THE PROCESS OF ENGINEERING

by

Erik W. Aslaksen
Ewbank Preece Sinclair Knight Pty. Ltd., and
The University of Technology, Sydney

1. INTRODUCTION

It is reasonably well accepted and documented [1,2] that engineering plays a central role in wealth creation through technology-based enterprises. However, there is much less agreement about exactly what that role is, how it can be characterised and, above all, how its fulfillment can be measured. One reason for this is the unclear and often erroneous view other players on the industrial scene have of engineers, another is, in the author's view, that many engineers themselves have lost sight of the essential characteristics of their profession. This paper is intended as a small contribution towards getting the role of the engineer back into focus and thereby setting the scene for the development of a quantitative characterisation of the engineering process.

Technology-based enterprises generate wealth by the process of **innovation**; the successful commercialisation of products, services and processes [3]. Innovation includes both the generation of an idea or invention, and the conversion of that invention into a business or other useful application [4]. Without any loss of generality we may consider the innovation process to consist of the following four sub-processes:

- R & D, including invention. This process results in a stock of **technology**.

- Market research. This process results in an understanding of the market and an identification of potential **needs**.

- Engineering, a process which converts a need into a **service** (or product) which satisfies that need.

- Marketing, a process which converts the potential of a product or service into revenue. It includes advertising, sales, and (logistic) support.

The success of the innovation process is therefore by no means dependent only on the process of engineering. Indeed, some would argue that there is an ongoing shift in importance from technology through manufacturing (which in the present model is included under engineering) to marketing, as the less developed nations catch up [5]. This argument has some truth and certainly a very immediate logic to it, but, aside from the fact that it is not very beneficial to try to assign a ranking to the processes, by equating engineering with manufacturing it overlooks the special role taken on by engineering in technology-based enterprises. This role arises because

a) engineering contains the **creative** element which is needed to successfully convert a need into a service or product; and

b) the engineering process provides the **integration** of all the processes into a single, coherent process.

The first point is one which even engineers sometimes overlook; it is this creativity which lies at the core of engineering. It has been said that the difference between a manager and an executive is the latter's use of intuition [6]; the difference between a technician and an engineer lies in the latter's creativity. It is unfortunate that this point has become obscured by an obsession with technology and engineering science, particularly in universities, as it has tended to turn out engineers which are a cross between a technician and a third-rate scientist.

The second point is the one which gives engineering the central role within the innovation process, its status as **primus inter pares**, as is illustrated in Fig.1. It also determines the nature of the engineering process itself, for while the purpose of the engineering process is to convert a need into a service which satisfies that need, the process will not be successful if it is carried out in isolation, in the sense of a back-room activity, as is often the case in Australian enterprises. Economic, social, legal, and environmental issues have to be considered along with the numerous engineering specialties, such as reliability, maintainability, and human engineering, and as a result a major feature of the process is its **multi-disciplinary and integrating** nature. Only through simultaneous consideration of all the issues can one make trade-offs between the whole set of them and so arrive at a truly optimal solution. The engineering process is **embedded** in the process of innovation, and a systematic approach to the diverse inputs to (or boundary conditions on) the latter is outlined in [7].

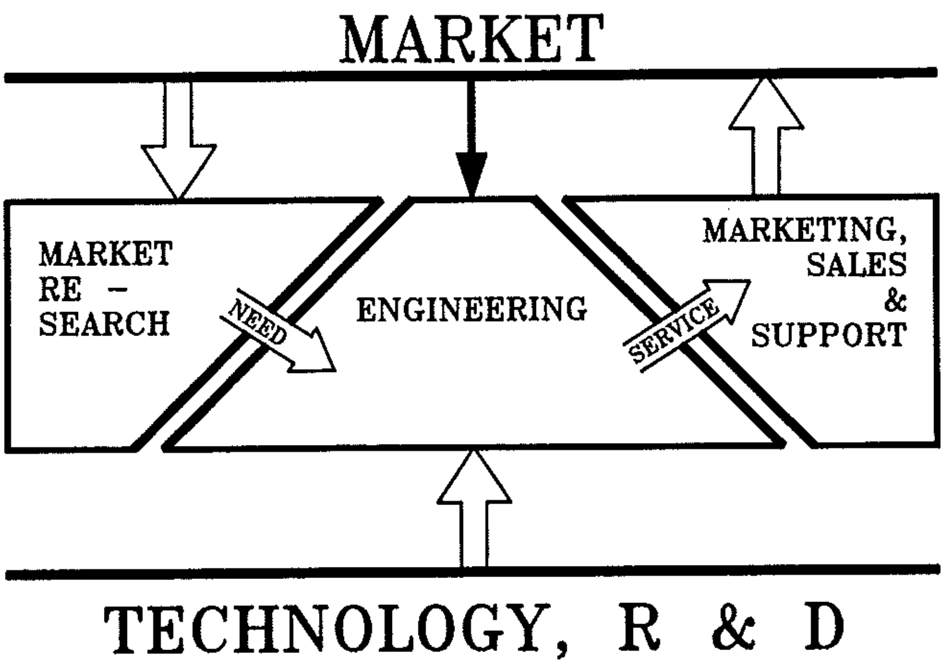

Fig.1 The central role of the engineering process.

Due to its multi-disciplinary nature, the engineering process is necessarily **complex**. This complexity is managed partly by subdividing the process into five distinct **phases**, they are:

- definition
- analysis
- design
- implementation
- verification .

Each phase has its own procedures and generates its own documentation.

The complexity is also reduced by employing a combination of bottom-up and top-down design methodologies. The latter, which forms the core of a methodology called **systems engineering**, acts as a preprocess which partitions the object of the process, the **system**, into a set of interacting subsystems, each of which is no more complex than that it can be designed using the classical bottom-up methodology [8].

2. PROCESS CHARACTERISATION

While we may now have an intuitive feel for what the concept "process of engineering" means, it is still not very useful in an operational sense. How does one go about expressing how well a process is working, or comparing processes in different companies or in different projects? In particular, the process of engineering should be amenable to optimisation. This implies that one can characterise the process by a set of **process parameters** and construct a measure on this parameter space which represents the **performance** of the process. However, due to the wide range of products and services to which engineering is applied, this has not been attempted with any degree of generality. The present situation is that individual companies or special sectors of the engineering profession, such as civil engineers, have developed sets of rules for the cost of engineering tasks as a percentage of the construction or acquisition cost of the project. Such rules are very useful in bidding for engineering work and have a certain relationship to the problem of measuring the process of engineering in the sense of averages over large numbers of projects, but otherwise this sort of approach cannot be of much use in the present context. It is actually counterproductive as far as cost-effectiveness is concerned as there is a negative incentive to lower the acquisition cost of the object through more engineering effort, it takes no account of life cycle cost, it does not involve the effectiveness of the product and, above all, the cost of the engineering is not related to any parameters of the engineering process itself.

From the above, it follows that we are faced with two distinct problems. Firstly, to characterize the overall performance of the process by measuring its **result**. This is a problem because, as discussed in the introduction, the engineering process is not the only one involved in the innovation process, and its result is tightly coupled with the results of the other processes. Secondly, we need to characterize the engineering process itself by a set of process parameters, and then relate these parameters to the result, i.e. express the result as a function of the parameters. This function, however, will not be a fixed function, but will itself be dependent on a number of what might be called "environmental parameters", such as the particular industry, the country (or culture) in which the industry is located, etc.

An approach to the first problem is to consider the process as a series of successive approximations. The first, or zeroth-order, approximation consists of, at the beginning of the process, simply taking a guess at what the appropriate system might be, and depending on one's experience and the nature of the need (e.g. similar to an earlier case), there is a certain **probability** that one might have guessed correctly. Normally, this initial probability would be small, and for complex systems it would be very small. The second approximation consists of carrying out part of the process before, based on the information available at that point, taking a guess. Successive approximations take place at later points in the process, so that as the process progresses, the probability increases, and at the end of the engineering process, i.e. when the system goes operational, there is a probability that the system will produce a satisfactory service. Of course, if it actually does or not only becomes known after the system has gone through its **life cycle**, but it is this probability, or **predicted performance**, which is the only realistic basis on which to judge the engineering process.

Two issues arise immediately in connection with the above: Firstly, how does one define "satisfactory service" in a general way and, secondly, how does one introduce a measure of the **degree** to which a system does (or does not) produce a satisfactory service? Clearly, an engineering process which always results in an almost satisfactory service is better than one which usually results in a totally unsatisfactory service. These two issues are treated in the following section.

3. AN ENGINEERING PERFORMANCE PARAMETER

If the service is going to be used as a measure of the engineering process, one needs to consider both the customer's point of view, i.e. how good the service is, how close it comes to meeting his needs, and the provider's point of view, i.e. what does it cost to provide the service. Both of these influence the **profitability** of the project, so one could say that a well-engineered project is one which is profitable. But what measure of profitability should one use? It must be a measure which somehow allows one to perform operations on a set of projects, such as ordering them, or taking an average, and so on. It should also, as far as possible, be a parameter which depends only on the engineering process and not on factors over which the engineer has no control.

The latter point implies that one can extract the cost and profitability of the engineering process from those of the whole enterprise, something which is both difficult and contentious. For example, advertising can obviously have a significant effect on the profitability of a new product, but how does one determine exactly how great the effect is? And how much of general advertising costs (i.e. for corporate image) should be charged to this particular product? These questions and the difficulties associated with answering them are the reason for why the process of engineering is defined as starting with an agreed definition of the need and ending when the performance of the system has been verified. The agreed definition of the need (sometimes called the requirements specification) defines a definite point in time, after which all costs associated with the project are allocated to the engineering process. The end of the system performance verification provides a definite point in time after which no more costs are allocated to the engineering process, but it also provides a basis on which to **predict** the performance of the system over its lifetime, i.e. the extent to which the service will meet the need.

Let the cost allocated to the engineering process be called the **initial cost** (acquisition cost, investment, non-recurrent cost) and be denoted by C, and let the performance of the system (actual or predicted) be represented by a **net revenue** (income minus operating costs) over the lifetime of the system (i.e. the duration of the project) and be denoted by R, both referenced to the point in time at which the system goes operational. That is, these two quantities are the discounted cashflows prior to and subsequent to going into operation. Using these two quantities, several measures of profitability can be defined:

a. The **benefit**, being simply the difference between the two,

$$B = R - C .$$

b. The **relative return**, defined as the ratio of the two,

$$RR = R / C .$$

c. The **relative benefit**, defined as the benefit divided by the initial cost,

$$RB = (R-C) / C .$$

d. The **internal rate of return**, defined as that discount rate, p, which will make the two quantities equal,

$$IRR = p(R = C) .$$

The benefit, being a dollar value, is not suitable for comparing projects of different sizes as far as their profitability is concerned. The internal rate of return does not exist if R is less than C for all values of p, a case that will occur, for example, whenever a project is abandoned before the system becomes operational.

The relative return and the relative benefit are both acceptable measures; they are also very similar in that they are related by $RB = RR - 1$. The relative benefit may be more intuitive, in that the break-even point occurs at $RB = 0$, so that negative values of RB signifies a "loss". However, both of them suffer from the deficiency that any project abandoned before it goes operational (i.e. $R = 0$) yields a fixed value ($RR=0$ or $RB=-1$), irrespective of the value of the expenditure up to that point. That can be alleviated to a large extent by the following procedure: Whenever one wants to determine the value of RB for a particular organisation, one will look at a (large) number of finished projects (or projects for which the results can be predicted with sufficient accuracy) and form the average. Instead of calculating RB for each project and then forming the average of the RB values, one forms the averages of the C values and of the R values separately, and then determines the "average" value of RB. In this way projects that were abandoned early contribute less to lowering the average value of RB, as one would desire.

The relative benefit, RB, calculated for an organisation in the above manner, shall be called the **engineering performance parameter**. But, having defined this parameter, the two issues raised at the end of the last section still remain. The first of these, defining "satisfactory service", is solved by applying **benchmarking** techniques [9] and reaching a company-internal agreement on what value of RB constitutes "best" service and what fraction of it is "satisfactory".

The second issue is handled by placing certain requirements on the way in which the need is defined. On the one hand, the definition of the need must be such that at the end of the engineering process, when the service and whatever support infrastructure it requires have been developed, it shall be possible to determine whether the service meets the need or not. That is, one can determine whether the service is potentially capable of generating the projected revenue R; whether this potential is realised or not is a different matter which lies outside the engineering process. On the other hand, the definition must contain information about the change in **value** of the service as a function of changes in the values of the parameters describing the service. In other words, one must spell out how "bad" it is if the need is not completely met, and how "beneficial" it is if the requirement is exceeded, or, in mathematical terms, one needs to specify the values of the partial derivatives of R with respect to the performance parameters.

4. PROCESS PARAMETERS

The engineering process is characterised by the methodologies, tools, and procedures employed in its execution; process parameters are therefore primarily parameters which measure the existence and effectiveness of such methodologies, tools, and procedures. Each parameter relates to some area or aspect of the process, and the existence of the appropriate entities within each area is established by means of answering a set of questions. (A similar approach, but to the special case of software engineering, is documented in [10]). Consequently, the first step is to define the types of entities whose presence we shall be looking for.

Mechanism A documented means or technique whereby the performance of a task, procedure, or process is assured.

Plan A document defining the execution of a project or a major activity within a specific project (e.g. management, reliability engineering, human engineering, quality assurance, etc.). It normally consists of a description of the main work packages and the procedures used in their execution, a work breakdown structure (WBS), a time schedule (e.g. bar chart, PERT diagram, etc.), estimate of resources required, assignment of responsibility, and a schedule of deliverables.

Procedure A documented series of steps for performing an activity. The document often includes guidelines.

Process An ordered set of activities for producing a defined result within a given framework or context (e.g. type of business).

Standard An approved and documented set of criteria used to determine the adequacy of an action or object.

The first group of questions relate to the definition of projects in terms of the phased structure, the latter being the most immediate characteristic of the engineering process.

A1. Is a *standard* applied which defines the five phases in terms of content and output specific to the area of business in which the organisation is engaged?

A2. Is a management *plan* developed and applied to each project which tailors the requirements of the *standard* to the characteristics of the particular project?

A3. Is a *standard* applied which defines the (minimum) content of the management *plan*?

A4. Is a *procedure* used in the review of the management *plan*?

A5. Is a *mechanism* used for ensuring compliance with the management *plan*?

The second group of questions is concerned with the documentation of the results of the process.

B1. Is a *standard* applied which defines the acceptable formats of project definition documents?

B2. Is a *standard* applied which defines the acceptable formats of system specifications?

B3. Is a *standard* applied which defines the requirements for specialist engineering plans (e.g. reliability, maintainability, human engineering, test, logistic support)?

B4. Do all *plans* and *procedures* distinguish clearly between the functional and physical domains?

B5. Is a *procedure* used for reviewing technical documentation?

B6. Is a *mechanism* used for ensuring that all documentation required in one phase is finalized before the next phase commences?

B7. Is a *procedure* used for performing configuration control?

A third group of questions relate to the extent to which the process is subjected to measurement and the gathering of data:

C1. Is a *procedure* (incl. checklists) used for carrying out design reviews?

C2. Are the action items resulting from design reviews tracked to closure?

C3. Are statistics on action items resulting from design reviews gathered?

C4. Is a *procedure* used to perform technical performance measurement?

C5. Are statistics on engineering change proposals gathered?

C6. Are engineering change proposals analysed to determine their *process* related causes?

C7. Is a *mechanism* used for initiationg actions to prevent excessive levels of engineering change proposals?

A further group of questions relate to the management of the process, in particular the control of the process:

D1. Does senior management have a *mechanism* for the regular review of the status of projects?

D2. Is a *mechanism* used for periodically assessing the engineering *process* and implementing indicated improvements?

D3. Is a *mechanism* used for assuring the correct conversion of engineering change proposals into contract amendments?

D4. Is a *mechanism* used for ensuring adherence to all *plans*?

D5. Is a *mechanism* used for ensuring the traceability between contractual requirements and requirements resulting from the engineering process?

The final group of questions is concerned with the support of the engineering process:

E1. Is there a clearly defined engineering process function within the organisation?

E2. Are engineering managers subjected to training in the company's engineering methodology?

E3. Is a *mechanism* used for maintaining awareness of state-of-the-art in engineering methodologies and tools?

E4. Is a *mechanism* used for managing and supporting the introduction of new engineering computer tools?

E5. Are engineering computer tools placed under configuration control?

E6. Does the organisation support a technical data library?

Each question is to be answered with a "yes" or a "no", with "yes" having the value 1 and "no" the value 0. Within each group of questions the values are added and the sum divided by the number of questions in the group. Thus, each group can be considered to represent one process (or process-related) parameter, each with a value between 0 and1, as follows:

A Structure
B Documentation
C Data
D Management
E Support

These parameters (i.e. groups of questions) were chosen so as to be of roughly equal importance (and there is at present no evidence that they are not), so one can form a single measure of the engineering process by taking their average. For a perfect process, i.e. if the answer to every question is "yes", the value of this measure will equal 1. The deviation from 1 in the case of a non-perfect process must be related to the extent to which the relative benefit, RB, is less than satisfactory, but the exact form of this relationship is not known and will be the subject of further research.

4. CONCLUSION

The proposed definition of the process of engineering and of the performance measure for that process form a point of departure for the evaluation of engineering within individual technology-based enterprises. However, in order for the information needed for such evaluation to be available (and implicitly assumed in the above), it is necessary for each project to have been subjected to a properly defined life cycle costing and a rigorous definition process. This is not a requirement in addition to what is normally required for project management, and both of these activities have recently been confirmed as critical to project success

[11,12]. The somewhat astonishing fact is that so many projects are carried out without attention to one or more such critical success factors.

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