"the engineer's work will always be largely a systems operation"

Systems Approach and Engineering Education*

by

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In recent discussions about higher education or, more correctly, in the opinions advanced about it, special attention has been given to the administration and forms of the education, with an emphasis varying from country to country. The importance of the contents of education and of their development has been admitted, but hardly any subjects or subject groups, have been mentioned in public. For example, the aims of the engineering educational curricula have by no means been exhaustively discussed. Independently of public discussion, both the form and the content have been considered in the educational establishments themselves, and certain changes are taking place. Therefore, it is timely to reconsider, at least to some extent, the content and aims of engineering education. The following reflections are directed to the system of engineering education which consists of basic education in universities and subsequent supplementary training, and to the division of the objectives between these two. Besides a general discussion of the goals, conclusions are also sought concerning the importance of the systems disciplines, and their role in the education.

The Engineer and the Systems

A statement of the goals of engineering education requires that the general characteristics of practical engineering are recognized. A knowledge of the technical methods in a given sector of production, and the basing of practical work on this knowledge, are so integral to the concept of the profession that not even in the future can they be separated from it. The work must be adapted to the economic realities; what an engineer produces could be produced by an amateur if costs could be disregarded. The part played by creative synthesis is essential when new equipment, systems and methods are being planned.

The methods of work used by the engineer are not confined to any narrow sector of engineering, although the basic education is arranged in this way. The dissimilarity of the working and the educational environments was very clearly demonstrated by Prof. J. Balchen[x] at a recent EUSEC/FEANI Conference. He also suggested a two-dimensional engineering education in university. Traditionally, in-

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x J. Balchen: Systems engineering in engineering education, EUSEC/FEANI Education Conference, Oslo, 1969 struction and research are divided by departments working on the various sectors of engineering, and these again are divided into smaller units; the ties between them often remain very weak. The type of production, in its turn, determines the working environment of the practical engineer, and he has to cooperate both with engineers of other sectors and with professionals in trade, law, personal relations, etc. To a certain extent, therefore, he must understand and even master methods which in actual fact belong to the sphere of another branch of education.

Thus the engineers are everywhere members of a productional system. On the other hand, the representatives of other professions have also to work in various systems. A special characteristic of the systems of economic life is that they have a given objective, primarily of an economic nature, whose achievement can be quantitatively evaluated. A special characteristic of the work of an engineer is its close liaison with the production of material commodities. The engineer's success in his work depends on how well he takes care of his role on the road to this overall objective, and not only on how well he masters the methods of his own special sector of engineering.

On the levels closest to the designing and manufacturing production, the engineer's knowledge of his own sector and of the adjacent sectors is of prime importance. On levels that are further removed from production, but at the same time are administratively higher, the importance of the knowledge of non-technical, i.e. commercial, administrative, legal,etc. factors increases. This is evidenced by the fact that managerial jobs of industrial production enterprises may sometimes lie in the hands of non-technical people who, having acquired supplementary education or practical experience, apparently have been proven capable of operating also systems of this type.

On the basis of the above, engineering education should, from two points of view, give training for systems work. General aims that can be outlined are to provide such basic knowledge, and to develop such skills, that the engineer is continuously able to operate, design and develop productional and technical systems and their technical components, on the one hand, and, on the other, to work at his own level, as an active factor in the productional system. These aims can obviously be considered to corresspond with the demands of both the engineering design and operation.

The basic engineering education is currently organized on the basis of the sectors of technology, and apparently gives little indication of aiming at the systems approach. A more detailed study, however, reveals that systems aspects are nevertheless included in the education.

Basics of Engineering Education

In the following discussion, the subjects of study are divided into five groups: basic mathematics and science, basic engineering, professional engineering subjects, systems subjects and other subjects. These groups will not be discussed in the sequence in which they follow one another in the curricula, as it is assumed that the normal sequence is sufficiently well known.

Instruction in professional engineering subjects holds the key position. The teacher should provide the student with the basic knowledge for the work within a given professional field. He should base it theoretically on the content of the basic subjects. He should also initiate the student into the nature of engineering problems and into the methods of their solution in his particular professional field, at the same time giving him an idea of the extent to which the solutions are to be based on detailed analysis, or on appraisal, experience or established practice which perhaps is limited by special stipulations. These two dimensional claims of the professional subjects should be maintained although it is clearly hard to find teachers meeting these demands.

Analysis of the observed need, and the setting of the requirements for a solution, i.e. the design criteria, are important engineering tasks which precede the development and comparison of alternative solutions. It is essential to find a feasible solution to a meaningful engineering level problem, rather than to seek it among the normal practices of a sector represented by only one discipline or department. Accordingly, near-optimal solutions to more demanding problems often end up with systems of components and sub-solutions belonging to several sectors of engineering.

Most teachers of professional engineering subjects, therefore, must include systems aspects in their instruction. This normally assumes the form of qualitative considerations of matter supplementing the core of the subject. As the trend is towards increasingly large systems, the system studies gain in importance. Logically, if the restricted number of lessons reserved for professional engineering subjects and the human limitations of the teacher's capacity could be disregarded, one might claim an introduction into the application of quantitative systems methods in analysis and synthesis associated with design. In connection with device and plant constructions, this means in the first place the application of steady state optimization, even though stability and controllability may also require attention. In operational engineering, on the other hand, we are faced with the methods of control engineering for continuous production systems and with those of operations analysis for the discrete ones.

According to their nature, the systems are composed of a number of parts or components. Operational systems may also contain human factors. The operation of a complex depends decisively on the way in which the basic parts are linked together. Engineering systems regularly involve a drive towards the best overall result. Its evaluation needs a criterion of optimality which, at least implicitly, takes all the influencing factors into consideration.

The methods of systems engineering are used for construction of mathematical models for both small and large systems, for simulation, and for optimization of the operation, control and structure of the systems. All studies are made with a view to the total system. The methods of work are mathematical, i.e. quantitative, but in view of the extent and the usually dynamic character of the tasks, it is usually not possible to penetrate very deeply into the scientific fundamentals of details; approximations must be used for the unit processes, on which the range of the solution's validity depends. The applied systems subjects, therefore, differ from mathematics and science by their practical engineering trend.

The quantitative treatment of a unit process or component, on the one hand, from scientific fundamentals of components and, on the other, from systems engineering analyses are two methods of approach which seemingly cannot be equitably united within the same formal discipline. Owing to their logical theoretical doctrinal structures, unbound with any particular field of application, the systems subjects, expressly controlling engineering and systems theory, have become separate disciplines. Also subjects like systems dynamics, studied in the early phase of engineering education, are being adopted by certain European universities following American examples.

As was concluded above, the engineer's work is and will always be largely a systems operation. It follows from this that the importance of systems subjects is of a permanent character. In this sense, they are basic subjects and their content will not become obsolete with time except perhaps for applications connected with a given sector of technology. For their permanent and general significance they are therefore comparable with natural sciences, for their technical character with basic engineering subjects, and for the professional competence they lend to the specializing engineer, the applied systems subjects are true professional engineering subjects.

As in the instruction of professional engineering subjects, the content of the basic subjects is also utilized in a considerable part of practical engineering work. The development of technology leads continuously to new types of solutions, for which reason an extensive knowledge of basic mathematics and science is important. At the moment, an adequate range of these subjects is included in the programmes of technological universities and faculties for the departments and students to choose from. Their theoretical logical approach attracts especially a student with a bent for research, but specialization and degrees in pure science are, of course, more naturally pursued in other institutions with which the technological universities or faculties hardly should compete.

Engineering has its special characteristics and in the same way technological research should be distinguished from research in pure science. A division into basic and applied research is too indefinite here, for any research can be claimed to have its applications, should one so desire. Research really associated with or aiming at essentially technological applications has to start from a given complex system of phenomena. Analysis of the problem, and reduction of the essential research object by eliminating the unessential phenomena is an important, little visible but very laborious part of engineering research. Often, moreover, no complete reduction is possible, and the basic phenomena must be examined in their complex environment. Research in pure science is concentrated on more or less isolated phenomena of the research worker's choice which can be reproduced in the laboratory.

Systems subjects are essential in engineering, and they should be sufficiently included in all engineering education. Otherwise, a curriculum composed of separate courses of short duration does not encourage the student to tackle systems which extend beyond the sector covered by his professional engineering subject. This educational background apparently accounts also for the engineers' much-discussed unwillingness to take part in social systems, and the reluctance towards accepting commercial and administrative duties felt by many. A confusing additional circumstance is that qualitative factors and values hold a central position in society and administration. The representatives of many other fields become used to them during the basic phase of their training, whereas the engineers' arguments are typically quantitative. Even here, each separated solution creates new problems, and the systems approach which helps to understand consequential and multiplicative effects and to distinguish between essential and non-essential factors is worth developing.

Basic mathematics and science, basic engineering subjects and systems subjects compose, or should compose, a basis of permanent importance from which specialization to practically all engineering professions can take place. Education for professional specialization must in any case also be provided by universities, i.e. by their specialized departments. In addition to the reasons already listed, the industry expects that a graduating engineer is able to undertake at least limited practical responsibilities, at the same time obtaining supplementary familiarity both with solutions applied to practice and with the productional system. Expectations of this kind are natural and justified, both as regards engineering and other professional graduates. Leaving the education for professional life to be given entirely in the environment in which the graduate will work can hardly enter into the question. It would lead to one-sidedness and make for a difficult period of transition for the newly graduated, due to his practical incompetence. Even in the present situation, the immediate practical significance of university training is not much appreciated. And of course the organization of theoretical part of professional training at the sites of work would involve considerable difficulties.

Professional engineering education, however, is hard pressed as other groups of subjects require an increasing share. The foundation given in basic mathematics and science, and in basic engineering subjects, is not yet extensive enough in all departments. The reasons for the necessity to increase the instruction in systems subjects were presented above. The proportion of other subjects, i.e. economic, social and administrative, seems to be growing also, whereas the total period reserved for basic education does not increase but should preferably be cut down. The inevitable result is that education in the professional engineering subjects is reduced, or more precisely, the sector of professional education is narrowed, at the same time as the practice reaches ever higher technical levels and sets increasing demands on professional skills.

The same trend is advocated also by the students' activity towards increasing the choice of curricula for a degree. Judging from the opinions they have expressed, there is reason to assume that priority in choice is largely given to subjects with a social and humanistic content, which means a corresponding curtailing of their professional engineering competence. Industry is by no means always able to offer to a specialist with a narrow scope a job that falls exactly within his sector, and as a result it becomes increasingly necessary to provide some type of widening training at the sites of work or in supplementary educational establishments. This means that a part of the education is transferred from the university to the industry which has to take care of and pay for it. Not many opinions on this trend of development have been heard so far from the organizations representing the economic life or the graduated engineers.

The student of today assumes that, on graduating, he will be more enlightened humanistically and socially than his predecessors. This might be true though the practical difference is probably not great. He certainly cannot obtain professional competence in these fields but remains an amateur compared with the genuinely professional humanists and sociologists. What is needed is a working knowledge in those humanistic and social questions directly associated with the engineer's mainly technical profession. The nature of the problems associated with the profession is, however, hard to perceive in the course of the studies, as education is given mainly in the form of lectures, Although the practical benefits may be limited, an introduction is to be recommended, in order not to underestimate the role of this sector. If the studies terminate with an engineer's thesis or project, this may afford a suitable chance of teaching human and social aspects as component problems of a larger technological problem system, e.g., by having the student to include in his study the effects of technological changes, such as automation, on the jobs and the conditions of work, or the consideration of ergonomic factors in design. This presupposes that the teachers of the relevant special subjects, e.g., psychology of work, can take part in supervising the thesis.

A deeper penetration into these subjects is best done, however, through postgraduate continuing education, when the student will already have obtained from his practical experience a personal idea of the human and social problems in engineering. This is also supported by the fact that such mathematical theoretical structures, which are hard to learn or even to remember after the phase of basic education, are not required here. Courses dealing with human questions connected to technology have in fact continuously been on the programmes of institutions for postgraduate continuing education.

Systems on Borderline Fields of Engineering

It has been repeatedly told that engineers could make a great contribution to social decision-making and its preparation. This is self-evident in questions of a primarily technical character. In other respects, the contribution by engineers, to deserve emphasis, must be original, i.e., something that others would not easily realize by themselves. Is the engineer's attitude sufficiently original also for the consideration of more general problems?

A typical feature of the work of the engineer is the use of quantitative physico-mathematical methods for technical tasks, the closeness of the problems to practice, and their systems character. It must be regarded as a shortcoming that only a minor number of engineers get a somewhat thorough introduction into quantitative systems methods. To the extent that applications are presented in this connection, they are taken almost exclusively from a technical environment. However, extensive systems containing social and living natural components, i.e., the phenomena on the borderline between society and engineering, or living nature and engineering, can be quantitatively studied only by methods of systems engineering. The engineer's characteristic attitude to these problems and so his original contribution should involve that the total relevant system will be considered and that mathematical systems methods are utilized. Since current attitude to these problems generally implies a restriction to individual phenomena and to their qualitative treatment, this method of approach could be very fruitful. In this way, the importance of education in systems subjects is emphasized, for very topical reasons.

The foregoing should not lead to a conclusion that the students taking a long syllabus in systems subjects today were competent to solve this type of borderline problem of engineering. A knowledge of the theory and mathematical methods, a developing systems attitude, and an introduction to their application in engineering are not enough to give such a competence, for any application to a strange environment requires special guidance and time-consuming studies. Teachers familiar with such extensive applications must first be made available, and their education is only possible in connection with research work of an adequate time span into the particular field of applications. Furthermore, research in the borderlines between engineering and other sciences needs a working team consisting of representatives of the various branches, for a single researcher can today represent a thorough knowledge of only one field of science. And naturally, the creation of teams devoted to long-term research also requires material resources which should be made separately available.

Postgraduate Continuing Education

The basics of engineering education and the requirements arising from a consideration of the systems approach were discussed in the foregoing. In the following, the demands to be made of supplementary education will be discussed from the same angle. Since the forms of supplementary education are much more varied than those of the basic education, details must be dispensed with even more than the above. The starting point chosen is the basic educational background of the present university level engineers.

One of the duties of education, supplementary to the basics, is instruction for cooperation with the representatives of other, mainly technical branches, i.e., for work within an industrial system, in which the trainee is a member together with other individuals of equal standing. Except in connection with the engineer's thesis, it is hardly possible, before the student takes his degree, to give him the opportunity to participate in project work with teams covering a wide field. A mixed degree compiled of courses in various disciplines is also not recommended for a basis of interdisciplinary work. It is now generally considered important that each member of a team, say, in bio-engineering work, has a distinct professional identity, and the education required for mutual communication takes place after graduation, either in connection with the regular daily work, or separately.

This education materializes today mainly on the work sites, especially in work with practical projects, and at the same time it provides training into the production system and hardware systems. Generous time should be allowed for training of this type in order to avoid mistakes which, in their turn, cost money. The necessary education cannot be provided by short-term courses, with instruction in the form of lectures; it requires a longer time span and team work in which different branches are fairly represented.

An establishment which can be mentioned as an example of this kind of supplementary education, expressly for land surveyors, building engineers, architects, and also for an equal or even a larger number of representatives of branches other than engineering, is the Centre for Regional and Urban Studies operating in connection with the Helsinki University of Technology. According to definition, the Centre gives postgraduate education in regional and urban planning to persons with an academic or similar degree, who already have practical or research experience. The purpose is to promote cooperation between various experts in the field of regional and urban planning by completing their interdisciplinary knowledge. The education also covers a deeper penetration into various special fields, reciprocal research activities and practical training in the form of seminars. A Nordic Institute for Regional and Urban Planning for corresponding international education, has been founded by the Nordic countries.

Similar centres could beneficially provide supplementary education and also carry out research in many other interdisciplinary sectors of engineering and in sectors bordering to engineering. The lack of financial support largely prevents their establishment so far and the only possible financial source would apparently be the government which defrays the cost of the Institute for Regional and Urban Studies.

Education aiming at the operation, control and design of technical production and hardware systems begins within the relevant professional subject of the basic university course. Familiarity with the systems then increases through self-instruction and in professional work, and also at the regular meetings of engineers in individual branches of industry, various production system alternatives are often presented and scrutinized. On the other hand, the demand for supplementary courses concentrating on theory seems to be limited although they should be available at an appropriate frequency to engineers with a bent for research. For practical engineers, the applicability of the learned matter is important, and this can seldom be accommodated with profound theory in a short-term course of supplementary education. An adequate introduction into systems subjects should in fact be included in the basic education, for it is difficult to adopt unfamiliar theoretical structures and the systems attitude based on them, while being occupied by practical professional work.

Keeping the engineer on the level with technological advances is usually stated as the most important purpose of supplementary education. No regular updating of knowledge has as yet been reached in this respect. The engineering societies have, however, organized courses concerned with new applications and developments in narrow sectors of engineering, often at a very early stage. Supplementary courses meeting the topical requirements have in this way been available to those interested. Practical specialists have taught these courses even more often than university teachers, which shows that the industry is able to follow the practical engineering developments more flexibly than the universities. The programmes of organizations for postgraduate engineering education have contained also a selection of themes classified as other subjects. These courses require no advanced background knowledge of mathematics and science, and even less its supplementation, and for this reason these subjects can in principle be studied at any stage of education or work.

The subject matter is not personally experienced before the practical work in industry, and therefore a realistic definition of the problems and a better motivation of studies are in favour of providing this education in the postgraduate phase. Recently the Educational Centre of Finnish Engineering Societies has appointed some of its courses especially for the basic training of newly graduated engineers, and their themes have covered trade, law and other fields.

Supplementary education is naturally also concerned with engineers with longer professional experience. The nature of the work of an individual engineer is liable to change dynamically, since his duties and business environment change with time. Besides updating in technology, supplementary education has to bring the engineer on the level with the changing duties. An engineer who for several years has been engaged in practical engineering mostly needs no postgraduate training of a scientific type, but is increasingly faced with administrative responsibilities. Simultaneously, the size and productional importance of the systems to be supervised increase with time. While the proportion of detailed technological knowledge decreases, the scope of the objective overall view and thus the systems doctrines increases. Utilization of quantitative systems methods at these levels is progressing. Many of the necessary discrete mathematical methods of management, aiming directly at economic goals, can be learned by both engineers and others separately, for they usually require no particular background in mathematics or in engineering and science which, on the other hand, is often still required by particular applications. Postgraduate courses on themes such as value analysis, critical path methods, linear programming, etc., have been relatively well-attended.

It may be emphasized that continuing education in engineering has to be discussed separately from some other types of education, for engineers of university level, such as scientific postgraduate education. The continuing education should meet the needs of an engineer who wishes to supplement and increase his professional competence regardless of academic degrees. Such a practicing engineer who wants to reroute himself to scientific research must continue his studies either on his own, alongside his daily work, or return to the university. This is also necessary today for an engineer interested in essentially improving the theoretical background of his own work, whether in systems or other disciplines. The university's normal courses of lectures offered to postgraduates in a chronologically condensed and suitably grouped form have been used in some countries as an intermediate solution for the acquisition of theoretical knowledge within a reasonably short period. At the same time they could offer the possibility of partial examinations for a higher degree, but expectations of the immediate practical benefits to be derived from this arrangement should not be too great.

Concluding Remarks

The analysis of engineering education and educational needs leads to certain conclusions concerning the inclusion of systems subjects in the curricula an introduction to systems approach. Attention has also to be paid to the engineering education as a system of continuing education which includes both the basic and postgraduate education. Although the analysis has been confined to the present time, more extensive educational systems should be kept in mind when partial solutions are made. The conclusions reached in this discussion may be expanded further, when continuing development of engineering education is being sought.