

Article

The Role of Applied Mechanics in Bridging the Gaps in Prior Learning for Aspirants of Engineering Education

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Abstract: Building a technology-driven world appears to be the main motivational force behind students choosing to undertake engineering studies. The first year of engineering education plays a significant role in demonstrating sufficient mathematical and scientific rigor to satisfy these motivational factors. The common applied mechanics courses play a central role in achieving this. At the same time, a vast majority of students suffer from a lack of the necessary mathematical skills and analytical orientation for various reasons. Due to different educational philosophies and teaching pedagogies, a lack of proper integration between mathematics and applied mechanics is common. Several efforts were made to build better curriculum, teaching, and learning systems, resulting in widely varied solutions, but most of them require drastically different implementation approaches. With sufficient rigor in teaching and assessment, the first-year applied mechanics (common) courses designed for engineering students can solve students' mathematical and motivational lapses and help bridge the gaps between pre-university and university education endeavours. This paper presents evidence supporting this argument. In particular, datasets collected from the direct experiences delivering the first-year static and dynamics courses to many students over the past decade and a half are analysed to establish the proposition.



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1. Background

Applied mechanics concepts are taught through one or two courses as part of the common Year-1 engineering curriculum employed around the world. Some classical physics concepts and/or introductory topics in statics and dynamics typically constitute the contents of these courses. While the core engineering courses and the specific contents of the curriculum structures in the sophomore year and beyond are centred around the specialisation, the common Year-1 curriculum often takes the brunt of most scepticism, discussions, experimentation, and amendments, in general. The Year-1 engineering is at the crossroads between the secondary school studies and the university education system. Students enter the engineering programs offered by universities with specific motivations and aspirations. The ambitions of the parents, the university enrolment and retention targets, and the future technical expertise of the country in general are all intertwined and subjected to scrutiny at the same time. Consequently, there is a general consensus that the Year-1 engineering curriculum should be carefully tailored to be in alignment with all these aspirations, targeting the total customer satisfaction scenarios [1].

At the same time, the Year-1 mechanics courses are often perceived to be more difficult by a vast majority of students. Presumably, the actual contents are not at fault, but the significant step change associated with the need for the consolidation of the mathematical skills from the pre-university studies and the immediate application of the same to solve problems close to the reality is the main bottleneck. Huge differences often exist between the expectations and the actual merits of students in terms of their readiness with the appropriate mathematical skills. This has been a global problem, as decreasing levels of mathematical abilities in school-leavers were identified as a problem in many engineering

educational systems around the world [2]. This will lead to the lack of persistence of students enrolled into engineering programs as was observed in the PhD dissertation by Shryock, based on an elaborate study at Texas A&M University [3]. Strong links were identified between the contents and skills developed in the first-year mathematics and physics mechanics courses to the performance in the sophomore year and beyond. It was also observed that success in the first-year mechanics indicates success in later years of engineering. A strong mathematical foundation will pave ways to overcoming the true obstacles in reaching the goal of understanding the science fundamentals and successfully completing an engineering degree.

With the length of engineering honours degrees constrained to four years, the new subject areas such as software engineering growing to considerable common needs and requirement, and aspects of morals, ethics, and the sustainability considerations, often imposed by accreditation bodies as mandatory topics to be covered, the engineering Year-1 curricula have gradually grown to be quite crammed. Despite the congestion in space and ever-growing constraints, both statics and dynamics survived in some form or the other to be the commonly taught topics for all engineering students around the world. This brief acquaintance of the mechanical engineering principles is believed to orient the freshman engineering minds towards engineering thinking and the analytically challenging academic careers they preferred to pursue.

In reality, beyond the introduction of some basic principles of mechanics, these topics play significant roles in moulding the learning aptitudes of the engineering aspirants. Being at the crossroads between school leaving and the entrance to the university education system, the gaps in analytical orientation are actually bridged with the mathematical experiences acquired from analysing problems and systems representative of real-world scenarios. From an educational perspective, these courses lay the foundation for the academic endeavours of any engineering discipline. This paper focuses on ascertaining these attributes of the Year-1 mechanics courses as offered at the Auckland University of Technology as per the common engineering curriculum currently followed. The teaching and learning concerns centred around these courses, the emphasis placed on their significances and some constructive efforts made around the world to fulfil these quests are briefly reviewed first.

2. Integrated STEM Education and the Year 1 Applied Mechanics

Higher education in science, technology, engineering, and mathematics in general promotes the global information-based and technology-driven economies. However, a serious lack of continuity was often noted, and the consequent need to develop a curriculum, that bridges the gap between secondary and higher STEM education [4]. The STEM@school initiative in Flanders (Belgium) was focused on the integrated STEM (iSTEM) practices in the middle and upper secondary education, grounded in the principles of integration, problem-, inquiry- and design-based, cooperative learning methods, and the use of appropriate pedagogies that can effectively bridge the gap between secondary and higher STEM education practices. Extending this line of thinking to the whole engineering curriculum, the international collaboration between four Swedish universities and the Massachusetts Institute of Technology (MIT) in the USA led to the vision of an overall engineering education system, stressing engineering fundamentals set in the context of Conceiving–Design–Implementing–Operating (CDIO) real-world systems and products [5].

In similar lines, multiple government agencies, educational societies, and university-based committees reviewed the undergraduate engineering programs in the mid-1980s and came to a common understanding to retain the basic elements of mathematics, natural sciences, engineering sciences, and fundamental concepts of analysis and design [6]. Increased emphasis was also found to be necessary in maintaining the depth and strength in technical matters, while also maintaining a deeper inquiry and problem-solving skills and non-technical education, developing historical and societal perspectives, communication skills, career-long learning, and professional development attitudes. Evaluating these

widely varying multitude of requirements, the committee at the Drexel University came up with a list of characteristics that future graduates should possess to become leaders of the profession [6]. A strong foundation in basic sciences, mathematics, and engineering fundamentals is at the top of this list, with the capacity to apply these fundamentals to a variety of problems.

Considering the Year-1 engineering curriculum closely, based on the data collected on individual responses and research publications from around 12 countries and over 70 institutions, Baillie concluded that the offering of a new first year introductory subject as the most plausible solution to realising the end goals of an engineering degree and the learning methods to be used to reach them [2]. Pendergrass et al. presented a novel, cooperative, and quite involving approach to enhance the first-year engineering education [7]. The faculty delivering the Year-1 engineering courses worked as a team and developed a new 31 credit Integrated, Math, Physics, Undergraduate Laboratory Science, English, and Engineering: IMPULSE curriculum. The courses were well integrated to enhance the synergies in between. For example, both calculus and physics were carefully sequenced so that the mathematical knowledge and the application in physics mutually strengthen the overall understanding and fundamental knowledge of the students. The implementation of the new curriculum structure was demonstrated to be successful in terms of the achievements of the students in a selected cohort of 48 students. While all these are different models that evolved at different times, addressing different scenarios, the root cause of the predominant learning and teaching difficulties boil down to the lack of the necessary mathematical skills and analytical abilities of students joining engineering degrees.

3. Engineering Cohorts and Mathematical Inadequacies

The analytical and mathematical skills acquired by students before entering engineering programs vary vastly as do the aspirations and the motivational virtues. It has been expressed repeatedly that a vast multitude of students enrolling into engineering programs lack the pre-requisite mathematical skills [8–11]. Grinter's report in 1956 recommends a significant emphasis on mathematics and engineering sciences, as reviewed by Floyd et al. [12], considering the major changes that took place in engineering education. Lack of communication skills and awareness to the environmental and societal concerns have become central issues in the recommendations based on the recent collective efforts by different groups [2,5–7]. While these aspects are important, a more intensive focus on the core mathematical skills was found to be necessary during the first year of engineering courses [13]. Being unable to perform in the Year-1 applied mechanics courses and the consequent failure to achieve the pass grades could become a critical factor in adversely affecting the retention rates [14].

Auckland University of Technology, though the fastest growing, is younger, compared to many other universities offering engineering honours degrees in New Zealand. The implication of this is the student cohorts opting for the engineering honours programs are relatively weaker in mathematical abilities to varying degrees. It is pertinent to draw some similarities here based on the simple but straight and honest appraisal of the scenarios common to most engineering situations by Strum and Kirk [15]. The differences in approaches such as the mathematics faculty being more abstract and keener on concepts rather than applications and the engineering faculty requiring the students to be ready with skills to be applied to real world problems, often lead to confusion, and further complicate the general lack of mathematical abilities of students enrolled in engineering degrees. It was rightly observed that the continuous lack of the essential mathematical skills restrains students from effectively learning the fundamental concepts in engineering courses. Similar conditions prevail in the engineering education system at AUT. Further, the solution proposed by Strum and Kirk [15] to bring both engineering and mathematical faculties together to discuss and adjust the course structures and delivery methods is too idealistic and often only leads to a temporary readjustment of roles and then quickly sliding back into the common divided efforts resulting in highly personalised learning and teaching

methods and two distinctly different and parallel academic endeavours imposed on the young learners. The overall effectiveness of the academic endeavours further deteriorates with a substantial number of students lacking the mathematical rigour and orientation from their pre-university studies.

Based on the experiences of delivering the Year-1 applied mechanics courses over a decade and half, the author observed that the two applied mechanics courses taught common to all engineering students at AUT play crucial roles in bridging some of these gaps and enhancing the learning aptitudes of a majority of students. This is an attempt to shed some light on the significance of the roles of these courses in building the analytical abilities of students pursuing engineering degrees at AUT. The focus is on the Statics and Dynamics components of two specific courses, Mechanical Principles A and B, taught in the first and the second semesters of the Year-1 curriculum, respectively, common to all engineering students. The efforts made in fulfilling the roles these courses can play, building the analytical capabilities of students and bridging the gaps in prior learning, will be discussed together with local constraints and other aspects such as the lack of coordinated efforts as is common in most engineering educational systems.

4. Acquiring Applied Mathematical Skills

Initiatives of the Committee on Curricular Emphasis in Basic Mechanics (CCEBM) evaluating the quality of instruction in basic mechanics led to the conduction of a standard test assessing the pre-requisite mathematical skills [16]. The standard test comprising of a set of questions covering elements of trigonometry, geometry, vectors, and calculus offered to several thousands of students at engineering schools, junior colleges, and engineering technology programs over a period of a decade [16–18]. Following in the same lines, the author has been implementing a simple assessment evaluating the mathematical readiness of students enrolling into the Statics and Dynamics courses. The first test (Test 1) is done at the start of Semester 1, where the vast majority of students are still fresh from pre-university schools and enrolled into the Statics component. A second test (Test 2) is done at the start of Semester 2, before the students begin their course in Dynamics and is set to examine the skills of students as they have already acquired from the first semester education at the university.

Each test is made up of 10 questions, with Test 1 mainly covering the common basic principles of trigonometry, analytical solid geometry, and algebra, while Test 2 includes integration problems requiring the use of very basic skills. The degree of difficulty increases slightly from the first question to the last question. The first three questions are generally very simple and any student with a reasonable confidence in the prior mathematical skills will be able to score. The purpose of these three questions is mainly to identify the magnitude of the problem of lack of mathematical confidence in the cohort. The last three questions are truly representative of the level of mathematical skills expected from the prior learning, which are the high school (NCEA Level 3 in New Zealand) for Test 1 and the first semester STEM studies at AUT for Test 2. Answering these three questions really reflects the readiness of the students for the Statics and Dynamics courses and the education along the engineering pathways they choose. Ideally, all the students correctly solving all the questions allows the engineering education to take off from the first day and reach the best possible level of preparing the graduates for the world beyond. In reality, this does not happen ever, and in fact, the results from the author's experiences fall on the other side of the spectrum, as elaborated next. The test sheets are distributed to students in the class and given enough time for completing all the 10 problems. At the end, the key solutions are shown on the screen and the students are asked to self-assess their own work, allocating 1 mark for each right answer and recording the total mark out of 10. The students are instructed strictly not to write their names anywhere and the marked sheets are collected back purely for statistical evaluation of the overall strengths of the cohorts in basic mathematical skills. The end results of the anonymous test sheets are

compiled to produce bar charts similar to the examples presented in Figure 1 indicating the mathematical readiness of students prior to taking the Statics and Dynamics.

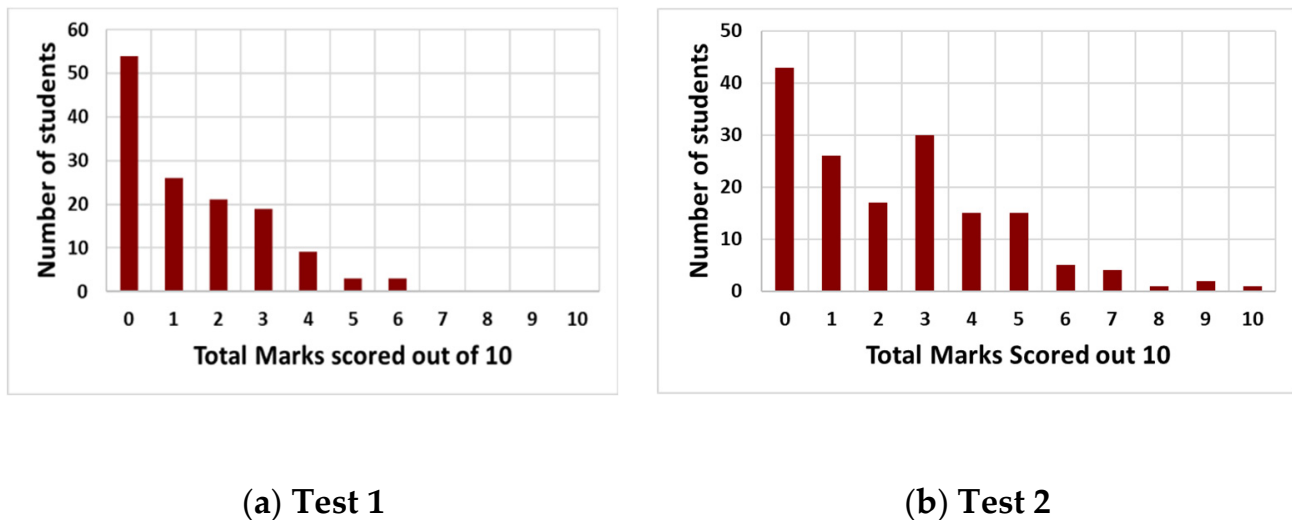


Figure 1. Typical patterns of mathematical abilities of students in a cohort, prior to taking Statics and Dynamics components of the Year 1 common engineering courses at AUT, based on (a) Test 1 and (b) Test 2 results collected anonymously at the start of Semester 1 and Semester 2, respectively.

The results are not very encouraging to begin with and are typically in the same patterns as observed earlier by others taking similar courses [8–11]. Around 150 to 160 students of a cohort of 250 often participate in these assessments, that are conducted without any preannouncement or preparation. In both Test 1 and Test 2, it has been commonly observed that at least 40 to 50 students cannot answer even one question correctly, clearly reflecting the lowest level of prior mathematical abilities at the point of entry into university level education. This is equivalent to almost around 20 percent of the students enrolled in each cohort. Moreover, considering 50 percent as the minimum pass mark, almost around 100 students often fail to reach this level, which is indicative of around 65 percent failure in terms of the basic mathematical abilities within the cohort. The same figures have been observed in similar tests conducted year after year. These results are clearly in accordance with the viewpoint by Snyder, that many students enrolled in engineering programs seriously lack the understanding and ability to use even the elementary mathematical skills [16]. Snyder also emphasises the consequences that the basic mechanics courses provide the framework for first identifying these weaknesses and then also resolving the problems by forcing students to upgrade the mathematical abilities in situ, by all means. Let us now examine this second premise in the context of the Year-1 mechanics courses at AUT.

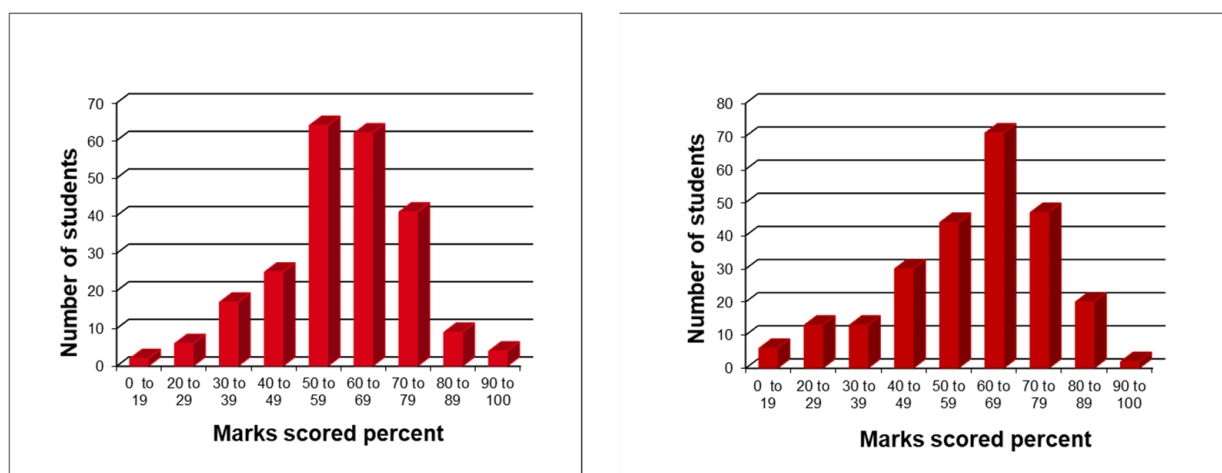
5. Statics and Dynamics Bridging the Gaps

While focused at gradually building the flair towards real world and engineering science comprehension, the topics from both statics and dynamics also keep challenging the students from the mathematical skills required. Moreover, distinctly different from the pure mathematics courses, analytical skills continue to evolve and accumulate more effectively, due to the applied nature of the learning contents. For example, a problem of integrating a given function is generally given in that form in the undergraduate mathematics courses and the learner has to essentially identify and apply the specific techniques that can be used to solve the particular given function. This keeps the problem as well as the solution in a particular context and simplifies the fuzzy front-end and ambiguity if any, that play more significant roles in retarding the learning process. Whereas an integration problem in the applied mechanics context begins with the understanding of the physics of the problem

first, followed by the identification of the basic principles to be applied, and finally building the function to be integrated to find the solution to the given problem. This kind of applied learning allows the student to clearly comprehend the true merits of the mathematical tools used and acquire experiences of contextualising the mathematical expertise in the concepts learnt.

Ellis et al. presented the use of concept maps as a means of seeing the 'big picture' and enhancing the understanding in engineering education [19]. Concept maps can remove the all too easy problem solving, and disjointed approach used in traditional course structures and the teaching methodologies. In this case, the pre-requisite knowledge of the essential tools, the basic mathematical expertise, though given to the students, due to the isolated nature of teaching, they cannot in the first place consolidate that knowledge and apply it to solving problems in mechanics. Following the concept mapping paradigm, a preliminary orientation around the mathematical solution methods and mapping of the same in a broader context, giving the big picture of applying the right tools to the right situations are practised integral with the teaching methodology of the Statics and Dynamics courses at AUT. During the initial stages of the course, concepts around specific topics are consolidated, clearly identifying the mathematical tools and methods to be employed in evaluating different problem scenarios. This will help the struggling students to gain confidence over the use of the mathematical techniques and also realise the true usefulness of applied mathematics, leading to the gradual building of the familiarity and becoming comfortable with mathematical skills.

Further, as the course progresses, a bigger picture is given, introducing general problems that require the integration of the knowledge acquired from solving problems in different topics. Instead of teaching the Newtonian mechanics concepts as a series of discrete topics, the emphasis is placed on connecting the topics into a central theme of understanding the core concepts, integrated with the acquisition of the essential mathematical skills and analytical thinking through solving problems that are close to the real-world scenarios. These approaches generally stimulate interest in engineering learning, gradually building the confidence and achievement levels of many students that struggle with the lack of mathematical and analytical abilities at the start of the university engineering education. Evidence of the improved performance is reflected in the final results of both Statics and Dynamics. The overall results vary over the years, but the average levels of achievements are as per the trends depicted in Figure 2a,b in Statics and Dynamics components, respectively.



(a) Statics: Total number of students 246, Failed: 25%

(b) Dynamics: Total number of students 230, Failed: 22%

Figure 2. The overall course results typical of a given cohort in (a) Statics and (b) Dynamics components of the applied mechanics courses.

A closer look at the results presented in Figure 2 will highlight the drastic improvements achieved with the mathematical abilities of a vast majority of students that began with almost negligible basic skill levels. As is commonly known, both statics and dynamics components involve the understanding and applications of Newtonian physics together with the application of the mathematical solutions based on introductory algebra, geometry, trigonometry, and calculus. From a complete lack of even the basic analytical skills as reflected in the evidence with more than 60 percent students failing the simple mathematical abilities tests as in the results of Figure 1, many students achieved pass or in many cases even better grades. This is in the intensive and secure assessments involving applied mechanics problems that require understanding of the basic physics, identification of the relevant principles, and integration of all this understanding in solutions based on the use of a variety of mixed mathematical skills. It may be noted that the assessments in Test 1 and the Statics and Dynamics do not address the same skillsets. Test 1 and 2 discussed above are assessments to evaluate the basic skills in related mathematical topics. Statics and Dynamics assessments go far beyond this, and the results reflect the performance of the students in much wider topics utilising the added mathematical abilities acquired in an applied manner and integrated into the contents and teaching of these two courses during the course of the first two semesters of the Year 1 common engineering curriculum.

This is a rapid and drastic achievement in terms of the teaching and learning endeavours and a marked change in the attitudes and aptitudes of most of the students can be clearly realised during the delivery and progression of the courses. Evidence of the changes in the motivational behaviour could be attained only qualitatively, observing the presence and the active participation of the students in the interactive tutorial sessions delivered in inductive teaching methodologies. Moreover, the student feedback comments often reflect the gradual changes in the aptitudes and attitudes; comments such as 'Never thought math could be so interesting,' and 'For the first time, I really enjoyed Dynamics,' are metrics of the improving mathematical motivations in the cohort. The core mathematical courses also play significant roles in building the underpinning knowledge and analytical abilities in the students. However, the 60 percent struggling students often benefit more from the applied learning methodologies integral with the problem-based delivery of the statics and dynamics components. The pedagogy promoting the realisation of the inter-relationships between core course contents and the mathematical tools makes the process more meaningful for the learners. The student feedback collected in the class clearly reflects this. The whole process provides the framework to gradually build the true learning citizenship for the vast majority of students on the brink of failure, while the relatively brighter students also experience satisfactory learning through the challenging academic endeavours, in the engineering education system at AUT. It may also be noted that around 20 to 25 percent of students still fail to reach the pass grades. This is essentially due to the personal attitudes of students, bad work ethics, and mainly absenteeism resulting in not being a part of the teaching and learning processes. Almost about half of these students realise the mistakes and rehabilitate themselves as they repeat these courses in the sophomore year and though belated, achieve the necessary maturity levels in learning eventually. A certain fraction of these students fails to raise to the required educational levels and mostly opt out and pursue other education or career pathways.

The overall results and the trends are clear evidence of the gradual improvements in the mathematical and analytical abilities acquired by the majority of the students in each cohort based on the experiences from the Statics and Dynamics courses. The main limitation of the current work is in the fact that only the average trends of results are used in the analysis leading up to the inferences drawn. A deeper insight into the results of different cohorts and a comparative evaluation of the changes within and across cohorts would further enhance the efforts in extracting the true roles these courses played in enhancing the academic value system in engineering. However, ethical constraints begin to restrain the freedom in using the data to any extent beyond this limit and for the sake of simplicity, the study is confined to the aggregate results as used and evaluated in this paper.

6. Conclusions

It is a globally realised fact that a vast majority of students enrolling into engineering education seriously lack the pre-requisite mathematical skills. Several different studies led to vastly different solutions to the problem. The IMPULSE curriculum and associated approaches are quite dynamic and effective but were only demonstrated with a relatively small group of students. Extending such studio-based learning facilities and closely coordinated teaching activities amongst a mixed class of teachers from different specialties is a huge task, when large groups of students are involved. Serious resource implications and the need to mobilise radical changes involving the university-level decision makers will arise, which are often quite difficult to mobilise, unless there is a university-wide drive for a drastic change. The other studies and the recommendations appear to address the issue of bringing a futuristic flair to the engineering degrees, but the general solutions envisioned appear to assume a certain level of pre-requisite skills for all students. In an idealistic scenario, where all the students are of a particular academic standard and with the same motivational levels, taught by highly cooperative, collaborative, and dedicated teaching staff, ready to adapt to changes, the idea of integrated curriculum and giving room for socio, economic, and environmental aspects can be considered duly and implemented effectively.

It was understood that the main aspects driving students towards engineering studies are mainly motivational such as making, building, or solving something and the desire to be technically challenged. The first-year engineering education is an important stage to show to the aspiring students that their main motives, being able to do and solve and to be technically challenged, are satisfied. The technical rigour of the first-year education should also be strategized, carefully balancing the technical challenges and the mathematical and science challenges. Mutually contradicting scenarios often arise. The mathematical and science rigour built into the applied mechanics courses as observed in the experiences leading up to this work appear to be the most economical and effective approach to the problem in the absence of a wider school-level initiative. The following are specific conclusions that can be drawn from the observations made in the current work:

- The mathematical abilities of many students enrolling into engineering education are not up to the required levels.
- These deficiencies continue even after the first semester of education at the university.
- The integrated mathematics and physics contents and teaching methods used in Year-1 common engineering courses Statics and Dynamics help achieve a drastic transition and align a vast majority of the struggling students on more confident, motivated, and successful pathways to higher engineering studies.
- In general, the Year-1 applied mechanics courses play unequivocal roles in bridging the gaps in mathematical abilities and analytical thinking from the pre-university to university studies.

This study further emphasizes the need to continue to teach the applied mechanics courses commonly to all engineering students as their role is unmistakable in keeping up the engineering education standards in general, whatever be the specialisation. These findings matter because, there is a gradual tendency for the Year-1 engineering curriculum to drift away from these classical patterns and embrace the more 'education for special purposes' kind of approach, promoting the more opportunistic pathways.

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