
- “I think an extra page with the employed equations for each model would be useful to exist. This way the user will be able to see the mathematics behind each template and easier explain the results”.

The suggestions provided above, are indeed constructive and the comments of the students are currently being considered and ways of implementing these changes are investigated. The on-point comments given by the students indicate their increased interest levels regarding the whole process of the AeroEngineS app integration within the course.

3.5 Discussion

The use of the app within an applied engineering course poses major challenges. This applies for the tutors as well, since the structure of the course must be modified, thus building up in teaching complexity. The tutors are responsible for the efficient and smooth integration of the app in the course, and this plays an important role in the overall outcome. The exact equations involved in the app, as well as the major assumptions of the models should be explicitly defined to the students to avoid any misinterpretation of the results. Because of the front-end nature of the app, able of providing rapid results with the touch of a button, not being aware of the assumptions or numerical logic of the embedded models could have the inverse effects on the students’ knowledge. Therefore, increased attention should be paid when designing the integration process of the app, or any novelty in

general, in the course’s traditional structure. The fundamental areas of propulsion must be covered before proceeding to the more advanced concepts and making use of the app.

The three assignments introduced in the course were the stepping stones for the students to engage and familiarize with concepts far beyond the traditional scope of aeroengines related courses. The role of the app was detrimental to this, acting as the key enabling technology. The main aim of broadly introducing the app in the course was twofold from the beginning. Firstly, to widen the range of propulsion systems that were being traditionally analyzed in the course, by providing a rapid simulation tool to the students with embedded models able to investigate the performance of advanced engines. The second was to enhance students’ interest in propulsion in general, and transform a fundamentally complex course into a more appealing one.

The results presented in this section exhibit statistically significant behavior suggesting that the overall implementation of the AeroEngineS app in the educational environment, features many benefits for the students. Therefore, both aims mentioned previously have been achieved to a large degree. Students were made aware of the fundamental assumptions and equations of the model before the assignments. This facilitated the appreciation of the apps capabilities, both in performance modeling and in education, given its straightforward mathematical approach. However, attention should be paid when interpreting the results obtained from a questionnaire, since the responses may be connected to other factors and not totally reflect the truth, as mentioned earlier. In any case, the results presented herein, including the comments made by the students, constitute a very positive feedback, suggesting that the students would like to see this initiative be continued in the future. In fact, their experience with this app seemed to be positive enough, so that they would like other courses to implement similar novelties in their conventional structure (question E in Fig. 8).

4. CONCLUSIONS AND FUTURE WORK

This article presented a novel, comprehensive multi-platform app for aeroengine simulation, which provides a rapid performance analysis tool for propulsion systems, with the overall aim of reshaping conventional educational processes in aeronautical disciplined curriculums. The development process of the app as well as the mathematical formulation for its embedded models has been described in detail. The current state and capabilities of the app have been broken down into their constituent components. The app has been employed into an aeroengine technology course at the Aristotle University of Thessaloniki, Greece to evaluate its potential of reforming contemporary educational practices. Three assignments were designed and handed to the students towards the end of the academic semester, each one related to the performance analysis of a propulsion system, namely a ramjet engine, a turboramjet engine as well as a pre-cooled, hybrid, air-breathing, rocket-cycle concept. Students were asked to provide anonymous feedback after submission of the assignments regarding their opinion on the implementation of the app. The main conclusions are as follows:

- All of the students fully or somewhat agreed that the Aero-EngineS app widened their knowledge on propulsion sys-

tems and increased their interest on this topic. There was not a single student found to disagree on this statement.

- Approximately 90% of the students agreed that the assignments helped them understand key performance characteristics of advanced propulsion systems as well as the fundamental operating principles of the HyRE pre-cooled cycle concept.
- The entirety of the students strongly considered the implementation of the app in the course, as a novelty towards the right direction in terms of future education in engineering.
- 70% of the students fully agreed that they would like similar initiatives in other courses as well, while the remaining 30% also agreed but to lower degree. This is considered a strong metric related to whether the implementation of the app in the course was successful or not.
- Based on students' exact comments, getting familiar with more complex engine cycles rather than only with conventional turbofan engines, was a very helpful and interesting experience. This phenomenon is enhanced especially in the case of the pre-cooled combined cycle.
- The performance analysis of such complex propulsion systems would be impossible without the implementation of the app within the timeframe of an academic semester. Therefore, the role of the AeroEngineS app on the course's learning outcomes was pivotal.
- The results of this study, strongly suggest that smartphone or web-based apps exhibit big potential in enhancing tutoring in engineering related courses and could play a critical role in future education in general, if treated properly.

The app has been made open-source and available to everyone, therefore it can be easily implemented in propulsion courses in other universities, with or without the suggested method of integration into the educational process. It is constantly being updated with new models and functionalities related to propulsion and performance modeling in specific. Future work will aim at implementing the constructive changes suggested by the students, since this will ensure that future versions of the AeroEngineS app are in line with students' needs and ideas. Additionally, focus will be given on employing the systematic approach proposed in this study across a number of universities, both in Greece and abroad, to further evaluate the app's educational benefits in a wider scale.

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A comprehensive educational App for propulsion systems

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