Chapter 14
Quality management

Graham Thompson
UMIST

The subject of quality in design process improvement can be considered from a number of perspectives. Indeed, it is quite possible that a survey of engineers could elicit views of the subject that differ markedly. Therefore, the treatment given here does not represent any specific school of thought or narrow perception of the subject. Rather, we cover a diverse range of topics that are influential on our theme of design process improvement and of interest to design practitioners.

Design activities and their timing, the use of appropriate design tools, human factors and, most importantly, satisfying the clients are discussed. No narrow definition of the client is assumed. The word *client* is understood here to include consumers who purchase products, internal clients within a company, services to another company, society at large or the environment. Thus, design activities may pertain to products and systems both large and small.

To achieve high-quality design, the design team must understand what is required by the client and what will best fulfil the client needs. Such a simple statement belies the difficulties that may be encountered. For example, does the client really know what he wants, has he thought through his needs in depth, does the design team believe mistakenly that they know best, and in a long project will the client perspective be lost?

To achieve high-quality design, the design team must understand what is required by the client and what will best fulfil the client needs.

Given a clear understanding of the client needs, the design team must undertake their work effectively and efficiently to create the desired outcome. This can involve a diverse range of activities ranging from conceptual to detailed design. Different thinking skills must be employed; for example, there will be times when divergent thinking and solution finding will be at a premium, whereas at other times convergent analytical ability will be essential to produce a quality product. The literature contains many design methods (tools) which are highly valuable when used competently and at the correct time. But used wrongly or inappropriately, the same design tools will achieve a poor quality outcome. Finally, it is people who will carry out the design work and, in addition to their ability to perform certain tasks, they have certain attributes that are highly influential on the outcome of any design activity. High-quality people who are unduly influenced by their personal traits will not achieve quality design outcomes.

The following sections explore the above factors, but it is not possible to provide a fully comprehensive treatment. The aim is to cover the topics noted in sufficient depth to be of use to practising engineers and to give references to enable further in-depth study if the reader is so minded.

Design activities

There are many publications that describe in-depth design activities and their relationship to each other (Pugh, 1991; Roozenburg and Eekels, 1991; Pahl and Beitz, 1996; Cross, 2000). Although authors differ in their descriptions, there is no fundamental variation between them, and the basic design activities may be described as follows:

- understanding the needs of the client (including market analysis);
- writing a design specification that defines requirements;
- generating and evaluating concepts;
- developing schemes (embodiment of concepts) and evaluation;
- detail design to enable manufacture to take place.

14.1 A novel and useful product

For a detailed discussion of what is involved in each of the above activities, the above references may be consulted.

Typically, these activities are presented in a sequential manner with iteration between stages, the iteration being stated either explicitly or implicitly. A design engineer could undertake each activity in turn and progress from the first contact with a client through to detail design. In fact, engineering design teachers will often refer to a 'design process' from analysis of need through to detail design. However, many design engineers in industry will not practice the process in the course of their work because their company departmental organisations are based on tasks, e.g. a body department in a motor company. Within each department, parts of the idealised design process will be carried out and the relationships between people within the same, or different, departments may well be recognised within the context of the overall process. The classical descriptions serve well to identify the principal design activities. But, for the objective of achieving high-quality design, a different approach can be taken, albeit within the context of the generalised design process.

It is useful to turn to the field of creative problem solving (CPS) to help understand how each individual design activity might be undertaken to achieve high-quality outcomes. Creativity can be defined as a combination of novelty and usefulness. It is a practical subject for engineers (Figure 14.1). Briefly, the CPS process starts, continues and ends with the client needs (Isaksen *et al.*, 1994; Fox and Fox, 2000). It can be summarised as:

Creativity can be defined as a combination of novelty and usefulness.

- need finding, making sure the requirements of the client are understood;
- problem finding, ensuring that the correct problem is solved;
- idea finding, finding potential solutions and evaluation using client focused criteria;
- acceptance finding, exploring how to implement solutions with the client.

The quality of the CPS process does not lie in the identification of activities and their sequencing. Of course, the correct sequencing of activities is necessary, but of more importance is *how* each activity is undertaken. The success of the process lies in the disciplined divergent and convergent thinking that takes place at each stage and the type of tools that are employed. Divergent thinking involves the suspension of judgement as one investigates a problem and searches for information, formulates problem statements, generates ideas, searches for solutions, *etc*. Convergent thinking involves the imposition of value judgements, analysis and decision making.

Divergent thinking involves the suspension of judgement as one investigates a problem and searches for information, formulates problem statements, generates ideas, searches for solutions, *etc*.

Superficially, we could map CPS process onto the design process and talk about equivalence, but it is more important to recognise that each design activity requires divergent–convergent thinking. The use of rigorous divergent–convergent thinking during each design activity is a significant step to achieve high-quality outputs for each activity. Also, it is important to use appropriate design methods (tools) at each stage, which will be considered later in this chapter.

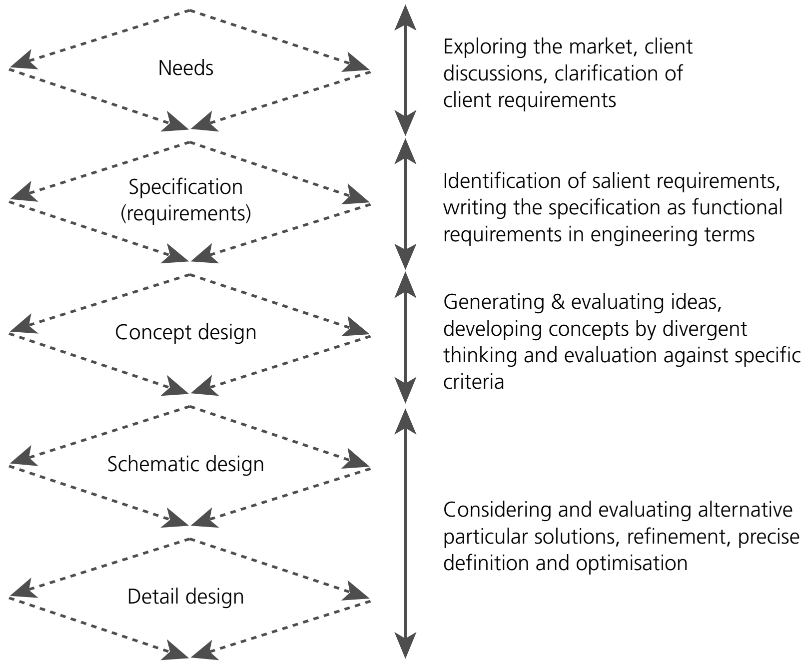
Therefore, each design activity should involve both divergent and convergent thinking:

- The identification of client needs and derivation of a design specification involves exploration of diverse factors (the market, environment, the aims of the client) and the analysis of the whole to clarify specific requirements.
- Concept design involves generation of ideas, their evaluation, development of ideas to create feasible concepts and finally a choice of preferred concept – this is a set of divergent–convergent activities.
- Schematic and detail design involves identification and consideration of alternative, particular detail solutions, and their evaluation and choice.

Figure 14.2 illustrates the divergent–convergent nature of design in the context of CPS.

If any stage of design omits, or does not treat effectively, the divergent thinking activity, then unsuitable, unimaginative, uncompetitive solutions will be produced. This is especially true if divergent thinking is lacking in the early stages of design. Engineers tend to be good at analysis and criticism, but exploration and suspending judgement is harder. At the heart of any consideration of quality design lies the creation of competitive solutions that are fit for purpose, solutions that satisfy the real needs of a client. Particular design methods may be used to create reliable products with high performance, but there is no point in creating an excellent solution to the wrong problem.

Convergent thinking involves the imposition of value judgements, analysis and decision making.



14.2 The divergent–convergent nature of design

People – cognitive style

The outcomes of design activities, processes and methods depend on people. In addition to abilities that may be described variously as academic, common sense, technical know-how, *etc*., there are certain personality traits that are highly influential in determining the outcomes of design work. There are a number of personality factors that can be described with confidence, e.g. the Myers–Briggs type indicator (Isaksen *et al*., 1994; Fox and Fox, 2000). A highly significant factor is that of personal preference for a particular problem-solving style, described by Kirton (2003) on a measurable continuum from *adaptor* to *innovator*.

The adaptor prefers to work within the paradigm, to improve existing solutions, and to achieve practical outcomes. When ideas are sought, the adaptor will generate a limited number of ideas but they will be practical. Adaptors can handle detail and prefer to work on a limited number of projects simultaneously.

Innovators will readily break the paradigm and look for solutions with a high degree of novelty. They prefer to change rather than seek to improve. When required to generate alternatives, innovators will produce many ideas and a number will be highly impracticable. The term 'innovator' is used here in a particular context with respect to problem-solving style, it does not equate to the word 'innovation'.

Of course, the above descriptions of innovators and adaptors are the extremes. Most people lie somewhere on the continuum between the extremes, but the differences between people are noticeable. Some engineers clearly prefer to improve on existing solutions whereas others have a marked tendency to look for a high degree of novelty.

The significance of problem-solving style is the influence it has on the outcomes of all types of design activity. If the workplace is dominated by adaptors, then that culture will prevail long term because innovators will be uncomfortable, perhaps not be appreciated, and may well leave. The converse is also true. Innovators and adaptors will tend to prefer design methods that best suit their style. For example, innovators will not be attracted to detailed methods that tend to improve solutions. Conversely, adaptors will not be comfortable with extreme divergent methods that generate abstract concepts. The choice of design method affects the type of solution generated; for example, brainstorming will tend to produce innovative solutions.

Therefore, it is important that the *solution requirements* shape the choice of solution. It is the client needs that have to be satisfied, not those of the designer. Whist this may appear to be an obvious point, too many times one can see problem solving style preferences reflected in the solutions opted for by designers. In all design activity, the personal traits of individuals will be influential. With suitable training, one may flex between styles to suit solution requirements. However, prolonged working outside personal preferences induces stress. Thompson and Lordan (1999) give a discussion of CPS principles and their applicability to engineering design.

It is important that the *solution requirements* shape the choice of solution. It is the client needs that have to be satisfied, not those of the designer.

Design methods (tools)

The literature contains many design methods (tools), many of which can be used effectively to improve the design process and achieve high levels of quality. Those methods that have specific uses, e.g. finite element analysis, are used widely and need no further mention here. However, there are a number of general design methods, particularly concerned with simulating divergent thinking, convergent analysis, and especially multi-objective decision making, that do not find wide application even though they have much to offer. A study of the use of design methods in industry (Lopez-Meza and Thompson, 2003) reveals typical results:

- the number of methods used in industry is relatively small and those that are used are used in a non-systematic way;
- the wrong implementation of methods and their *ad hoc* selection prevents companies from using a wide range of methods;
- the way the methods are delivered to engineers today does not suit their needs.

Incorrect application of a method invalidates its results. One typical failing is to use evaluation methods that rely on detailed information too early in the design process. Engineers can be found 'guessing scores' for performance criteria in concept evaluation when there is absolutely no justification. Also, whilst brainstorming may potentially be the single most beneficial method to generate ideas, it is often practised badly with scant regard for suspended judgement, the group dynamic and the use of extended effort.

There are many actions that could be taken in order to enhance the use of methods in industry, and there are also many levels at which those actions could be taken, e.g. management level, product development level, university level, *etc*. Some authors have pointed out that an important factor for the successful implementation of design methods in industry is the availability of easy-to-use software tools (e.g. Killander, 2001). Others have pointed to the need for support teams or help desks in industry and that management should encourage the use of methods (Ernzer and Birkhofer, 2002). An Internet-based integrated learning, information, and training environment is being developed to train learners in validated methods (Birkhofer *et al*., 2001).

For divergent thinking, the most effective methods are brainstorming, brainwriting and the use of a morphological chart.

One of the earliest texts that described design methods was by Jones (1970), in which numerous methods were discussed. Over the last three decades new methods have been introduced and old ones developed and refined. Interestingly, there are certain methods that have stood the test of time and which have been found to be very effective. Cross (2000) gives a concise account of engineering design methods for product design, as do the other main text books (Pugh, 1991; Roozenburg and Eekels, 1991; Pahl and Beitz, 1996).

Methods for divergent and convergent thinking

For divergent thinking, the most effective methods are brainstorming, brainwriting and the use of a morphological chart. Brainstorming is often misused and should be practised with a high degree of discipline with respect to the group dynamic and suspension of judgement. Brainwriting is practised in groups where each person has a sheet on which they describe, say, three ideas at the top of columns. The sheets are exchanged and the next person develops the idea in each column, or possibly produces a new idea stimulated from the first idea. Brainstorming and brainwriting are, therefore, a valuable pair of methods. Brainstorming tends to produce a diverse range of ideas that can well be paradigm breaking, whilst brainwriting tends to encourage adaptive change. In early concept design, paradigm breaking may be advantageous, but later in concept development a more adaptive style of change in which improvements are sought is the better way to progress.

A morphological chart is very useful if a problem can be broken down into particular functions, e.g. in the case of a motor vehicle there is the power generation, power transmission, body, suspension, *etc*. The functions are set out in the first column of a matrix. Alternative solutions are sought for each function and are described briefly in the row defined by each function. The objective is then to determine the optimum permutation of solutions to produce the best overall design. Note, the best solution for each row may not be the best overall solution. For example, in a manufacturing system it may be preferable to choose either pneumatic or hydraulic equipment rather than a hybrid to reduce spares and ease maintenance.

The evaluation of any aspect of design depends upon two factors: the criteria used to evaluate the proposals and the appropriate choice of method. For convergent thinking, two particular methods deserve mention: one for conceptual design and one for detail design. It is important that methods are used at the appropriate stage.

The evaluation of any aspect of design depends upon two factors: the criteria used to evaluate the proposals and the appropriate choice of method.

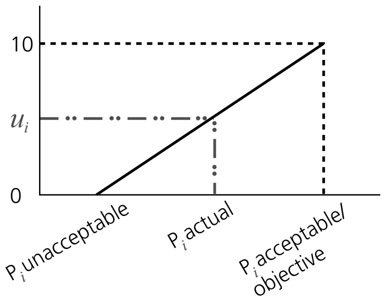
The method advocated by Pugh (1991) has proved highly effective for evaluating concepts. In this method, the concepts under consideration are described briefly along the top row of a matrix. The evaluation criteria are listed in a column to the left of the matrix; see Figure 14.3. One of the concepts is selected as the reference or datum (a preferred choice or an existing solution) and the other concepts are compared with it.

The method proceeds as follows. For each criterion individually, a concept is compared to the reference concept and a decision of 'better than', 'worse than', 'same as' or 'don't know' is made. Note that it always possible to compare two things with respect to one criterion in this way. For 'better than' a '+' is inserted into the matrix, for 'worse than' a '–' is inserted, and for 'same as' or 'don't know' an 'S' is used. Note that no numerical scores are used at any stage. In Figure 14.3, concept 1 is judged to be better than the

		Concepts							
		1	2	3	4	5	6	7	8
Assessment criteria	A	+	+	–	S	D	S	S	+
	B	+	+	+	+	A	+	S	S
	C	–	+	S	+	T	–	S	S
	D	–	–	S	–	U	+	–	–
	E	S	S	S	–	M	–	+	–
Sums	+	2	3	1	2		2	1	1
	S	1	1	3	1		1	3	2
	–	2	1	1	2		2	1	2

14.3 Concept evaluation (Pugh, 1991)

datum with respect to criterion A; therefore, a '+' is inserted under the concept 1 column against criterion A. After the matrix is completed, the total '+', '–' and 'S' ratings are added. Each concept (perhaps the top few if there are many concepts) is reviewed to determine if any '–' or 'S' ratings can be improved to '+'. Eventually, the preferred concept emerges. The strength of the process is that it forces the designers to think about the evaluation criteria and the appropriate assessment of concepts with respect to the criteria.



14.4 A numerical scoring method

For detailed design evaluation, a numerical scoring method can be used as follows. First the evaluation criteria are defined. For each criterion, two performance levels are prescribed and a performance defined: the minimum acceptable level below which a product or system is unacceptable and a level of performance which, considering engineering feasibility and market aspirations, would be perfectly acceptable. The unacceptable performance is scored 0 and the perfectly acceptable score is 10. For each criterion, a calculation of the expected performance of the proposed design is undertaken. Using a linear function, a score is determined for that criterion between 0 and 10 (see Figure 14.4). A total score can then be calculated by combining the components as follows:

$$\text{Total\_score} = N\left[\left(1/_{\text{score1}}\right)+\left(1/_{\text{score2}}\right)+\left(1/_{\text{score3}}\right)+\cdots\left(1/_{\text{scoreN}}\right)\right]^{-1}$$

where N is the number of criteria.

Such a method avoids estimating (guessing) scores and the use of an inverse calculation avoids the problem of addition in which a very low score can be compensated by high scores. Multiplying by N simply brings the total score to a range 0–10. Scale factors can also be used (Thompson, 1999).

For a comprehensive treatment of methods to stimulate divergent thinking see Pahl and Beitz (1996), Pugh (1991) and Thompson and Lordan (1999). Pugh's concept evaluation method is described fully in Pugh (1991). Pahl and Beitz (1996), Pugh (1991) and Roozenburg and Eekels (1991) describe a wide range of methods.

Specific design methods to improve quality

Whilst the objective of all design methods is to improve the quality of engineering solutions, there are specific methods that require particular elaboration. They are quality function deployment (QFD) and Taguchi methods. As will be seen below, QFD is very useful in the early stages of design and Taguchi methods are applicable to improvements through testing and development.

Quality function deployment

Total quality management (TQM) is concerned with the continual improvement of company processes and activities with the aim of achieving a high level of customer satisfaction. The focus, throughout all company activity, is the customer and all activities are evaluated with respect to their contribution to the achievement of customer satisfaction. In the context of this general picture, an important method in engineering design is QFD.

Total quality management (TQM) is concerned with the continual improvement of company processes and activities with the aim of achieving a high level of customer satisfaction.

QFD is a specific design tool that links the customer requirements to an engineering specification. The method is well described in Pugh (1991), Cross (2000), Roozenburg and Eekels (1991) and Bergman and Klefsjo (2003), and in numerous other texts; therefore, only a brief outline is given here.

The basic objective of QFD is to relate customer needs to engineering characteristics. For a particular product, the attributes of the product that a customer will perceive are first identified. Using a matrix, particular engineering characteristics are then related to customer attributes so that it is clear which engineering characteristics influence which customer attributes.

For example, in the case of an electric hover-type lawnmower, a customer may use the following criteria to judge competing models: appearance, switch feel, responsiveness, noise, cut width, cut quality, ease of cut adjustment and number of times the bag needs emptying. The engineering characteristics could be defined as: motor torque and speed; blade diameter, toughness, adjustability of blade assembly; bag volume and pressure in the bag; force to operate the switch and switch travel; structural stiffness weight, and surface finish; soundproofing. Figure 14.5 gives a matrix that shows the particular engineering characteristics that determine the product attributes, *i.e.* cut quality is determined by the torque and speed of the motor and the toughness and hardness of the blade.

The matrix can then be developed further to determine design objectives or target values for each engineering characteristic. The target values, including those of competitors if required, are shown placed at the base of the matrix (Figure 14.6). A further development is to show which engineering characteristics influence other characteristics. The interactions between characteristics are indicated on the top of the matrix (Figure 14.6), which is the 'roof' of the so-called 'house of quality'.

QFD does provide a clear link between the customers' perception of a product and the engineering characteristics that will be the objects of designers' attention throughout the project. The customers' needs are translated into specific engineering requirements. It is clear that QFD is an attractive method in product design. For engineering system design, such as process plant or other manufacturing systems, customer requirements may be specified more directly in engineering terms (for example, plant throughput, product purity, availability), therefore, there may be less need to apply the QFD method.

Engineering characteristics

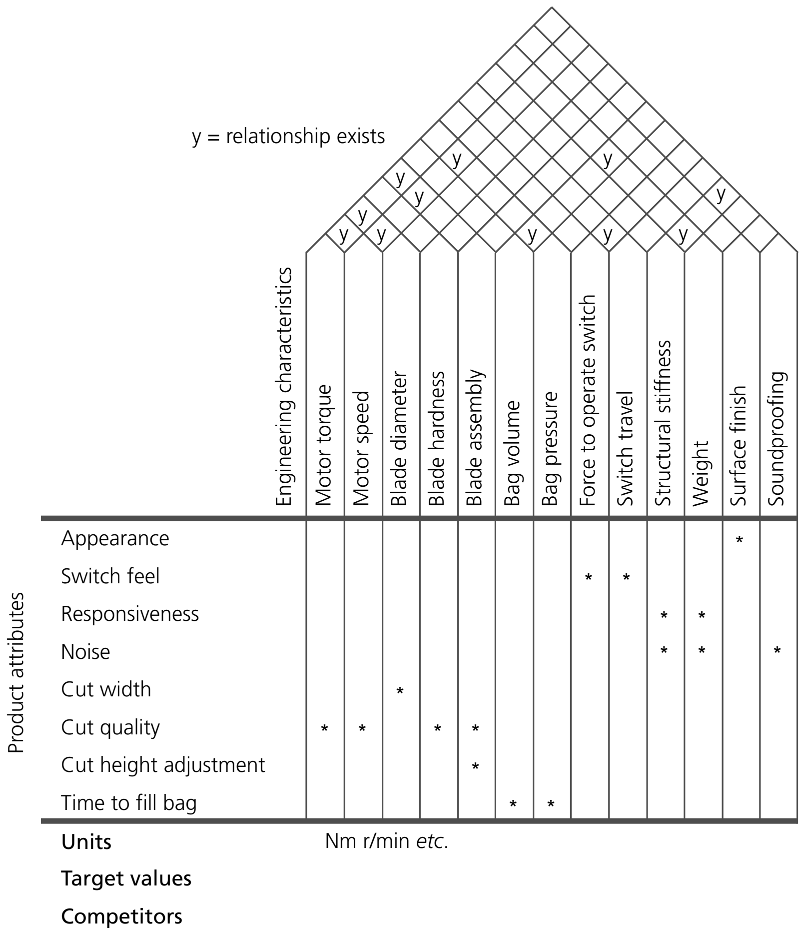
Product attributes	Motor torque	Motor speed	Blade diameter	Blade hardness	Blade assembly	Bag volume	Bag pressure	Force to operate switch	Switch travel	Structural stiffness	Weight	Surface finish	Soundproofing
Appearance												*	
Switch feel								*	*				
Responsiveness										*	*		
Noise										*	*		*
Cut width			*										
Cut quality	*	*		*	*								
Cut height adjustment					*								
Time to fill bag						*	*						

14.5 Engineering characteristics and product attributes

The above description of QFD deals with the salient principles as applied to the early stages of design concerning customer needs. A more comprehensive approach can be taken to apply the method at four stages: customer needs vs. engineering attributes, engineering characteristics vs. parts characteristics, parts vs. process operations and key process operations vs. production requirements. Bergman and Klefsjo (2003) gives a comprehensive description of QFD applied through design and manufacture.

Taguchi principles

The Taguchi principle is based on the achievement of precise product performance values that relate to customer values. A quality improvement programme is used to ensure that deviations from target product performance values are minimised. Such deviation is seen as bringing about serious deleterious effects on product quality. Emphasis is placed on specific product performance



14.6 The 'house of quality'

targets rather than tolerance bounds of acceptable performance. Product quality is understood to deteriorate rapidly if precise targets are not achieved.

The process is one of continual improvement. The objectives are to achieve precise product performance targets that determine quality and to drive down costs. To this end, the method encompasses design and manufacturing. Manufacturing has a highly significant role to play in Taguchi principles. However good the design process has been, the potential product quality may not be attained if the manufacturing process is poor. The focus of attention is that set of parameters, especially parameter combinations, that relate to customer quality, not just general manufacturing tolerances. Statistical design of experiments is used to link design parameters with product characteristics;

for further information see Roy (2001). There has been some controversy regarding Taguchi methods, but undeniably the Taguchi approach has led to many improvements in quality. For a good discussion of Taguchi principles see Bergman and Klefsjo (2003).

The perceived quality of many products depends upon their reliability.

In design, there is a clear link between the objectives of the QFD method and Taguchi. The QFD method creates the relationship between the customers' perception of a product and the engineering characteristics that determine product performance. The outcome of the QFD method is a set of precise product performance targets. The Taguchi principles are based on such targets and are concerned with minimising deviation from them.

Reliability and maintainability

The perceived quality of many products depends upon their reliability. Failures are perceived by many clients as an indication of poor quality, and quite rightly so. Many designers are reluctant to consider failure; indeed, some will even claim that they produce designs that work rather than designs that fail. Therefore, it is important to adopt proactive methods at all stages of design, and in all activities, that will improve reliability.

Similar arguments apply with respect to maintainability. The client may, or may not, undertake maintenance and repair operations, but he certainly pays for the maintenance of products throughout the product lifecycle.

Failure rate prediction and the 'reliability case'

Reliability is the probability that a device, system or component will continue to perform a specified duty under prescribed environment and loading conditions for a given time.

Reliability is the probability that a device, system or component will continue to perform a specified duty under prescribed environment and loading conditions for a given time. Failure rate prediction has been of interest to engineers since the 1970s and is best carried out using failure rate data from equipment operated under similar environment and loading conditions to the case under examination. When this is not possible, a nominal failure rate (obtained from such data sources as are available) is modified by two factors: one for environment and one for loading. The failure rates for all components are added (assuming no redundancy in the system) to obtain a failure rate for the system. This 'component count' method has found more success for electronic equipment than for mechanical components.

However, in recent times there has been a shift away from an attempt to predict a precise failure rate that may not be accurate. The emphasis today is on identifying the key factors that affect system or product reliability and setting down a clear strategy, with detailed actions, to ensure that a high standard of product reliability is achieved. Thus, reliability is achieved through control of the product design and manufacturing process.

In *engineering design*, reliability and maintainability (R & M) considerations should be, and can be, included in every stage and in all design activities:

- when the specification is derived;
- during concept generation and evaluation;
- in detail design.

An overview of these is given next; for a full discussion see Thompson (1999).

The design specification

If the design specification does not include appropriate clauses pertaining to R & M then the client has no contractual comeback if poor R & M is provided. But the client may then not purchase again, or a design team's reputation may be sullied in the eyes of others. Either way it is the designers who lose in the long term. Therefore, it is important that the designer takes a proactive stance with respect to R & M (Figure 14.7).

R & M may be included both quantitatively and qualitatively into the design specification. Quantitatively, this may be done by the inclusion of mean corrective repair time and mean time to failure objectives. Mean corrective repair time (or mean active repair time) is the mean time that is required to return a machine or system to operation given that spare parts and manpower are available. It may be estimated by a simple calculation and demonstrated before contract completion. The mean-time-to-failure calculation is subject to greater error since it relies on absolute values of failure rate data, which can be erroneous and cannot be demonstrated in the short term.

Qualitative inclusion of maintainability criteria can refer to the skill levels required for maintenance and repair; for example, is multi-tasking an option, is maintenance to be carried out by a highly skilled, or otherwise, workforce? Specific skills should be cited. In the case of reliability, the specification should describe clearly and precisely the operating environment of the machine or system. Also, the skill level of operators should be described realistically. The environment in which a machine will work and the way it is operated will also occasionally have a highly significant affect on reliability.

14.7 Reliability and maintainability should be considered at every stage of the design process

The specification may require that certain design methods be used. For example, the specification could state that a top set of critical items that would be most influential on system reliability must be identified by, say, a system reliability model or a HAZOP study plus fault tree analysis (FTA). Then, a detailed reliability assessment should be carried out for each critical machine. A failure mode effect analysis could be required for a critical system to identify the areas of high risk.

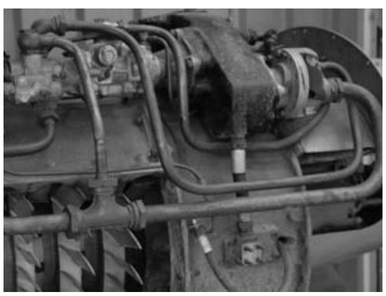
Qualitative statements that refer to R & M in the design specification are extremely valuable. They capture the operating climate of the system and involve the client thinking deeply about the design. However, qualitative statements should be made very specific. It is largely worthless to include terms in a specification such as 'good maintainability', 'maximum reliability must be achieved', 'full attention should be given to maintainability and reliability', *etc*. They mean nothing and add little value to the document; for example, how good is 'good', how can maximum reliability be achieved – at what cost or expense to other parameters? Often R & M are linked; for example, joints may be introduced to improve maintainability but their presence reduces reliability.

Concept design

It is quite possible to include R & M considerations in concept design. One attractive way is to undertake a specific R & M evaluation using Pugh's method. Specific R & M criteria can be defined for use in Pugh's evaluation method; for example:

- simplicity and elegance;
- minimum number of parts;
- suitability for modular construction;
- accessibility;
- sensibly sized components;
- ease of adjustments;
- precise definition of maintenance skill levels;
- minimum number of moving parts.

The above criteria appear rather general; more specific criteria can be defined for particular cases (Figure 14.8).



14.8 Products should be designed for ease of maintenance

Detail design

There are certain analysis methods that are suitable for detail design that integrate R & M considerations with other performance parameters. However, the simple checklist remains one of the most cost-effective ways of ensuring that the client will be satisfied. Taken from Thompson (1999), typical examples include:

- *Spares*. Is the variety of spares required reasonable and not excessive? Is the future availability of spares assured?
- *Ergonomics*. Can the forces/torques required for maintenance be provided by persons of average physique?
- *Faults*. Are people safe in the event of mal-operation? Is other equipment protected in the event of mal-operation? Can the operator readily detect if the machine operates out of specification?
- *Condition monitoring*. Is provision made for hand-held condition monitoring devices to be used? Is provision made for installed condition monitoring instrumentation if required?
- *Corrosion*. Are the components, and especially fasteners, resistant to external corrosion? Are the materials selected to resist the internal corrosion of any parts in contact with fluids?

Specific design methods for failure analysis

Failure mode and maintenance analysis (FMMA), FTA and failure mode effect and criticality analysis (FMECA) are precise methods that specifically consider the consequences of failure.

FMMA is a simple approach in which, on completion of a piece of design, the principal failure modes are listed and, with reference to the design work carried out, the ways in which failure is corrected are written down for each failure mode. It is best done by someone other than the designer and is suitable for a design review of critical machines. Such a study may lead to redesign and/or the introduction of condition monitoring equipment.

Failure mode effect and criticality analysis is a 'bottom up' approach to failure analysis.

FMECA is a 'bottom up' approach based on a risk assessment. Firstly, the components of a system are listed, and for large systems the study will sometimes begin at an intermediate level. For each component, the failure mode is defined and the consequences of failure are considered. The likelihood of failure can be predicted using failure rate data if available, but more commonly an estimate is made on a 0–10 or 0–5 scale (high number equates to more likely).

The consequences of failure may be estimated in real terms, e.g. serious injuries/year, or more often as a severity rating on a scale similar to the likelihood of failure. The most critical items are identified by the product of the likelihood of failure and consequence ratings, *i.e.* maximum risk, and a decision taken whether or not the risk is acceptable or whether remedial action is called for. FMECA studies can be carried out for products and processes. In some cases, the analysis is extended to include the likelihood of detecting a failure mode and a risk priority number calculated as the product of the three factors: likelihood of occurrence, consequence and likelihood of detection.

The FMECA approach is a simple method that is widely used. Its drawbacks are that it can be time consuming and consequences of combinations of individual failure events can be undetected.

Fault tree analysis is a top-down approach to failure analysis.

FTA is a top-down approach to failure analysis and begins with a clear statement of a system failure. The events that must occur to create that top failure mode are then identified and arranged under the top event in a tree with logic gates (the most common ones used are 'and' gates and 'or' gates). Then, for each failure on the second level, the events are identified that need to occur in order for that particular event to occur and the events drawn on a tree using logic gates. Thus, a comprehensive fault tree is created showing all the failure events and their dependencies that need to occur if a certain top-level failure is to transpire.

The tree can be analysed to give a figure for the top-level failure rate by inserting failure rates for each event. However, for the designer, especially when failure rate data are not available, the fault tree can be used to identify the key components or subsystems that are likely to lead to a system-level failure. A fault tree can become quite complicated, but, by using modern software, fault trees for the diverse parts of complex systems can be derived separately and linked with common elements if required.

BS 5760-0 reliability of systems, equipment and components

British Standard 5760-0 (1986) gives a description of reliability concepts, processes and methods. In addition to precise definitions in the field of reliability, the standard covers business organisation to achieve reliability and descriptions of particular methods and their use in practice. It is a very useful standard and is used by many companies. It guides the reader in the practical application of reliability principles and methods to industrial practice. In this way, it is more useful to the practitioner than certain text books.

British Standard 5760-0 gives a description of reliability concepts, processes and methods.

There are links between the quality standard (BS EN ISO 9000-1 (1994), *etc.*, see below) and BS 5760-0. For example, BS CECC00804 (1996) is concerned with a harmonised system of quality aspects for electronic components: Interpretation of 'ISO 9000:1994' – reliability aspects for electronic components. There are many such helpful examples, too numerous to list here, and the BSI Web site should be consulted to search for appropriate standards and guides.

Design review

A design review is a quantitative and qualitative examination of a proposed design to ensure that it is safe and has optimum performance with respect to maintainability, reliability and those performance variables needed to specify equipment.

Maintainability and reliability are included in the definition to ensure they are considered, but they should be dealt with in conjunction with other parameters. An effective design review will ensure that design proposals are fit for purpose. A design review is much more than a perusal of drawings and calculations. It should be a systematic procedure that is integrated with normal design activity, which is outlined below. For a full description see Thompson (1999).

A design review is a quantitative and qualitative examination of a proposed design.

A systematic procedure

The review should begin from the derivation of the design specification and continue through to detail design.

Specification. The objective is to ensure that all salient points in the design specification are understood by the design teams, including maintainability and reliability requirements and influential factors. This is especially important when design work is put out to sub-contract.

System level review. The aim is to identify critical areas that are most sensitive to the achievement of client needs. The outcomes of a QFD analysis would be useful in this respect. The design review team might also comment on the need to follow high-risk options, say the introduction of new technology, to satisfy certain system requirements.

Functional unit level. Particular designs of equipment are reviewed in detail, say by a applying multi-criteria, quantitative assessment method. Such detailed evaluations would only be carried out for critical items. Checklists could be used more generally as a cost-effective solution.

Detail level. Generally a major project cannot be reviewed at a detailed level due to time constraints, nor would one ever expect so to do. Rather, one would expect the design review team to identify particular areas for detailed scrutiny, say the seals in part of a chemical plant.

The review should begin from the derivation of the design specification and continue through to detail design.

Design review team

In some cases a design review team is formed that remains together for the duration of a project and which has an important management role to play. From the above, it can be seen that an experienced multi-disciplinary team is required comprising design personnel, particular technical experts, maintenance engineers, production staff and safety specialists.

Design review teams may be formed from personnel within a company, from an external consultancy or from internal and external sources. The advantage of in-house personnel is that they must 'live' with the outcome long term. If internal expertise is limited, then external consultants have benefits and the consultants can point to best practice elsewhere.

EN ISO 9001 quality systems

BS EN ISO 9001: 1994 (formerly BS 5750) is the international standard on quality systems that includes product design. It is the model for quality assurance in design, development, production, installation and servicing. The quality system requirements include:

- management policy;
- quality system;
- contract review;
- design control;
- document and data control.

Other sections of the standard refer to aspects of purchasing, customer-supplied product, inspection, measurement and testing.

A quality system includes planning that defines how quality requirements will be met and the controls that will be put in place.

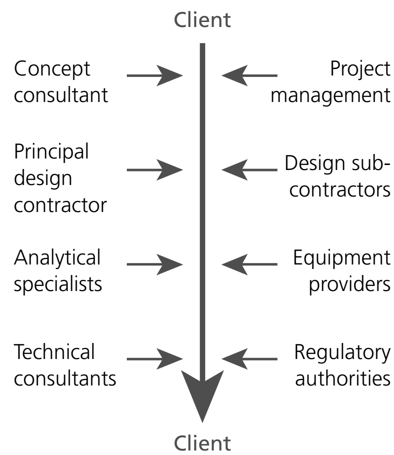
The standard unequivocally states that the responsibility of the management of the product supply company is to define and document its quality policy, including specific goals and the expectations of the customer. Therefore, the client needs are again at the heart of design activity. The particular responsibilities and authority of management personnel should be stated clearly. The quality system includes planning that defines how quality requirements will be met and the controls that will be put in place. At the tender stage, the contract requirements must be reviewed thoroughly.

Design control is a significant part of the standard and the following activities are covered:

- design and development planning for each design activity;
- organisation of the technical interfaces between different groups;
- design inputs that refer unambiguously to requirements;
- design outputs that specify terms that can be verified and validated with respect to the requirements;
- design review at each stage of design;
- verification and validation;
- design changes.

To achieve good quality in design, reliability and maintainability, the requirements in the design specification are important and have been discussed above. Importantly, in order to satisfy the quality standard a design review must be undertaken. The design review is a very important means by which R&M may be included in the design process in order to achieve high levels of quality.

Another important aspect of the quality standard which, perhaps, does not receive the prominence it deserves is organisation of the technical interfaces between groups. Figure 14.9 shows the range of inputs to a major project. *All projects start and finish with the client*. On the way there are many inputs to the project, including mainstream designers, sub-contract designers, technical specialists, regulatory authorities (municipal authorities and specific government departments), consultants, *etc*. If the interfaces between all these groups are not managed then the output of the design activity will suffer badly.



14.9 The range of inputs to a major project

Conclusion

Quality is perceived in many different ways, but the only view that counts is that of the client or customer. Unless the client perceives good quality then sales will suffer and a company will not survive. The client will perceive quality in terms of performance, and in reliability terms, *i.e.*: Does the product continue to perform satisfactorily without failure or without deterioration in performance?

In order to achieve good quality in design, design activities need to be carried out using appropriate methods that will yield solutions meeting the problem requirements, especially with respect to innovative or adaptive change. The people undertaking the design must select solutions that are client focused and not be unduly influenced by their personal cognitive style. There are many methods that can be used in different design activities. Reliability, QFD and Taguchi methods are very significant in the achievement of high reliability.

Reliability in design can be achieved by considering apposite reliability parameters at each design stage, from specification through to detail design. Qualitative and quantitative methods can be used in all design activities and a comprehensive design review is an important contribution to quality improvement. The building up of a reliability case in this way by including reliability in all design activities is preferred to relying on a precise, but possibly inaccurate, failure rate prediction calculation.

Quality is a major subject that encompasses much more than design. The above sections have outlined briefly certain aspects that are highly pertinent to design. No claim to exhaustiveness can be made, and different authors will place different emphasis on topics. The wide subject of quality is covered in ISO 9000 and its associated parts.

References

Bergman B, Klefsjo B (2003) Quality: from customer needs to customer satisfaction. Pub Studentlitterature, Lund, Sweden

Birkhofer H, Lindemann U, Albers A, Meier M (2001) Product development as a structured and interactive network of knowledge – a revolutionary approach. ICED'01, Glasgow, UK

BS 5760-0 (1986) Reliability of systems, equipment and components – introductory guide to reliability. http://www.bsi-global.com

BS CECC00804 (1996) Harmonized system of quality assessment for electronic components: interpretation of ISO 9000:1994 – reliability aspects for electronic components. http://www.bsi-global.com

BS EN ISO 9000-1 (1994) Quality management and quality assurance standards – guidelines for selection and use. http://www.bsi-global.com

Cross N (2000) Engineering design method: strategies for product design. John Wiley

Ernzer M, Birkhofer H (2002) Selecting methods for life cycle design based on the needs of a company. Design 2002, Dubrovnik, Croatia

Fox JM, Fox RL (2000) Exploring the nature of creativity. Kendall/Hunt

Isaksen SG, Dorval KB, Treffinger DJ (1994) Creative approaches to problem solving. Kendall/Hunt

Jones CJ (1970) Design methods. John Wiley

Killander AJ (2001) Why design methodologies are difficult to implement. International Journal of Technology Management, 21(3/4): 271–276

Kirton MJ (2003) Adaptors and innovators: styles of creativity and problem solving. Routledge

Lopez-Meza B, Thompson G (2003) Exploring the need for an interactive software tool for the appropriate selection of design methods. ICED'03, Stockholm, Sweden

Pahl G, Beitz W (1996) Engineering design: a systematic approach. Springer

Pugh S (1991) Total design: integrated methods for successful product engineering. Addison-Wesley

Roozenburg NFM, Eekels J (1991) Product design: fundamentals and methods. John Wiley
Roy RK (2001) Design of experiments using the Taguchi approach: 16 steps to product and process improvement. John Wiley
Thompson G (1999) Improving maintainability and reliability through design. Professional Engineering Publications
Thompson G, Lordan MA (1999) Review of creativity principles applied to engineering design. IMechE, Part E1, 213: 17–31