The Place of TRIZ in a Holistic Design Methodology

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Design is key to a project's profitability and therefore increased PROFIT by DESIGN is the goal of improvements to the design process. Business requirements can be summarised as Better, Faster, Cheaper and considerable investment has been made in technology and methods for the design process to enable this. There is evidence to suggest that these investments have resulted in products themselves getting better but not necessarily produced faster or cheaper.

A model of the design process has been developed which makes explicit its key elements. The six key elements or dimensions of the design process are: Analyse; Understand; Decide; Create; Capture; and Know.

Investments in design technology may not be reaching their full potential due to a mismatch between the relative importance of the attributes of a good designer and the areas where investments have been made, leading to a potential loss of balance in the design process. This is compounded by failure to take a holistic view of changes to the process including mitigation of any downside. In particular the Create dimension, which is seen as the most important attribute of a good designer, has had the least investment and also is the most vulnerable because it is optional. In recognition of this fact, Rolls-Royce is using the TRIZ methodology to provide designers with an improved capability. However it also is recognised that providing capability alone is not enough. The right motivation and opportunity are also needed, and this requires the appropriate organisational and cultural features to be in place. What is needed is a people centred process that is business driven and product focused.

Business Environment

BETTER, FASTER, CHEAPER summarises the drive for continuous improvement within the Aerospace and many other industries. Rolls-Royce operates in a highly competitive global market, and this drive for improvement is essential in order for the organisation to realise its strategic intent of being a world leading power systems business, that meets the needs and expectations of its customers, shareholders and employees. The goal of Engineering Design is to generate wealth by meeting customer needs, and studies have shown that up to 70% or more of a project's profitability is determined during the design process. Further more it is the earliest stages of design that have the greatest influence. Therefore it is very important to study, understand and improve the design process if better, faster, cheaper is to be realised, leading to PROFIT by DESIGN.

Aero Engine Industry Trends

By far the clearest trend is that engines are getting better, when measured against any technical criteria. Figure 1 shows the trend in gas turbine Specific Fuel Consumption (SFC) over the last 50 years. The rate of improvement over the last 30 years has been much less as the industry has matured, however the current improvement rate of 0.5% per year shows no sign of reducing. This trend has only been possible due to continued investment in new technology, IT, design / analysis techniques etc. and more recently due to the revolution in Computational Fluid Dynamics (CFD).

New component introduction lead-times are being reduced quite dramatically in some cases. However this trend is not clearly reflected at whole engine level. The same can also be said of non-recurring development costs. One implication of these observations is

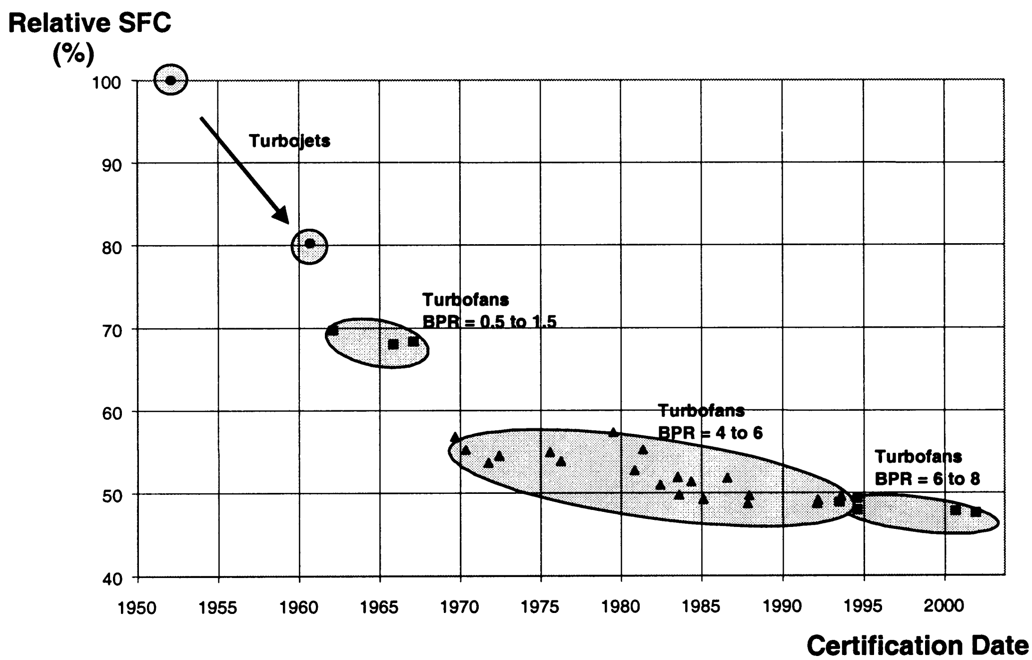

Figure 1. Gas Turbine SFC Trends with Time

that the substantial investments made in IT, improved methods and working practices etc. have in the main gone into improving the product, rather than reducing lead-time or non-recurring costs. There are two other trends that support this inference:

1. Engineering Technical Time is increasing as a proportion of total development costs. In the early 1980's under 30% of total costs were engineering time. In the late 1990's the figure is over 40%.
2. The number of Design / Analysis iterations per component is increasing, aided in particular by the development of automatic and semi-automatic finite element analysis and optimisation techniques.

It would seem reasonable then to conclude that increased speed of analysis is being cashed-in to enable many more design iterations to be carried out in the same time, resulting in an improved, more optimised product which needs less physical testing to validate.

Therefore potential explanations for the apparent lack of improvement in ... Faster, Cheaper can be inferred as:

1. Investments being realised in better products.
2. Lack of integration at whole engine / process level preventing investments made at local / component level being realised for the product as a whole.
3. Investments being neutralised by other effects.

Recognising that the first item is not a bad thing in itself, and that the second is receiving much investment in the form of improvement initiatives such as Integrated Product Development (IPD), then item three will be considered further in relation to the Design process. However, first if we want to use TRIZ or any other tool to improve the Design process it will help to clarify more precisely what is meant by Design.

The Design Process

Design is not a linear process, but is iterative and evolutionary in nature. The input to the design cycle is a set of customer REQUIREMENTS or problem, which are often not clearly defined. In fact the MoD 'smart procurement' initiative is a recognition that it is often preferable to allow the requirements and solution to co-evolve. The design cycle itself is commonly represented by the three phases of GENERATE, EVALUATE and DECIDE. However a more precise model has been produced, as illustrated in Figure 2, which consists of five key elements. This has been achieved by breaking down both Generate and Evaluate into two further elements each.

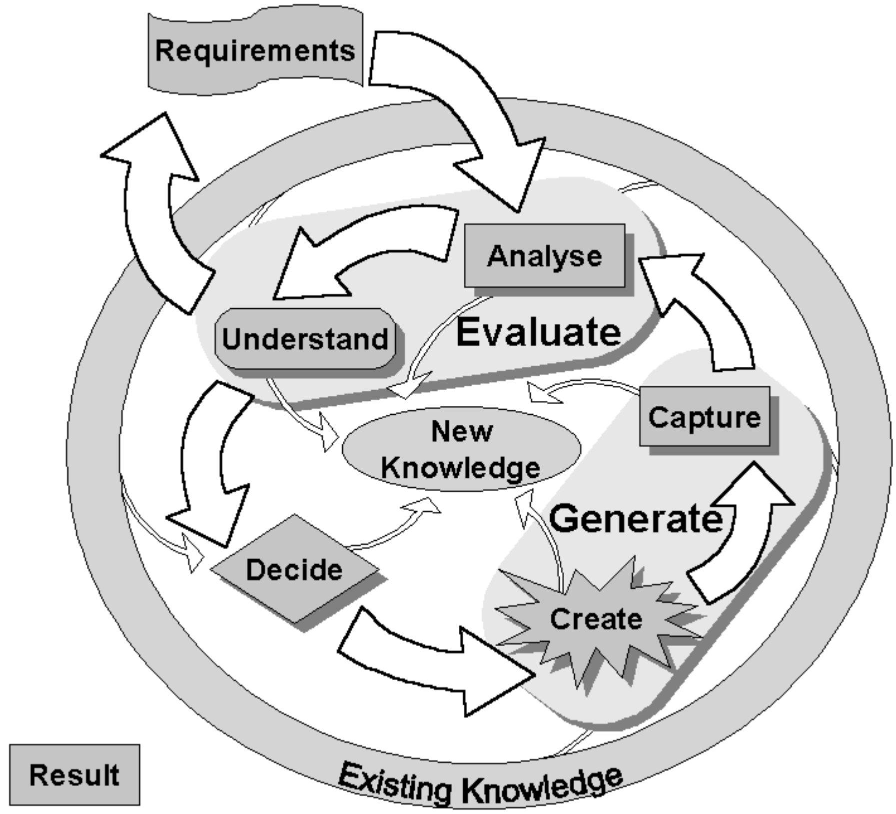

Figure 2. The Design Process

The first step in the cycle is to ANALYSE the problem or requirements. This stage is often neglected, but if formulated properly problems can often be solved at this stage. Activities may include functional and risk analysis, Quality Function Deployment (QFD) or hand calculations through to finite element CFD or stress analysis. As the design progresses the emphasis will move from analysis of the problem to analysis of solutions.

The next step is to UNDERSTAND the results. This is often an implied part of the evaluate phase, however in this model analyse represents the "mechanics" whereas understand represents the "dynamics" of the evaluate process. For this reason and because in practice the need to understand can easily be neglected it has been made explicit. To gain understanding is an intellectual exercise that is not mandatory and that requires time, time that can be easily squeezed out by other pressures. Understanding will improve as the design cycle progresses, and it is from this understanding that requirements and constraints can be challenged or re-negotiated and even new possibilities suggested.

DECIDE is the element that controls the process and it is clearly important that decisions are based on understanding. One of the most important decisions to be made is when to stop designing, because it is always possible to improve on a design given more time. This is where project management skills are important, and sometimes the need to make a decision is more important than which decision is made. Other important decisions include choosing the appropriate activities to perform and the level of detail with which to perform them at that stage in the design process. This is one area where an expert can significantly out perform a novice. Selecting from a potentially very large number of alternatives generated in a create phase is also an activity in this stage.

As with evaluate the generate stage has been divided into two parts. CREATE is the "dynamics" part, it is about finding a better way, and it is essential if the product or process is to improve.

> "If we always do what we have always done. We will always get what we have always got."

Even repeating a currently successful formula is no guarantee of success in the future due to increasing customer expectations, and a changing environment. This process is closely related to understand, because while not all experts are creative, most creators are experts. Also as with understanding the create element requires time, and there are many potential barriers that can hinder it.

CAPTURE is the "mechanics" of the generate phase. The activities here can vary from sketching in the early stages, through to complex 3D CAD solid models as a complete engineering definition of the final solution. Also models are often produced in this stage which are passed onto the analyse stage for processing, thus completing an iteration of the design cycle.

The speed with which design iterations take place varies enormously, from seconds for an iteration to occur in the mind of the designer to weeks for just one analysis. The general trend is for many quick iterations to occur early in the design process and for far fewer much slower ones to occur at the end. In addition the proportion of time spent on the different elements will vary through the process, with capture and analyse dominating the later phases.

The design cycle itself and its five key elements, as defined above, can also be viewed from a different perspective: that of the Designer. Table 1 below illustrates the different types of question that a designer might ask during each stage, together with the corresponding designer attributes and skills.

The designer attributes have been compiled from the results of a series of structured interviews with design experts within Rolls-Royce, who were asked to identify and prioritise those attributes that they thought made a good designer (for definitions of the 24 attributes used here see (Knott, 1999)). These attributes have been allocated to one of the five elements of design. In most cases the relationship is reasonably clear and objective, however in some cases the allocation is to some extent subjective. The importance score represents the relative priority placed on each attribute by the experts. "Ability to Visualise" was classed as the most important and given

Table 1. Alignment of Key Design Process Elements with Designer Attributes

DESIGN ELEMENT	TYPICAL QUESTIONS	DESIGNER SKILLS & ATTRIBUTES	IMPORTANCE SCORE
Analyse	Does this meet the criteria? What are the advantages? What are the disadvantages? What is the performance?	Problem Analysis Accuracy Handle Complexity Optimise Anticipate Obstacles	9.9 8.5 8.1 7.5 7.0
Understand	What is the significance of this? Why is it like this? Is this right? What is the problem? Does this requirement still make sense?	Spatial Awareness Ability to Learn Challenge Curiosity Handle Abstract Concepts	9.8 9.8 8.5 8.4 7.4
Decide	Which option is best? What needs to be done, in what order? Is there time to do this? What level of detail is appropriate?	Sound Judgement Logical Reasoning Clarity Project Management	9.8 9.2 7.8 6.9
Create	What are the alternatives? How can this be improved? Is there a better way? What if this was possible? How can this be made simpler?	Ability to Visualise Creative Ability to Conceptualise Innovative Ability to Synthesise Lateral Thinking	10.0 9.5 9.2 9.0 8.6 8.2
Capture	How can this be communicated clearly? How can this be made unambiguous? What standards apply? Are there any rules?	Communicate Pictorially Communicate Textually Ability to Display Brevity of Communication	8.4 7.0 6.9 6.0

a score of 10, the least important being "Brevity of Communication" with a relative score of 6.

It would seem a reasonable assumption that targeting investment in design technology to support and enhance those attributes that make a good designer ought be the very effective.

There is a sixth vital element to the design process that is required by all the other elements, discussed so far, at all stages: KNOWLEDGE. Figure 2 illustrates the fact that existing knowledge is constantly required to support the process. Studies of design teams have shown (March, 1997) that design activity is characterised by rapidly repeating cycles consisting of periods of intense effort followed by a need for information or knowledge. Designing is learning, and continuous learning results in expertise, therefore as design iterations progress NEW KNOWLEDGE is generated (Blessing, 1999). This also is illustrated in Figure 2, and has implications for the way organisations should manage this knowledge, because it often resides in a different location to that of the existing knowledge.

Improving the Design Process (In Retrospect)

Considerable investment has been made in design computer aids, with the vast majority being in the areas of CAD (which in this context could be called Computer Aided Capture), and analysis methods. These technologies have brought many advantages, but as discussed earlier they may not be reaching their full potential due to other factors that can neutralise some of their benefits. The following are examples of such neutralisers:

1. Loss of balance between key elements of the design process.
2. Adverse effects on informal communication and relationships.
3. Lack of flexibility in tools and systems.

Balance

There is a mismatch between the relative importance of the attributes of a good designer and the areas of investment. Although this may not be a problem in itself tools have often been implemented in ignorance of the potential effect on the design process as a whole resulting in the absence of appropriate checks and balances.

Figure 3 shows the designer attributes shown in Table 1 combined to give a relative importance for their respective key element of the design process.

The most important element comes out as create, because not only does it have the most attributes relevant to it, but it also accounts for five of the top ten including the most important. The least important element is capture and has half the score of create. It is interesting to note that both create and understand (which is the second most important) together account for half of the total score, but are also the elements that are the easiest to neglect because they are not mandatory.

Figure 4 illustrates the fact that in the past investments aimed at improving the design process have been very unevenly distributed among the five key elements, particularly relating to CAD and analysis tools. These

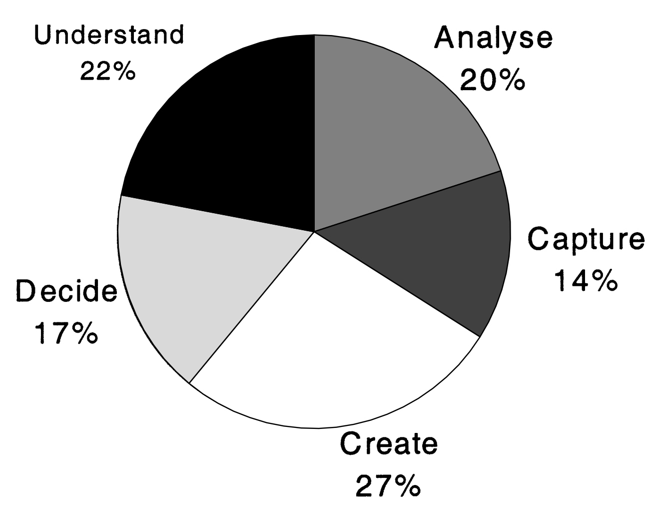

Figure 3. Relative Importance of Elements of the Design Cycle Based on Designer Attributes

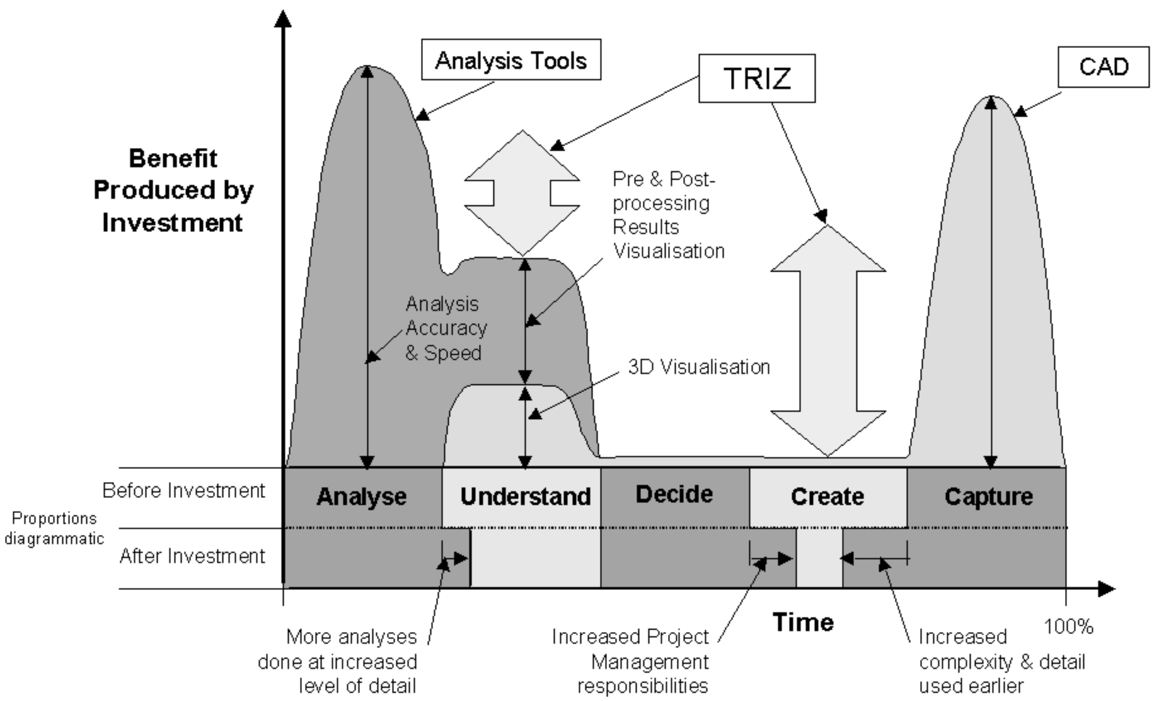

Figure 4. Qualitative Effect of Some Investments Aimed at Improving the Design Process

tools produce improvements which in themselves are desirable, however Figure 4 also shows the potential that these tools have for impacting the relative time distribution between the key elements of design.

For example analysis tools may not generate time savings, and can increase the proportion of time spent on analysis because more complex and detailed calculations are done more often. There is a tendency to apply a more powerful tool to everything, and the easier it is to use, the more tempting it becomes. When a calculation is manual it is carried out sparingly and requires understanding of the problem, but automation can encourage understanding to be replaced by trial and error.

Pressure on time for creativity can potentially come from increased project management requirements with increasing levels of detailed planning, and from increased time for the capture element. Capture time can increase due to increased complexity, partly driven by increased CAD functionality, and also because of the temptation to move from PAD (Pencil Aided Design) (Ottosson, 1997) to CAD too early, with all the increased detail, loss of flexibility and hence additional time that that incurs. This squeeze on time for creativity that can be caused by some modern computer design tools, systems and working practices is certainly felt and expressed by many designers. It takes just as much creativity to do things faster or cheaper as it does to make things better.

The create element in particular then has suffered in the past from lack of investment. There is therefore a need to invest in tools and working practices that can correct this imbalance, and TRIZ is ideally placed to provide an increased capability in both the create and understand elements. In recognition of this TRIZ has been selected by Rolls-Royce as one of 11 core tools for Integrated Project Teams, with about 200 people trained so far, the aim being to change the way people think.

Communication & Relationships

Computers can isolate people as well as bring them together. One example of this is the observation that when design was done on drawing boards the work was very visible to other designers and team members. This would encourage informal comment and discussion that resulted in the sharing of knowledge and experience.

Today the computer screen makes design work far less visible and therefore this informal communication process is made much more difficult. For this reason TRIZ in Rolls-Royce tends to occur in group sessions.

Flexibility

Flexibility is a fragile capability. Systems designed to foolproof, streamline and speed up a process for a particular set of circumstances or product / component architecture can be made too restrictive or prescriptive. As a result they can become a barrier to subsequent improvements in the product itself or its associated design process, causing a designer's creative energy to be spent on 'beating the system'. Creativity and innovation are unpredictable and unstructured processes that can be killed by applying the wrong control or support strategies. However creativity is essential if long-term profitability is to be maintained.

Improving the Design Process (The Future)

A good design process, like a good product, is rounded, balanced and holistic in nature. It is always very easy to optimise one or more elements of a process in isolation and make the performance of the whole worse as a result. One analogy of this is in a manufacturing operation where increasing capacity utilisation beyond a certain point, i.e. increasing 'efficiency', can dramatically increase queuing time, lead time and cost, as illustrated in Figure 5 (Reinertsen, 1997).

It is therefore important to be able to take a holistic view of the effect of new tools, working practices etc. on the designer, the design process and the business. This enables the tools themselves to be better optimised and also to identify the need for action to mitigate against any downside, because there usually is a downside. The three themes of PRODUCT, PROCESS and PEOPLE need to be effectively balanced, and of the three the people theme, though arguably the most important, has been the most neglected. What is needed is a people centred process that is business driven and product focused.

There is a simple equation which needs to be bourn in mind when introducing any change that affects people. It is:

$$\text{Business Benefit from Change} = \text{Capability} \times \text{Motivation} \times \text{Opportunity}$$

Effective change requires people to be provided with an improved capability AND have the motivation to use it AND also the opportunity to use it. It is shown as a multiplying relationship in the equation because, no matter how big the improvement, if you only have one or even two out of the three the benefit will still be zero. Therefore it has to be recognised that providing designers with training in TRIZ alone is not enough. The training certainly gives them improved capability, and a degree of motivation, but unless they are provided with the opportunity to use it no benefit will result. Now motivation and opportunity are very much organisational and cultural issues, and therefore can tend to be neglected, the tendency

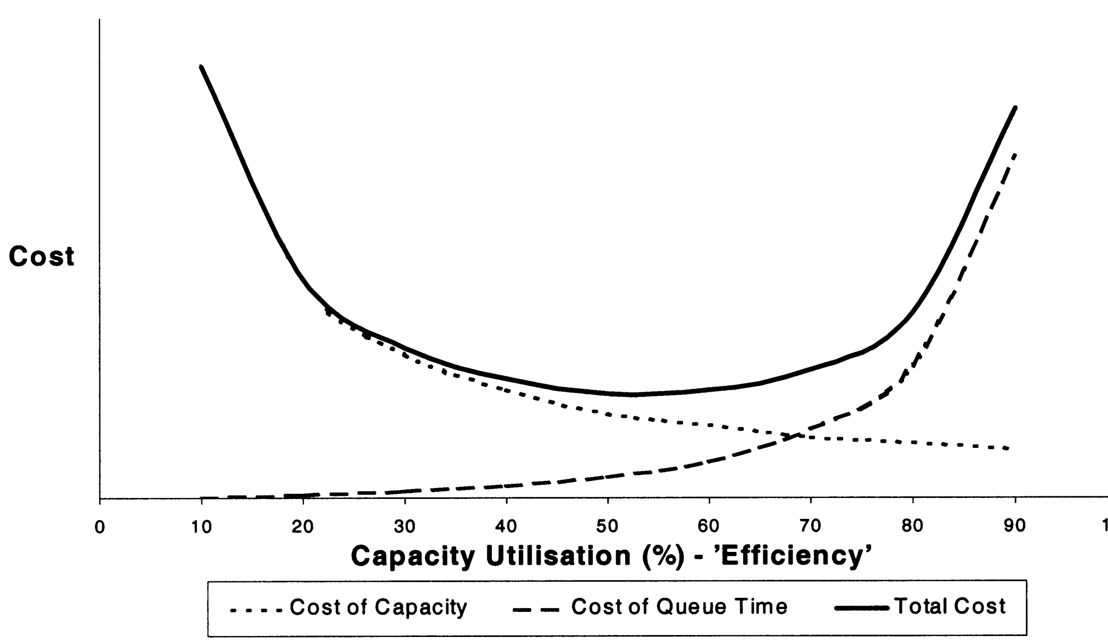

Figure 5. Variation in Cost with Capacity Utilisation in a Manufacturing Operation

being to focus almost entirely on the capability issue because it is the most "technical", and also often more manageable.

Conclusions

A model of the design process has been developed which makes explicit its key elements. The six key elements or dimensions of the design process are: Analyse; Understand; Decide; Create; Capture; and Know.

Investments in design technology may not be reaching their full potential due to a mismatch between the relative importance of the attributes of a good designer and the areas where investments have been made, leading to a potential loss of balance in the design process. This is compounded by failure to take a holistic view of changes to the process including mitigation of any downside. In particular the Create dimension, which is seen as the most important attribute of a good designer, has had the least investment and also is the most vulnerable because it is optional. In recognition of this fact, Rolls-Royce is using the TRIZ methodology to provide designers with an improved capability. However it also is recognised that providing capability alone is not enough. The right motivation and opportunity are also needed, and this requires the appropriate organisational and cultural features to be in place. What is needed is a people centred process that is business driven and product focused.

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He gained wide experience in mechanical design through 13 years experience as a designer and design supervisor.

In 2000 he was appointed as Company Specialist – Design Technology with a responsibility for improving the design process across Rolls-Royce by acquiring appropriate technology and supporting its application to the company's products and processes.