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Elements of the Design Process

The design process consists of several stages that commence once it is agreed that the idea for a product is worth the investment of time and resources. To establish this prior to starting the design process in earnest, the following are required:

- an initiating need, or driving force, that requires resolution;
- a business case to justify the investment.

Initiating Need

This pre-design stage is concerned with understanding the high-level goal or ambition of the client as well as what this is intended to resolve. For example, the goal may be a new design of car in order to seize upon a current gap in the marketplace, but car design obviously encompasses a great many styles, types, performance levels, and design possibilities. Refining that goal during this stage to "a car that can carry five persons comfortably, with luggage, and be powered electrically" reduces the number of possible design outputs for consideration and may also reduce the overall design costs.

Some possible reasons and underlying factors for an initiating need might include those in the following list.

- To support current growth in the business through:
  - adding an extension to existing premises;
  - adding new premises, either acquired or purpose-built;
  - moving en masse to a new location;
  - developing an additional or enhanced range of products for the market.
- To support a change in technology or invention that will:
  - increase production;
  - reduce operational costs;
  - improve safety and reduce levels of risk.
- As a result of new or changed legislation that:
  - is designed to improve air quality;
  - is designed to enhance water quality;
  - impacts the use of restricted or hazardous materials;
  - makes material changes to workplace assets.

An Effective Strategy for Safe Design in Engineering and Construction, First Edition.
David England & Dr Andy Painting.

- To effect a change to the client's undertaking due to:
  - a recent safety-related case that highlighted poor practice;
  - an expansion into new markets or product lines;
  - preparing for the sale of the undertaking;
  - a change in direction of the board or a fundamental injection of capital.

The initiating need may lead to a number of initial ideas that could push the limits of technical capability and possibility. Whilst some of these ideas might be ruled out very quickly, some of the more novel or unorthodox ones may help the client re-evaluate their ambition for the product. It may transpire that for a modest capital investment, the client can blaze a new trail in their particular sector, perhaps in aesthetics, technology, or product sustainability. This balance of investment against return is resolved through conducting a business case.

Business Case

This stage is where the outline costs and benefits of progressing with the initiating idea are captured. There may well be more than one possible solution to any requirement, each of which may have different investment costs (capital expenditure) and running costs throughout its life (operational expenditure). Combined with this will be the level of risk each option exposes the business to. The business case must balance these positive and negative outcomes for each option against the levels of exposure to risk—in terms of financial, reputational, and corporate risk, and so forth—that the organization is prepared to accept. This should provide the client with a balanced argument from which to make an informed decision. There is also always the "do nothing" option to consider if this is ascertained to be less impactive to the organization than the value of the investment in an ambitious new project. Each organization has a level of risk it is prepared to accept under various circumstances and this in itself will play some part in the potential design options considered later on.

The business case of course provides an informed approval based on knowledge at the time it was conducted. Should issues arise during subsequent stages of the design process, or risks become apparent that had not been hitherto identified, then there should always remain the option to halt the project; either temporarily in order to reassess the business case or permanently to prevent unnecessary further expenditure.

Requirements Capture

Once the initiating need has been defined and the business case to proceed has been approved, a statement of requirements (SoR) is created to document what the client *actually* needs. This is because the client's ambition may include a "wish list" of qualities for the product that cannot be justified in terms of current technology, capability, or probity. The involvement of a wider group of stakeholders, such as suppliers, manufacturers, or teams within the client's organization, should result in a more balanced and

informed SoR. This should then be checked against the initiating need to ensure that the key objectives of it are being met.

At this stage, a risk register (covered in the risk management chapter) is also created and populated with risks to the project. Sometimes with complex projects, it may be that the design requirements have to mature before some risks become apparent. This is in part due to how risk can be either foreseeable or observable; that is, foreseeable risks are those that we can speculate with some certainty *might happen* and observable risks are those that *readily present themselves to us*. For example, the requirement might state that the product is intended for use in atmospheres that contain explosible or volatile substances. In this case, the *foreseeable* risk is that the product might cause an explosion if it is not made to the correct tolerances. The *observable* risk is in the capability of the production stage to maintain those tolerances against the design specification.

The statement of requirements should state the client's design intention clearly but without specificity. In our "car" example from the initiating need stage earlier, we might demand electric power with a range of at least 300 km in the SoR. If we were to qualify this by stating that the power is to come from lithium-ion batteries we might exclude, at the project's expense, emerging battery technology; just as lithium-ion supplanted nickel metal-hydride batteries, which in turn supplanted nickel-cadmium batteries before that. The SoR should pose the question to which the full design is the answer, thus allowing the designer some degree of flexibility in proposing solutions.

The Design Process

Once the SoR is completed, the designers can be approached and the design process can begin. This process is composed of four key stages that follow the product's life cycle through to completion of production. These stages may be combined or repeated according to the size and complexity of the design itself (see Figure 1.1). The stages are:

- feasibility;
- specification;
- full (or technical) design;
- validation.

There may also be further independent reiterations of the design process during the in-service stage of the product's life cycle—for example, where the product is repurposed or amended—and these should be considered as separate iterations of the design process.

Design Feasibility

By interpreting the client's needs from the SoR as well as considering the initial risks captured in the risk register, the designer may arrive at the most likely solution quickly. Indeed, the solution may be quite obvious. This should not, however, preclude the designer from suggesting alternatives, regardless of their apparent obscurity. Similarly, the client would do well to examine each suggestion dispassionately in case any of

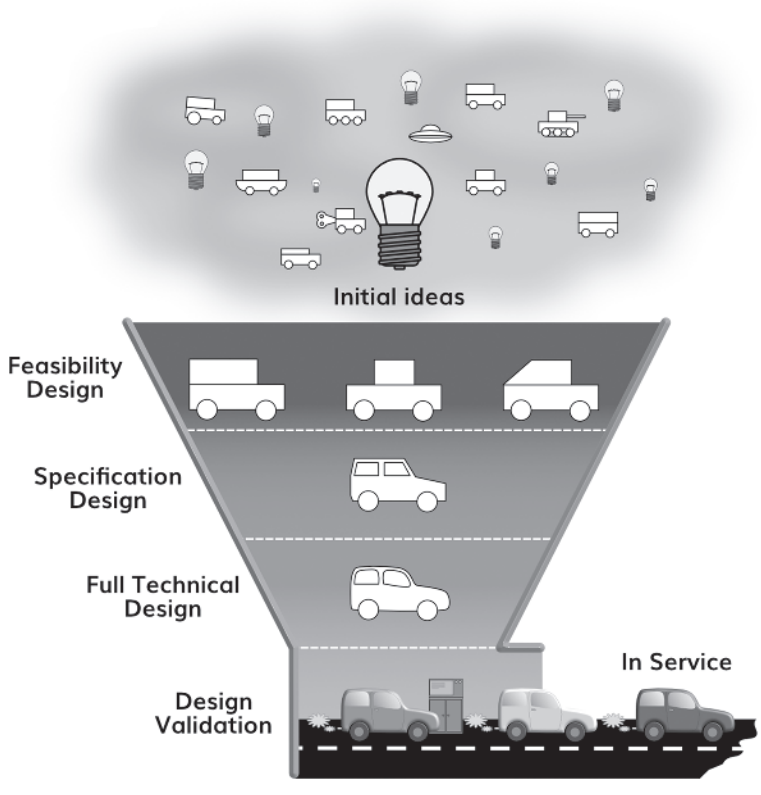

Figure 1.1 The Design Process.

them expose a hitherto unconsidered solution or potential cost saving, perhaps over the lifetime of the product. Such considerations are a matter for the client to review as often as necessary to whittle down the prospective design concepts to those that best fit their business case.

The SoR will assist in reducing the number of initial ideas to a select few that fall within the agreed levels of suitability and affordability. All the while, the designer should be referring to any control measures necessary to ensure the safety of each design (see the section on the general principles of prevention) and to establish that, at this early stage, the risk with each one has been—or is being—considered.

During the feasibility phase, various tests, experiments, and calculations may be required to substantiate one design over another. Once again, the output of these tests should be considered with reference to the SoR and the risk register to ensure that they are providing relevant data.

Towards the end of this stage, a design review might be undertaken to qualify that the SoR has been adhered to and whether the proposed design meets with the client's objectives for the project. The design review will also examine key stakeholder requirements,

as well as identify any potential risks concerning design, production, in-service use, and disposal, and these can help to inform the design risk assessment as well as the design specification.

Design Specification

The specification stage is where a single design concept from the feasibility stage is agreed for further development and progression. The design can now be imbued with enough detail in order to fully understand its functionality and any potential impacts associated with the end product. This level of detail may still be a little way from being enough to go to production, but should be enough to provide modelling data and to understand whether it will perform as specified in the SoR.

As the design matures during this stage it will become more complex and this can lead to a tendency to drift away from the original idea. To help prevent this, it will need to be tested against the SoR as well as additional issues such as: whether the product can still be technically produced, whether it creates additional hazards, and whether risks have been captured and managed by the designer. All the while throughout this stage the design should continue to be developed in accordance with the general principles of prevention.

As with the previous stage, a design review may be undertaken to assess whether the design meets with the client's intentions as captured in the SoR and whether the benefits continue to outweigh any perceived risks. The review should question how the design is to be tested to ensure that it is compliant and will meet all the required operational parameters. At this point the design is formally accepted by the client and any subsequent substantive changes made by them will result in any additional costs being borne by the client.

Full or Technical Design

The full or technical design part of the process is where the design gains ever more detail in preparation for production. The design is modified in accordance with all aspects of the stakeholders' requirements, as far as the client demands. It must consider how the product will be produced as well as the implications of time and cost for all relevant testing and certification required in order to demonstrate that it meets the initiating need and the SoR, as well as any relevant legislation and standards. At this stage the designer should be cognizant of any appropriate testing requirements and any operational or functional tests that need to be demonstrated to the client. This will inform the validation criteria required at the end of the production stage and how this is to be managed by the production programme. These criteria are what the producer will use to demonstrate that the product has been completed strictly in accordance with the full design. Where the product is designed to be produced in phases, the validation criteria will also be used to ensure each successive phase begins only after appropriate testing and acceptance of the previous phase is complete.

The full design should continue to be developed in accordance with the general principles of prevention and this will be reflected in the design risk assessment which should be updated as appropriate throughout this stage. This ensures that due consideration is paid to the later areas of in-service use (specifically operation, maintenance, and disposal) and any potential risks during these stages which might be mitigated by amending the full design.

A design review at this stage will consider all these various aspects and provide an agreed "freeze" of the design, in preparation for elevating to the production phase.

Production Phase

During the production phase the "frozen" design is of course the de facto design that the producer will work to. There may, however, be a requirement to alter the design as issues and interactions are identified. Whilst these minor updates always demand the attention of all stakeholders, thereby allowing inclusive and demonstrable decisions to be made on any amendment, there is often also a need to provide some level of autonomy to the producer and allow the installing engineers to make working decisions. This level of responsibility and accountability will have been formally agreed and documented prior to the production phase. Any changes made to the design, irrespective of size, will be captured on updated design drawings. Whether the original designer or another progresses the design through the production phase, they should be aware of how a small change can have a major impact on any subsequent phases, especially in complex projects. Minor changes may also introduce additional risks into the final product, or impose previously undocumented limitations of use.

As production progresses, there may be a need to test or validate elements of the product prior to subsequent elements being produced. Here, the test will be against the element's agreed design and should be in accordance with criteria previously identified in the validation plan. Often in long or complex projects where there is a gradual delivery of the product, the client may become responsible for the maintenance and upkeep of completed elements now under their control. Again, this is subject to formal agreement prior to the production phase and any required documentary evidence from the client to prove the criteria of any maintenance has been met, thereby ensuring any warranties with the final product delivery remain valid.

Validating the Design

The validation design review takes place at the end of the production phase when all the predetermined tests and checks have passed the guidance and tolerances set out in the validation plan. A typical validation plan should contain:

- a brief description of the project;
- a list of the elements that require testing;
- manufacturer/supplier details;
- any unique item codes, references or asset numbers;

- who is accountable for conducting each test;
- who is accountable for witnessing each test;
- what information should be officially recorded as part of each test;
- any items of special test equipment that are required (some may require pre-booking);
- specific hazards associated with each test;
- risk assessments for each test (high energy systems, power systems, working at height, confined spaces, etc.).

The plan should identify all the tests that need to be undertaken, when each is planned, any prerequisites that need to be in place, and what needs to be tested in a specific order (this will identify the critical path of the testing process). There should be signature boxes available to allow both those conducting and accepting the tests to sign them off, as well as any witnesses if required. If applicable, serial numbers and calibration certificates for test equipment used should be captured at the time to prove they were in date during the test. All of this information should be included in the health and safety file, technical file, and/or safety case.

Once the validation plan has been created it should be signed by all stakeholders involved in the test, thus confirming their accountabilities. The plan should then be formally authorized by the client and the conducting authority.

The validation plan can be examined as part of the validation design review to ensure that everything has been installed and is operating as expected and, if there are any arising issues or risks, that suitable mitigations have been put in place.

The review also examines the accuracy and completeness of any maintenance and operational information that has been supplied by the producer to the client. This should also combine with a review of the project's risk register to determine that any residual actions of the production stage have been achieved, or are at least scheduled to take place. These actions may include any that are connected to residual risks with the final product where, perhaps, the mitigation lies in operational or maintenance procedures, or even training regimes, that the client (or end user) must implement prior to the product being used for the first time.

The validation design review may also be used to fully agree the contents of any technical documentation regarding the product that may be required by appropriate regulation. Known as either a "technical file" or a "health and safety file," it takes a specific form of documentation that, usually, has already been laid down during the design and production phases. As this can be of a regulatory nature, the client may wish to seek expert assistance with its creation. This forms part of the "golden thread" of information that helps to inform the owners, operators, and users of products about its safety—in terms of use, maintenance, and repair.

For complex designs such as nuclear powerplants or warships, this validation phase may well take several years, whereby some responsibility is handed over to the client for the day-to-day running and maintenance, with certain items left in the control of the producer until they are validated. The Royal Navy aircraft carriers, HMS Queen Elizabeth and HMS Prince of Wales, were launched and sent to sea years before final acceptance of the flight equipment/systems into operational service.

Often, after all production and reviews have been completed, the senior stakeholders, designer(s), and producer(s) will attend a "lessons learnt" exercise in order to capture

any issues with the project and the design. These exercises can prove invaluable in providing feedback to all parties on where the project went well and where it did not. In cases where the client has further projects to undertake, a review such as this can be extremely useful.

Lessons Learned

A valuable component in virtually any type of design process is the conducting of a "lessons learned" review towards the end of the project. Also known as a "wash-up meeting" or "post mortem," this type of review can, when conducted properly, provide valuable information for all stakeholders, particularly for any future projects and, for professional stakeholders such as designers, useful feedback in terms of competency and communication. This can be important in respect of their continuous professional development.

Discussing what went well and what did not go well across a number of elements in a project can often identify sometimes simple but effective changes that can be made in the future. A client not organizing a communication plan sufficiently well; a designer not being provided with a robust statement of requirements; pre-construction information not being supplied early enough—these are all examples of where small detail changes can be made in future projects that will have a positive impact on costs and may reduce potential delays. In effect, learning lessons from previous projects is a strong path to preventing error.

Learning lessons in this way can sometimes be a disquieting procedure—possibly one reason why they are often overlooked. Some stakeholders may view them as merely a way to apportion blame, but this is not the raison d'être. Any project can suffer from hindrances and pitfalls, even when all those concerned are working to a well-defined system to prevent errors. The reason for reviewing the lessons of any project is to attempt to *prevent the same mistakes happening again*; and, by doing so, incrementally adapt each successive project in the pursuit of continuous improvement.

Towards the end of a project, a "lessons learned" document should be sent to each stakeholder or group of stakeholders to elicit from them their responses to the two simple questions: "what went well" and "what did not go well." Responses can be anonymized if need be but this can detract from rooting out problems that may have only been apparent to one type of stakeholder. Difficulties in the supply chain, for example, may be of enormous concern to the producer but the client may not have been aware of them, or even have been unduly concerned if they were. Physically meeting as a group on the return of these submissions will then greatly assist everyone in understanding not only the difficulties that each other had during the project, but also *how* those difficulties were perceived and what they meant in real terms to the project's efficacy.

The elements of the project to be reviewed in this way fall variously under the categories of control, competency, communication, and cooperation and might be arranged under the following topic headings:

- Technical competence. How well did each stakeholder, particularly those in a profession or trade, act during the project? Did anyone deal magnificently with a particular issue or was anyone felt to need improvement in their competency?

- Project management. Was the project managed well? Was information passed in a precise and timely way? Did everyone have the right access to the project at the right time?
- Resource management. Usage of time is important, as is the availability of other resources, such as money, materials, and equipment.
- Organizational management. However well-planned a project is there is likely to be some facet, however small, that can cause disruption to any otherwise smooth progress. Perhaps the introduction at a late stage of an additional stakeholder that had been unforeseen—could this have been better planned at the outset as a "potential risk"?
- Relationship management. Communication and cooperation between various groups can always suffer from disagreements. It is not that these take place but how they are dealt with and reconciled that matters. Was the structure in place to deal with these or did certain groups excel in conjointly dealing with a particular issue?
- Communications. The type, frequency, and output of communications should be planned at the beginning of any project, but did it actually all go to plan, or were there issues that could have gone better or have benefited from more time allocated to them for discussion?

To ensure the success of any review of the lessons from a project, there should be clear definition of its style and framework—as well as its ground rules and ambitions—stated in the communications plan laid out at the beginning.

The Design Process—Summary

The design process begins once the statement of requirements has been agreed and goes on to encompass the feasibility review of the initial ideas all the way through to the delivery of a completed product to the end user. The design is matured, incrementally, from the single design agreed at the feasibility stage through modelling and defining of the specification, to the validation of the final product. Throughout the process the designer must ensure that the design fully realizes, where physically and technically possible, the intentions that the client originally had.

Far from being an obstruction to the design process, scrutinizing the design at predetermined points prevents it from moving too far from the original intention, and thereby saving costs associated with redesign, rework, and failed products. This scrutiny can be as an ongoing procedure or as a set-piece review at the end of each design stage. However it is achieved, any design will benefit from being scrutinized from the outset because the greatest savings—and the best chances of reducing error—are to be gained before the design has matured. Asking questions should never be seen as obstructive.

The original intention of the client—whether they are an organization, an individual, or even another design project—should be firmly understood, not only from the technical aspect of the intended product but also from the initiating need of the client: the reason why the product is required in the first place. Understanding this helps to ensure the relevant stakeholders are involved in the process as well as helping to deliver an appropriately worded statement of requirements that will guide the design process

along the right path. And along with the influences of those who will have to make, operate, and maintain the product, we must add the environment in which the product will be used.

Throughout the design process, the general principles of prevention will enable us to ensure that the design matures safely. Only by embedding safety as a *critical component* of the process can we maintain our duty of care to all those who will interact with the product as well as our duties under relevant regulations. Again, this is no obstacle to our endeavours, but a beneficial course of action to prevent error and waste, be that in terms of time, money, or materials.