Engineering curriculum development based on education theories

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Education theories stress not only societal context of education, but also educational philosophy, anthropology and psychology of learning. A formal curriculum theory, viz. Taba–Tyler rationale, has been proposed to incorporate philosophical, sociological, anthropological and psychological contexts of engineering education in the curriculum. The newly developed undergraduate curriculum at the Indian Institute of Technology Ropar is based on such education theories and has been presented as a case study. It has been demonstrated that the resulting curriculum can lead to unique courses that collectively bring out unique features such as core competency, strong connection to society, hands-on learning, creativity and innovation.

Keywords: Curriculum development, engineering education, entrepreneurship, innovation, societal needs.

Introduction and motivation

CURRICULUM development process consists of identifying courses or subjects, prescribing their contents, organizing their sequence and learning experience[1,2]. To come up with a logical structure of curriculum, the objectives should be clearly established first. Srinath[1], however, noted that the curricula in most of engineering colleges in India have seldom been based on any rational objectives, but have been simply copied from other engineering institutes.

Identification of the objectives requires detailed analysis. The works of Ralph Tyler[3] (regarded as 'the father of educational evaluation and assessment') and his illustrious co-worker Hilda Taba[4], elaborate the process of curriculum development, including steps to decide objectives and evaluate learning experience. The Taba–Tyler rationales are general, not specific to a particular country or discipline, still relevant and frequently referred while developing curricula[5,6]. They can be easily extended to designing engineering curriculum suitable for India.

Curricula at the Indian Institutes of Technology (IITs) have been based on that of the West, especially Massachusetts Institute of Technology (MIT), USA, because of a history of collaboration between IITs and some US universities[7]. Inclusion of abstract sciences, and the Western humanities and social sciences (HSS) in an IIT curriculum indicates the influence of MIT. As a result, current curricula in the IITs may be more suitable for the West than for India and may be responsible for the brain-drain[7,8]. Thus there is need for customization of engineering curriculum to India[1,5,7–10]. The Nayudamma Committee's IIT Review Report also recommends the following in this regard[8]: 'steps are required to reduce the incidence of migration abroad of fresh graduates from IITs. This may be done through conscious career development planning for bright students, their involvement in technology missions and rural development schemes rather than rely on restrictive measures alone. The Department of Humanities and Social Sciences in the IITs must emphasise in the curriculum the socioeconomic ethos in which technology development is taking place in India, so as to inculcate distinct Indian values.'

As Graduate Aptitude Test in Engineering (GATE) is conducted by the IITs based on their own curricula, other engineering colleges automatically follow an IIT curriculum and seldom have freedom to design their own[7,10]. An IIT should, therefore, consider its responsibility as a leader of engineering education and develop its engineering

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curriculum from scratch based on well-established theories of curriculum development incorporating the needs of Indian society.

There are ready-made, basic guidelines for engineering curriculum, as laid out in the Washington Accord to which 17 countries are permanent signatories, including the US through Accreditation Board for Engineering and Technology (ABET) and India through National Board of Accreditation (NBA)[11]. The recommendations of the Washington Accord are general in nature and philosophically reflect the Taba–Tyler rationales, but still need to be customized to the needs of Indian society[11].

Engineering is all about solving societal problems applying science and technology. In the West, companies play an active role in identifying societal problems, and the team-work of their specialized engineering employees solves these problems. A strong, abstract science-based, research-oriented engineering curriculum, therefore, may suit the West as the objectives of the engineering colleges there are mostly to produce manpower for these companies[12]. In India, however, there is a lack of companies that identify and solve societal problems peculiar to the country. There is also a culture of innovation and entrepreneurship in the West, especially in the US, which obviates the need of strongly connecting engineering curriculum to society. India still does not have such a culture and hence curriculum should be accordingly tailor-made to inculcate innovation and entrepreneurship, with a focus on identifying the problems Indian society is facing and solving them using engineering principles[1].

In accordance with Tyler[3] and Taba[4], the following steps were followed for curriculum development process at IIT Ropar: (i) identification of specific aims of the curriculum; (ii) selection and organization of the content; (iii) selection and organization of learning experience; (iv) preparation of implementation notes, and (v) evaluation of the learning experience after implementation.

Identification of specific aims

According to Tyler[3], the specific aims may be identified based on the following: (i) Philosophy of education; (ii) study of the learners; (iii) study of contemporary life outside the classroom; (iv) statement on psychology of learning, and (v) subject specialists' opinion.

Specific aims based on philosophy of education

According to Taba[3], the purpose of education is as follows: (a) to preserve and transmit cultural heritage; (b) to act as an instrument to transform culture, and (c) to facilitate individual development, including values and feelings, and preparation for the future and changing environment by bringing about autonomy, individuality and creativity.

The following specific aims may be selected based on philosophy of education: (i) awareness about history of science and technology in the Indian subcontinent; (ii) to transform culture in terms of social engagement, innovation, do-it-yourself (DIY) and entrepreneurship; (iii) to facilitate individual development by providing different options for the students to choose from, such as Minor, Honours and concentration; (iv) to facilitate individual development by encouraging students to participate in group activities (curricular as well as extra-curricular) and thus inculcating team-work and leadership; and (v) to facilitate individual development by imparting ethics and values, including gender equality, anti-plagiarism, professional honesty, etc.

Specific aims based on study of the learners

According to Tyler[3] and Taba[4], first of all Maslow's hierarchy of needs should be satisfied[13]. Accordingly, an extra-curricular system may be recommended to address students' physiological needs (air, water, food, privacy), security needs (personal, health, financial security), love and belonging needs (friends, family), self-esteem needs (hobbies, interests, self-respect) and self-realization needs (altruism, social work, spirituality).

Specific aims based on contemporary life outside the campus

India is a net importer of engineering products[14], which may be due to lack of innovation or entrepreneurship, absence of DIY culture and insufficient manufacturing in the country. It is therefore important to emphasize innovation, DIY and entrepreneurship in the curriculum. Innovation tools such as micro-controllers, their programming, sensors, CAD, 3D-printing, workshop training, mobile programming, etc. should be taught to every student as early as possible.

We have observed decline of social responsibility and ethics in students, as many of them have been being penalized every year for plagiarism and cheating during exams. A course on ethics is, therefore, needed.

IIT graduates typically opt for business (through MBA studies), civil services, higher studies and core industries (including Military Engineer Services and Indian Engineering Services). Problems from all these sectors may, therefore, be introduced to the students. There may be many 'installments' of the DIY component, one each, for example, for defence, civic issues, infrastructure, rural issues, agriculture, health, etc.

Specific aims based on psychology of learning

According to Tyler[3], values cannot be taught to the students unless they can feel about it. Moreover, it takes a long time to change the character of a student older than 16 years. As learning is not confined to the classrooms alone and students also learn from their environment; hostel life and institute environment should be regulated to make students learn what cannot be taught in the classrooms.

According to Tyler[3], the following factors help in remembering the subjects taught in schools: (a) connections among the topics, and (b) using the concepts frequently, in daily life.

The following specific aims may be accordingly chosen: (i) to teach ethics and social responsibility through feeling; (ii) to introduce history of technology as a subject to roughly connect most of the core courses, and (iii) to introduce and relate learning to common engineering products used in daily life, such as smartphones, bicycles, motorcycles, cars, computers, laptops, printers, etc.

Specific aims according to subject specialists

The following may be considered 'subject specialists': (a) an institute's vision regarding the curriculum; (b) guidelines of the Washington Accord (especially the recommended knowledge profile, and graduate attribute profiles[11]); (c) the existing systems at leading engineering colleges in the world (e.g. MIT, Stanford, Caltech, etc.); (d) recruiters' feedback; (e) recommendations from industries; (f) prominent academicians; (g) individual departments; (h) individual faculty members; (i) alumni, and (j) students.

As ABET is a signatory of the Washington Accord, the US engineering programme reflects the recommended knowledge profile and graduate attribute profiles. Some important observations not necessarily coming from the ABET requirements are described below.

There are typically 30–36 weeks of instruction in a year in the US. These are typically divided either into two semesters (15–18 weeks each) or three quarters (10–12 weeks each). For example, MIT and IITs follow the semester system, whereas Stanford and Caltech follow the quarter system. Approximately 15% of the US universities follow the quarter system, including the University of California system (excluding Berkeley), the University of Chicago, Northwestern University, and the University of Washington. About 71% of the US universities follow semester system[15].

The total number of hours that a student is required to spend on attending lectures, tutorials and labs, and preparing for the class (including reading assignments/homework) per week varies among universities. For example, at MIT, freshmen require to spend 52–54 h every week[16], while senior students have lower load. Caltech and Stanford, on the other hand, have weekly load of around 42 and 45 h respectively[17,18].

Regardless of the academic term systems they follow, the US universities typically provide 2 h of preparation (for self-study, assignments, etc.) to students for every one contact hour (of lecture)[19]. Indian engineering institutes typically give 1 h for preparation for each hour of lecture due to high credit requirements.

The US universities following the semester system have typically 120–130 semester-credits required for an undergraduate (UG) degree (e.g. MIT)[20]. Those following quarter system have 160–180 quarter-credits (e.g. Caltech and Stanford)[17,18]. The course load is thus 12–16 credits per semester or quarter. To keep up with the international standards, total credits have been decreasing over time in the IITs.

Based on the subject specialists' opinions, the following specific aims were considered at IIT Ropar: (i) to include unique features in the curriculum according to the institute's vision; (ii) to include recommendations of the Washington Accord; (iii) to intensify the courses and provide sufficient preparation hours to the students as practised by top engineering colleges, such as MIT, Stanford and Caltech; (iv) to enhance quality of learning experience so that the students easily grasp the fundamentals; (v) to enhance professionalism and soft skills in the students to address the recruiters' feedback; (vi) to make courses more practical, and (vii) to strongly connect the final year project to industries.

Selection of content and its unique features

Students have been given the following four options for the 4-year UG programme: (i) B Tech in an engineering major discipline (145 credits), (ii) B Tech with Minor (B Tech plus 15-credits minor coursework in any discipline other than the major discipline), (iii) B Tech with Concentration (B Tech plus 15-credits concentration coursework within the major discipline), and (iv) B Tech with Honours (B Tech plus 15-credits honours coursework plus 10-credits research project.)

Every course has been given a (L–T–P–S–C) designation, where L, T, P and S respectively, denote the number of lecture, tutorial, practical and self-study 'hours'. C is the total credits for the course. Here 'hours' mean 50 min. In general, $S = 2L + (P/2) - T$ and $C = (L + T + P + S)/3 = L + (P/2)$.

The following courses (L–T–P–S–C designation in brackets) are required to be completed for a basic B Tech degree:

Humanities and social sciences (21 credits):

- History of technology [3/2-1/2-0-5/2-1.5]
- Professional English communication or English language skills [2-2/3-2-13/3-3] for students weak in English
- Economics [3-1-0-5-3]
- Industrial management [3-1-0-5-3]
- Professional ethics [1-1/3-1-13/6-1.5]

- Human geography and societal needs [1-1/3-4-11/3-3]
- HSS electives (six credits)

Sciences (30 credits):

- Physics for engineers [3-1-4-7-5]
- Chemistry for engineers [3-1-2-6-4]
- Calculus [3-1-0-5-3]
- Linear algebra, integral transforms and special functions [3-1-0-5-3]
- Biology for engineers [3-1-0-5-3]
- Programme-specific science-maths I [3-1-0-5-3] (departmental choice; e.g. 'differential equations' opted by all engineering departments)
- Programme-specific science-maths II [3-1-0-5-3] (departmental choice; e.g. 'probability and statistics', 'probability and stochastic processes', 'introduction to organic chemistry and biochemistry', etc.)
- Sciences electives (6 credits)

General engineering (23.5 credits):

- Technology museum lab [0-0-2-1-1]
- Workshop practice [0-0-4-2-2]
- Introduction to computer programing and data structure [3-1-3-13/2-4.5]
- Introduction to electrical engineering [2-2/3-2-13/3-3]
- Engineering drawing [0-0-3-3/2-1.5]
- Basic electronics [2-2/3-2-13/3-3]
- Introduction to engineering products [0-0-2-1-1]
- Tinkering lab [0-0-3-3/2-1.5]
- Introduction to environmental science and engineering [2-2/3-2-13/3-3]
- Programme-specific general engineering [3-1-0-5-3] (e.g. 'Introduction to materials science and engineering', 'materials science for electrical and electronics engineers', 'materials science for civil engineers', 'signals and systems', etc.).

Programme core and electives (total 48 credits):

- Program core (36–42 credits)
- Program electives (6–12 credits)

Capstone projects (nine credits):

- Development engineering project [0-0-6-3-3]
- Capstone project I and II, each [0-0-6-3-3]

Industrial internship and comprehensive viva (3.5 credits):

Extra-curricular (four credits):

- NCC I/NSO I/NSS I [0-0-2-1-1]
- NCC II/NSO II/NSS II [0-0-2-1-1]
- NCC III/NSO III/NSS III [0-0-2-1-1]
- NCC IV/NSO IV/NSS IV [0-0-2-1-1]

Open electives (six credits):

It should be noted that the 'programme core' must include sufficient number of relevant engineering science courses not already covered by the 'general engineering' category. Rest of the programme core should have programme-specific, application-oriented courses. As a sample, the 'mechanical engineering' programme at IIT Ropar has the following proposed core courses:

- Engineering mechanics [3-1-0-5-3]
- Solid mechanics [3-1-0-5-3]
- Thermodynamics [3-1-0-5-3]
- Machine drawing lab [0-0-4-2-2]
- Theory of machines [3-1-0-5-3]
- Fluid mechanics [3-1-0-5-3]
- Design lab I [0-0-4-2-2]
- Machine design [3-1-0-5-3]
- Heat and mass transfer [3-1-0-5-3]
- Manufacturing technology I [3-1-0-5-3]
- Thermo-fluids lab I [0-0-2-1-1]
- Manufacturing lab I [0-0-4-2-2]
- Dynamics and control [3-1-0-5-3]
- Manufacturing technology II [3-1-0-5-3]
- Design lab II [0-0-3-3/2-1.5]
- Thermo-fluids lab II [0-0-3-3/2-1.5]
- Manufacturing lab II [0-0-4-2-2]

Taba–Tyler rationale emphasizes interests and individual purpose of the students. Therefore, the students are given 24 credits to choose courses based on their individual requirements and interests, in form of six credits each of HSS electives, sciences electives, programme electives and open electives. It is important that the departments offer important courses as electives that could not be offered as core due to several constraints. For example, HSS department must offer philosophy, psychology and sociology as electives. Similarly, important science courses (especially in physics and chemistry) should be offered as electives so that students can gain confidence in basic sciences. Course advisors should also recommend such courses, based on the purpose and interest of individual students.

Thus, the designed curriculum has the following unique courses:

(i) History of technology, which will briefly cover some important events of science, technology and engineering that led to modern engineering products and engineering education.

(ii) Technology museum lab, which will make students build and play with historically important products, such as Galileo's telescope, steam engines, electric motors, etc.

(iii) Introduction to engineering products (lab), which will make students disassemble and assemble important engineering products such as motorcycles, washing machines, refrigerators, mobile phones, TVs, laptops, tablets, etc.

(iv) Tinkering lab, which will briefly cover CAD, 3D printing, kinematic mechanisms (including gears and CAM), micro-controllers, electric motors and controllers, and RF controllers which will enable students to build remotely controlled vehicles.

(v) Human geography and societal needs, where students will visit villages, hospitals, towns, etc. to identify societal problems.

(vi) Development engineering project, where students will develop a complex and economical product to solve one of the problems identified during 'human geography and societal needs'.

(vii) Capstone projects, whose aim will be to design and build an engineering product (e.g. in response to a challenge proposed by professional bodies such as ASCE, ASME, IEEE, etc.), which will compete with other designs (by fellow students) to earn grades.

(viii) All courses will, by default, have a tutorial component ($T = L/3$), wherever appropriate.

(ix) There is a predefined self-study component for every course ($S = 2L + (P/2) - T$), which will be monitored and evaluated by the instructors.

(x) High laboratory to lecture credit ratio (40% : 60%, approximately).

(xi) Every laboratory will have roughly half of the lab hours devoted to learning the basic skills and the other half to using those skills to design an experiment and carry out an experimental study.

(xii) All courses will have credits. While it may not be necessary to give credits for courses such as industrial internship and extra-curricular activities (NCC, NSS, NSO), they will have credits in order to motivate students for good work.

The curriculum, thus, includes the following unique features: (a) Connection to society (i.e. going to the society to find problems and solve them applying innovation); (b) Hands-on learning (i.e. high practical/DIY components); (c) Creativity and innovation (i.e. creating or doing something new and original), and (d) Core competency (i.e. strong fundamentals through compulsory tutorials and more preparation time to students).

Discussion and conclusion

The Taba–Tyler rationale draws curriculum objectives not only from subject specialists, but also from societal needs, requirements of individual students, philosophy and psychology of education. For example, the unique courses on history of technology, technology museum lab, introduction to engineering products, tinkering lab, human geography and societal needs, and development engineering project were decided based on the need of directly solving societal problems. The given sequence of these courses was decided based on the psychology of education, viz. in accordance with Bloom's taxonomy[21]. Similarly, the 'professional ethics' course was decided based on philosophy of education.

After identification of specific aims and selection of the content, the courses may be organized in such a way to minimize the resources. Every course should not only have detailed syllabus, but also *L–T–P–S–C* designation along with prescribed learning experience and detailed course objectives; for example, in terms of the knowledge profile of the Washington Accord[11].

The students should have an objective learning experience[3,4]. According to the Taba–Tyler rationale, 'learning experience' is the outcome of students' active interactions with their environments. The teachers are, therefore, needed to control or simulate the environment to facilitate behavioural change in accordance with the learning objectives. Every student has a different strength for the modalities of learning, namely visual, kinesthetic and auditory modalities[22]. In general, the active or experiential learning (hands-on learning followed by reflection) has higher efficiency than passive learning such as listening, reading and writing[23].

Special attention should be given to society-oriented courses or projects (e.g. human geography and societal needs and development engineering project) as they will require extensive planning and coordination[24]. As such, a reasonably high quality and quantity of work should be expected from all projects, which should be carefully managed, i.e. planned, organized, staffed, coordinated and controlled, applying management principles[25,26]. Without close monitoring and weekly evaluation by faculty members, a project will not serve its purpose.

An output-based assessment, such as that prescribed by the Washington Accord (ABET, NBA, etc.), may be adopted to determine if the programme objectives or individual course objectives have been met. A 'Teaching–Learning Centre' may be recommended to facilitate teaching and learning according to the designed curriculum and existing education theories. On a macroscopic level in an institute, principles of total quality management may be applied[25,26]. Quality control of curriculum, instruction and assessment should accordingly be part of the vision, mission and strategic plans of an institute[27].

Although implementation is out of scope for this study, we assumed that existing knowledge in educational management and administration may be applied for efficient implementation of the present curriculum[25,26]. Our focus was to show applicability of education theories to design an engineering curriculum from the 'first principles'. The procedure followed gives importance to philosophy, sociology and psychology of education, which automatically make the curriculum relevant to the society and to the students themselves. A detailed report on the designed curriculum is available at the IIT Ropar (http://www.

iitrpr.ac.in/new-curriculum). This curriculum is being implemented at IIT Ropar starting July 2017 onwards for new UG students.

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