Concepts in Engineering Design

Designing is about people planning and creating ways to produce things that achieve some known goals.

Definition of Engineering Design

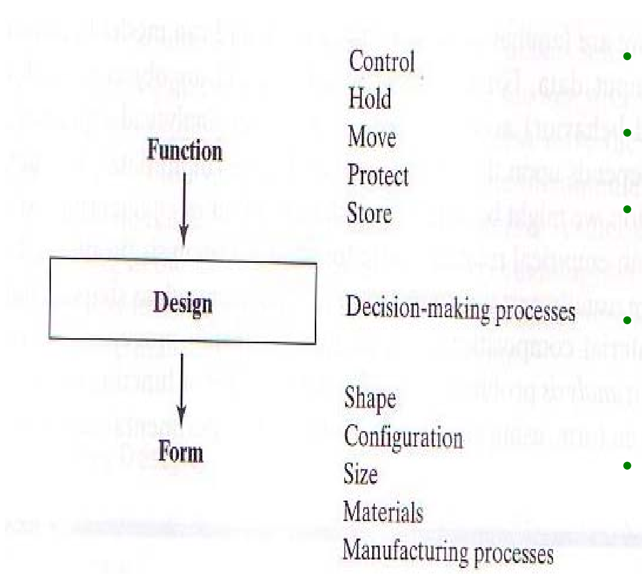
Definition 1 (Engineering Design by Rudolph J. Eggert):
The set of decision-making processes and activities used to determine the form of an object given the functions desired by the customer.

Definition 2 (Engineering Design by Rudolph J. Eggert):
The organized, thoughtful development and testing of characteristics of new objects that have a particular configuration or perform some desired function(s) that meets our aims without violating any specified limitations.

Definition 3 (Engineering Design: A Project based Introduction by Elizebeth Orwin, Patrick Little and Clive I. Dym):
The systematic, intelligent process in which engineers generate, evaluate, and specify solutions for devices, systems, or processes whose form(s) and function(s) achieve clients' 'objectives and users' needs while satisfying specified set of constraints.

Definition 4 (Fundamentals of Engineering Design by Barry Hyman):
The process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative) in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective.
i.e. ABET (Accreditation Board for Engineering and Technology) definition.

Engineering design is a thoughtful process for generating designs for devices, systems, or processes that attain given objectives while adhering to specified constraints.



- The form of an object usually depends on the function it performs.
- Function: things a designed device is supposed to do.
- Form: the shape/ geometry of the object/ artifact.
- Design objective: feature or behavior that we wish the design to have or exhibit
- Design constraint: a limit or restriction on the features or behaviors of the design. A proposed design is unacceptable if these limits are violated.
- Specifications: a scale on which the achievement of a design's functions can be measured. Specifications are engineering statements of the extent to which functions are performed by a design.

COMMUNICATION AND DESIGN

- *Communication is a key issue*. It is not that problem solving and evaluation are less important; they are extremely important. But problem solving and evaluation are done at levels and in styles—whether spoken or written languages, numbers, equations, rules, charts, or pictures—that are appropriate to the immediate task at hand. Successful work in design is inextricably bound up with the ability to communicate.
- Engineering designers do not typically produce their artifacts, except in the form of prototypes and proofs of concept. While these prototypes are useful for understanding the design space and demonstrating the feasibility of the design, the ultimate product of most contemporary design is a set of fabrication specifications for others to use in making the artifacts.
- Traditionally, fabrication specifications were presented in a combination of drawings (e.g., detailed engineering drawings, circuit diagrams, flow charts) and text (e.g., parts lists, materials specifications, assembly instructions). We can achieve completeness and specificity with such traditional specifications, but we may not capture the designer's intent—and this can lead to catastrophe. In 1981, a suspended walkway across the central atrium in the Hyatt Regency Hotel in Kansas City collapsed because a contractor fabricated the connections for the walkways in a manner different than intended by the original designer.

LEARNING AND DOING ENGINEERING DESIGN

Engineering design problems are challenging because they are usually *ill structured* and *open-ended:*

- Design problems are considered *ill structured* because their solutions cannot normally be found by applying mathematical formulas or algorithms in a routine or structured way. While mathematics is both useful and essential in engineering design, it is not possible to apply formulas to problems that are not well bounded or even defined. In the early stages of design, “formulas” are either unavailable or inapplicable. In fact, some experienced engineers find design difficult, simply because they can't fall back on structured, formulaic knowledge—but that's also what makes design a fascinating experience.
- Design problems are *open-ended* because they typically have several acceptable solutions. Uniqueness, so important in many mathematics and analysis problems, simply does not apply to design solutions. In fact, more often than not, designers work to reduce or bound the number of design options they consider, lest they be overwhelmed by the possibilities.

LEARNING DESIGN BY DOING

- Teaching someone *how* to do design is not that simple. Like riding a bike, painting, or dancing, it often seems easier to tell a student, "*Watch* what I'm doing and then try to do it yourself." There is an element of *learning by doing*, which we call a *studio* aspect, in trying to teach any of these activities.
- One of the reasons that it is hard to teach someone how to do design—or to throw a ball or draw or dance—is that people are often better at *demonstrating* a skill than they are at *articulating* what they know about applying their individual skills. Some of the skill sets just mentioned involve physical capabilities, but the difference of most interest to us is not simply that some people are more gifted physically than others. What is really interesting is that a talented softball pitcher cannot tell you just how much pressure she exerts when holding the ball, nor exactly how fast her hand ought to be going, or in what direction, when she releases it.
- In a similar way designers, like dancers and athletes, use drills and exercises to perfect their skills, rely on coaches to help them improve both the mechanical and interpretive aspects of their work, and pay close attention to other skilled practitioners of their art. Indeed, one of the highest compliments paid to an athlete is to say that he or she is "a student of the game."

The Engineering Design process

- There are several ways of describing the design process, of which 3 main categories have been identified. Though abstract and non-prescriptive, the most accurate description is the 'knowledge driven' design process, typified by C-K theory [1]. Here, the information contents of the several spaces are filled in a seemingly random order, the process ends when there is sufficient information in each space to terminate or make a design recommendation.
- Another, and frequently used description, is the divergent-convergent style process, which works along the idea of gaining then evaluating information and, generating then selecting alternatives [2].
- However, by far the most common is the linear type design process model. Table in the next slide contains the various design processes reviewed from the literature. As the models are predominantly of the linear style, column headings were chosen based around broad headings modelled on the Pahl and Beitz systematic design process [3]: 'Need', 'Analysis of Task', 'Conceptual Design', 'Embodiment Design' and 'Detailed Design' in that order. A further column was added to describe post design activities which are often also described by several process models.

1. Hatchuel, A., Weil, B. A new approach of Innovative Design: An introduction to C-K theory. In International Conference on Engineering Design, ICED 03. Stockholm, Aug. 19-21, 2003.
2. Design Council. Double Diamond Design Process [online]. Design Council. 2006. Available from: http://www.designcouncil.org.uk/webdav/
3. Pahl, G., Beitz, W. Engineering Design. (The Design Council, London, 1984).

Engineering design process models

Models	W	X	Y	Z	Need	Analysis of Task Phase	Conceptual Design Phase	Embodiment Design Phase	Detailed Design Phase	Production, Use, Retirement
1967 [22]	D	G	A	B	X	New Product Strategy Development	Idea Generation; Screening & Evaluation	Business Analysis; Development	Testing	Commercialisation
1968 [23]	P	G	A	B	X	Programming; Data collection	Analysis; Synthesis	Development	Communication	X
1974 [24]	D	G	A	M	Need	X	Concepts; Verification	Decisions	X	Manufacture
1980 [25]	D	G	A	M	Societal Need	Recognize & formalize; FR's & constraints	Ideate and Create	Analyze and/or test	Product, prototype, process	X
1980 [26]	D	G	A	B	Opportunity Identification	Design		Testing		Introduction (Launch); Life Cycle Management
1982 [27]	D	G	O	B	X	Planning	Conceptual Design	Embodiment Design	Detail Design	X
1982 [28]	D	G	A	B	X	X	Conceptual Design	Lay-out Design	Detail Design	X
1984 [29]	D	G	A	B	X	Strategic Planning	Concept Generation	Pretechnical Evaluation	Technical Development	Commercialisation
1984 [11]	P	G	O	M	Task	Clarification of Task	Conceptual Design	Embodiment Design	Detailed Design	X
1985 [19]	D	G	O	M	Need	Analysis of Problem	Conceptual Design	Embodiment of Schemes	Detailing	X
1985 [30]	D	G	B	M	Recognise Problem	Exploration of Problem; Define Problem	Search for Alternative Proposals	Predict Outcome; Test for Feasible Alternatives	Judge Feasible Alternatives; Specify Solution	Implement
1986 [31]	D	G	A	B	Ideation	Preliminary Investigation	Detailed Investigation	Development; Testing & Validation	X	Full Production & Market Launch
1987 [32]	D	G	A	M	Recognition of Need	Investigation of Need	Product Principle	Product Design	Production Preparation	Execution
1991 [33]	D	G	A	M	Market	Specification	Concept Design		Detail Design	Manufacture; Sell
1993 [34]	D	G	B	M	Idea, Need, Proposal, Brief	Task Clarification	Conceptual Design	Embodiment Design	Detail Design	X
1995 [35]	D	G	O	M	Assess innovation opportunity	Possible Products	Possible Concepts	Possible Embodiments	Possible Details	New Product
1995 [36]	D	G	A	M	X	Strategic Planning	Concept Development	System-Level Design	Detail Design	Testing & Refinement; Production Ramp-up
1997 [20]	P	G	A	B	Identify Needs; Plan for the Design Process	Develop Engineering Specifications	Develop Concept	Develop Product		X
1997 [37]	P	G	B	B	Concept	Feasibility	Implementation (or realisation)			Termination
1999 [18]	D	G	B	B	Brief/Concept	Review of 'State of the Art'	Synthesis; Inspiration	Experimentation; Analysis / Reflect	Synthesis; Decisions to constraints	Output; X
2000 [38]	D	G	A	B	X	Exploration	Generation	Evaluation	Communication	X
2006 [10]	D	G	A	B	Discover	Define	Develop		Deliver	X
I.I.P	P	S	B	B	Mission Statement	Market Research	Ideas Phase	Concept Phase	Feasibility Phase	Pre Production

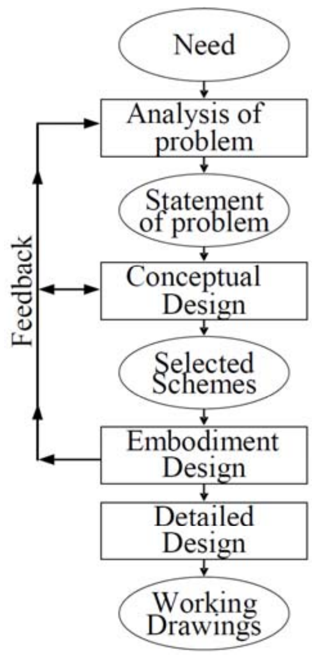
Column 'W' shows the breakdown between the Prescriptive (P) and Descriptive (D) models reviewed
Column 'X' shows the breakdown between the Generic (G) and Specific (S) models reviewed
Column 'Y' shows the breakdown between processes describing Outputs (O), Activities (A) or Both (B) from the models reviewed
Column 'Z' shows the breakdown between processes driven by Market (M), Technology (T) or Both (B) from the models reviewed

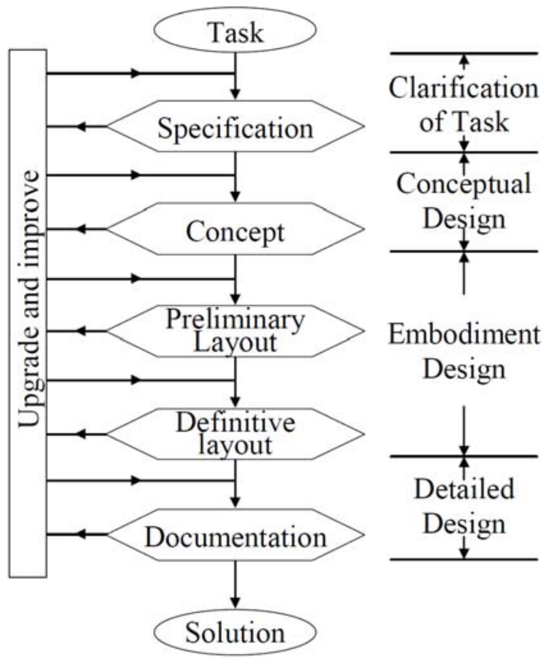
Descriptive or Prescriptive

- There have been many attempts to draw up maps or models of the design process. Some of these models simply describe the sequence of activities that typically occur in designing (describe the elements of the design process); other models attempt to prescribe a better or more appropriate pattern of activities (prescribe what must be done during the design process). [Nigel cross: Engineering Design Methods]
- There is much literature regarding the formalisation of the design process. These are traditionally split into two categories, the descriptive process models (for example see Figure 1) and the prescriptive process models (for example see Figure 2), both of which are commonly represented by flow diagrams. [Howard et al., 2007]
- The descriptive models attempt to replicate the sequence of occurrences throughout design, however, models are said to provide "over simplistic" [1] and "over idealistic" [2] views of the design process.
- The prescriptive models are then built upon these descriptive models in order to guide the designers more efficiently through the design process.

1. Suh, N.P. The principles of design. (Oxford University Press, New York, 1990).
2. Bucciarelli, L.L. Designing engineers. (MIT Press, Cambridge, Mass. ; London, 1994).

Descriptive or Prescriptive





Descriptive Process Model [1] **Prescriptive Process Model [2]**

1. French, M. Conceptual Design for Engineers. (The Design Council, The Pitman Press, 1985).
2. Pahl, G., Beitz, W. Engineering Design. (The Design Council, London, 1984).

Descriptive or Prescriptive

- Although the prescriptive models are by definition not natural design practice, many are so generic and well known that they only remain prescriptive to novice design engineers.
- Perhaps the most famous and commonly quoted of these processes is the Pahl and Beitz systematic design process (Figure 2), now more often used in reference for purposes of descriptive representation.
- When constructing process models there is always trade-off between how useful or prescriptive it can be, against, how inclusive it is to different projects and how user friendly it is to the designer. This results in very similarly structured process models between descriptive and prescriptive.

Describing the Design process

The simplest descriptive model of the design process defines three phases:

- *Generation:* the designer *generates* or creates various design concepts.
- *Evaluation:* the designer *tests* the chosen design against metrics that reflect the client's objectives and against specifications that stipulate how the design must function.
- *Communication:* the designer communicates the final design to the client and to manufacturers or fabricators.

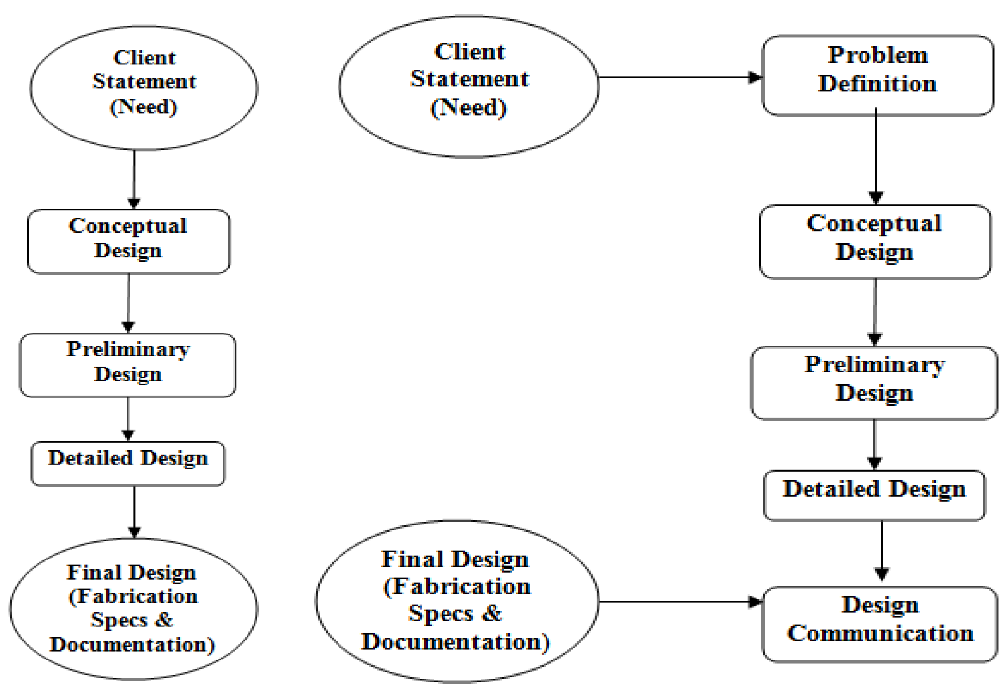
Another three stage model splits up the design process differently: Doing research, creating and implementing a final design, with the contexts providing meanings for these three steps.

While these two models have the virtue of simplicity, they are so abstract that they provide little useful advice on how to do a design.

They also assume the designer understands the client's objectives and the user's needs, and they both accept that the identification of the design problem has already occurred (and is implicitly not a part of design process).

Further, and perhaps most importantly, these models tell us nothing about how we might generate and create designs.

Describing the Design process



3-design phases **5-design phases**

Describing the Design process

Another widely accepted descriptive model of the design process in Fig (i) , with three active stages shown in boxes with round corners.

It also shows the client's problem statement, sometimes identified as the need for a design, as the starting point. The final design (or its fabrication specifications) is the end point.

The model's first phase is conceptual design, in which different concepts (also called schemes) are generated to achieve client's objectives. Thus the major functions and the means to achieve them are identified, as are the spatial and structural relationships of the components. Enough details are worked out so that costs, weights and overall dimensions can be estimated.

With its focus on tradeoffs between high level objectives, conceptual design is clearly the most abstract and open ended part of the design process. The output of the conceptual stage may include several competing concepts. Some argue that the conceptual design should produce two or more schemes since early commitment to or fixation on a single design choice may be mistake. This tendency is so well known among designers that it has produced a saying: "Don't marry your first design idea."

Describing the Design process

The second phase in this model of the design process is preliminary design or the embodiment of schemes.

- We embody or endow design schemes with their most important attributes.
- We select and size the major subsystems, based on lower level concerns that take into account the performance and operating requirements.
- Preliminary design is more technical in nature, so we might use various back-of-the envelope calculations.
- We make extensive use of rules of thumb about size, efficiency, and so on, that reflect the designer's experience. And, in this phase of the design process, we solidify our final choice of design concept.

The final stage of this model is detailed design.

- We now refine the choices we made in preliminary design, articulating the final choice in far greater detail, down to specific part types and dimensions.
- This phase typically follows design procedures that are quite well understood by experienced engineers. Relevant knowledge is found in design codes, hand books, databases, and catalogs.
- Design knowledge is often expressed in specific rules, formulas and algorithms.
- This stage of design is typically done by component specialists who use libraries of standard pieces.

Describing the Design process

The classic model just outlined can be extended to a five-stage model that delineates two additional sets of activities that precede and follow the three-stage model sequence.

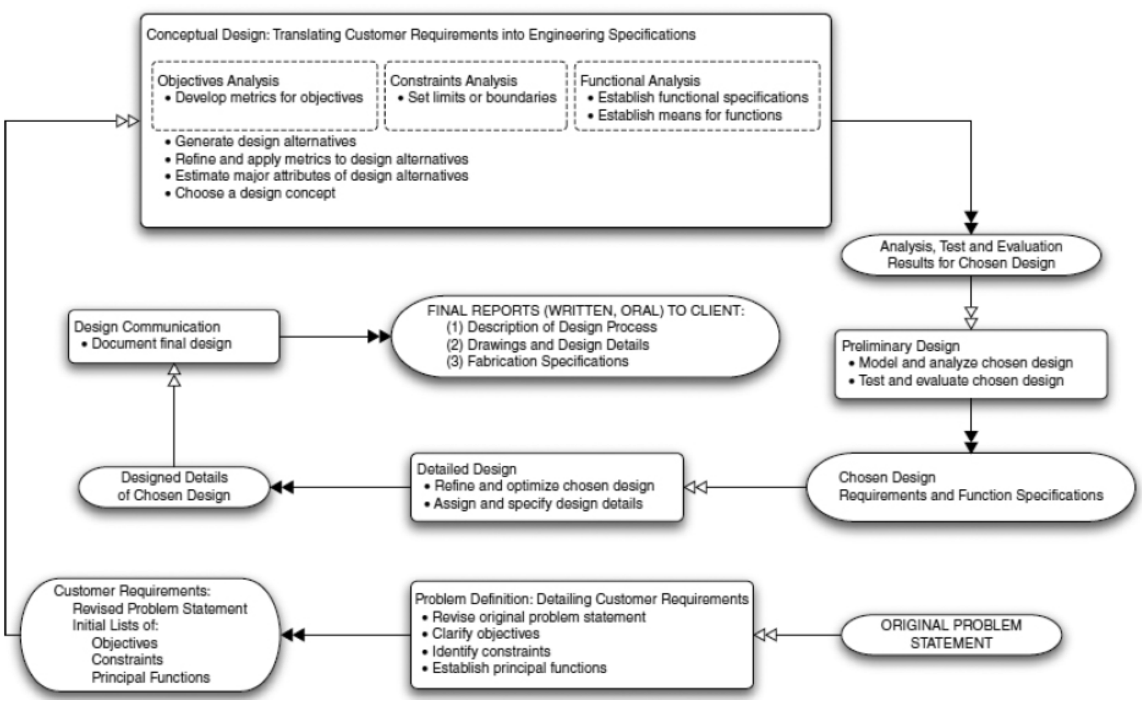
- Problem definition: a pre-processing stage that frames the problem by clarifying the client's original problem statement before conceptual design begins.
- Design communication: a post-processing phase that identifies the work done after detailed design to collect, organize, and present the final design and its fabrication specifications.

Note that in practice much of the documentation will have been developed along the way, so the communication phase is as much about tracking and organizing work products as it is about writing a "new" report from scratch.

This five stage model of the process, displayed in figure 2, is more detailed than the three stage models discussed earlier, but it does not bring us much closer to knowing how to do a design because it too is descriptive.

Prescribing the Design process

A five-stage *prescriptive* model of the design process, presented as a *spiral* to convey the idea that design is not a simple linear sequence of tasks to be done. The design *stages* are in rectangles, and each stage's *outputs* are in ovals.



Prescribing the Design process

Problem definition: We frame the problem by delineating the customer requirements, which means clarifying the client's objectives, identifying constraints, and establishing functions *before* we begin conceptual design

During *problem definition we frame the problem by clarifying* objectives, identifying constraints, establishing functions, and gathering the other information needed to develop an unambiguous statement of a client's wishes, needs, and limits, that is, the *customer requirements.*

Input:	*original problem statement*
Tasks:	*revise client's problem statement*
	clarify objectives
	identify constraints
	establish principal functions
Outputs:	*customer requirements:*
	revised problem statement
	initial list of final objectives
	initial list of constraints
	initial list of principal functions

Prescribing the Design process

Conceptual design: We generate different concepts or schemes to achieve a client's objectives, satisfy constraints, and perform functions. Enough details (e.g., the spatial and structural relationships of the principal components) are worked out to estimate costs, weights, overall dimensions, and so on. Ladder concepts might be an extension ladder, a stepladder, or a rope ladder. We evaluate these concepts first translating the customer requirements (i.e., objectives, constraints, and functions) into *engineering specifications that we use to articulate and benchmark* our design.

In the *conceptual design stage of the design process we* translate the *customer requirements into engineering specifications to generate concepts or schemes of design alternatives or feasible (i.e., acceptable) designs*

Input:	*customer requirements*
	revised problem statement
	initial list of final objectives
	initial list of constraints
	initial list of principal functions
Tasks:	*establish functional specifications*
	establish means for functions
	write limits or boundaries of constraints
	develop metrics for objectives
	generate design alternatives
	refine and apply metrics to design alternatives
	estimate design alternatives' major attributes
	choose a design concept
Output:	*a chosen design*
	analysis, test, and evaluation results for chosen design

Prescribing the Design process

Conceptual design: Continued….

With its focus on trade-offs between high-level objectives, conceptual design is clearly the most abstract and open-ended part of the design process. Its output may include several competing concepts. Some argue that conceptual design *should produce two or* more schemes since early commitment to or fixation on a single design choice may be a mistake. This tendency is so well known among designers that it has produced a saying: "Don't marry your first design idea."

Input: *customer requirements*
revised problem statement
initial list of final objectives
initial list of constraints
initial list of principal functions

Tasks: *establish functional specifications*
establish means for functions
write limits or boundaries of constraints
develop metrics for objectives
generate design alternatives
refine and apply metrics to design alternatives
estimate design alternatives' major attributes
choose a design concept

Output: *a chosen design*
analysis, test, and evaluation results for chosen design

Prescribing the Design process

Preliminary design or embodiment of schemes: Here we flesh out our proposed concepts, that is, we embody or endow design schemes with preliminary versions of their most important attributes. We select and size the major subsystems, based on lower-level concerns that take into account the performance and operating requirements. For a stepladder, for example, we size the side rails and the steps, and perhaps decide how to fasten the steps to the side rails.

Preliminary design is definitely more "technical": We might do back-of-the-envelope or computer calculations. We make extensive use of rules of thumb about size, efficiency, and so on, that reflect our design experience.

In the *preliminary design phase we identify and* preliminarily size/estimate the principal attributes of the chosen design concept or scheme.

Input:	*a chosen design* *specifications*
Tasks:	model and analyze chosen design test and evaluate chosen design
Output:	analysis, testing, evaluation of chosen design

Prescribing the Design process

Detailed design: We now articulate our final design in much greater detail, refining the choices we made in preliminary design down to specific part types and dimensions. We use detailed design knowledge and procedures expressed in specific rules, formulas, and algorithms that are found in design codes (e.g., the ASME Pressure Vessel and Piping Code, the Universal Building Code), handbooks, databases, and catalogs.

During *detailed design we refine and optimize the final design and* assign and fix the design details.

Input:	*the analyzed, tested, evaluated design*
Tasks:	*refine, optimize the chosen design* *assign and specify the design details*
Output:	*proposed design and design details*

Prescribing the Design process

Finally, during the *design communication phase we document the* fabrication specifications and their justification.

Design communication: We now spell out and present our design process, the resulting final design, and its fabrication specifications. In practice, the designer will usually have already developed much of the documentation along the way, and this communication phase will be more about tracking and organizing prior work products than writing a "new" report from "scratch."

Input:	*proposed design and design details*
Task:	*document the final design*
Outputs:	*final written, oral reports to client containing:* • (1) description of design process • (2) drawings and design details • (3) fabrication specifications

Describing and Prescribing a Design process

We have depicted the design process in Figure as a *spiral for several* reasons. Design processes are often described as a linear sequence that seems to imply: do task 1, then do task 2, then do task 3.

In practice, we actually keep completed phases and tasks in our minds as our design unfolds, and we refer back to them regularly. We may wonder while deep in a design project, "Why are we doing this?" By looking back at a project's objectives or constraints, or at a design decision we've already made, we can answer this question.

There are two other important elements that we hope the spiral depiction will help reinforce: *feedback and iteration. Feedback occurs in two* notable ways in the design process. First, *internal feedback comes during* the design process as test and evaluation results are used to *verify that* the design performs as intended. This feedback may come from the client and from internal customers, such as manufacturing (e.g., can it be made?) and maintenance (e.g., can it be fixed?). Second, *external feedback comes after a design reaches its market and user feedback validates (or not) a successful design.*

Describing and Prescribing a Design process

Iteration occurs when we repeatedly apply a common method or technique at different points in a design process. For example, we might write equilibrium equations for an entire structure, and then at a lower *level of abstraction (i.e., on a different scale) we write equilibrium* equations for structural components). Similarly, as we fix more details in a design and become less abstract, and we might review and reestablish means for our functions. Again, we always want to keep in mind the original objectives, constraints, and functions as we get closer to our final design. This may also mean that we have to do some redesign, in which case we will certainly repeat tasks such as analyzing the design or testing and evaluating the design.

Given that there are feedback loops and that we will reiterate some tasks, why didn't we include them in Figure? As important as feedback and iteration are, it is also important not to be overly distracted by these adaptive characteristics when learning about and doing design for the first time.

We now have a "checklist" we can use to ensure that we have done all of the "required" steps. Lists like this are often used by design organizations to specify and propagate approaches to design within their firms. However, we should keep in mind that this and other detailed elaborations add to our understanding of the design process only in a limited way. At the heart of the matter is our ability to model the tasks done within each phase of the design process.

Generic or Specific

The level of complexity of a design process model is of great importance and has large impact on its value.

Simple models generally follow a linear route with fewer, more broadly defined steps leading from the start to finish. These models are easy to apply to the variety of different design projects that may be encountered, making them more user friendly to the designer. Though the field of design research contains a number of these simplistic design process models, very few are adopted by industry as they are considered too generic [1].

Instead of actively guiding the designer these are approaches that are often used as management and documentation tools rather than as actual design aids. It is interesting to note that specific solutions to design processes are more frequently created than they are published. During the planning phase of industrial design projects, it is common to construct gant-charts, timelines and stage gates to map the process ahead. This can be time consuming, particularly when done without the use of a generic guideline. As a solution to this, engineering companies often produce their own generic design processes to suit capabilities, product ranges and customer base, such as the Rolls Royce Derwent Process [2].

1. Cross, M., Sivaloganathan, S. A methodology for developing company-specific design processmodels. Journal of Engineering Manufacturing, 2005, 219(B3), 265-282.
2. Agouridas, V., Winand, H., Mckay, A. and de Pennington, A. Early alignment of design requirements with stakeholder needs. Proceedings of the Institution of Mechanical Engineers Part B journal of Engineering Manufacture, 2006, 220(9), 1483-1507.

Generic or Specific

These design processes can be particularly effective if constructed on the basis of best known practice and are re-evaluated and updated on a regular basis. An example of a company specific innovation process can be seen at the bottom Table, labeled IIP (Industrial Innovation Process).

In both generic and specific design process models, few aid the actual ‘creating’ aspect of design further than suggesting activities, tools or techniques that can be applied, or the deliverables that should be achieved, at each particular stage. Several authors have attempted to fill this gap, though these may be considered to be more exclusive to the difficult conceptual design activities, rather than the rest of the extensive and difficult activities involved in engineering design. These processes neatly span the analysis of task, conceptual design and embodiment design phases as shown in Table.

A recently introduced tool, PRIZM [1], is a good example of this type of support process. Based around principles from the TRIZ [2] contradiction matrix, the process guides the user though a quest to reach the desired requirements and the ideal final result. Interestingly, here the requirements are placed at the end of the process as aims, rather than functional requirements typically found at the beginning of an engineering design process.

1. Pahl, A. PRIZM: TRIZ and transformation In ETRIA World Conference: TRIZ Future 2006, Vol. 2: Practitioners Contribution. Kortrijk, Belgium, Oct 9-11. p19-28
2. Al'tshuller, G.S. The innovation algorithm : TRIZ, systematic innovation and technical creativity. (Technical Innovation Center, Worcester, Mass., 1999).

Output or Activity

Not only do the phases of the design process take on different titles, covering slightly different amounts of the actual design process or viewing it from a slightly different perspective, within the phases authors vary on whether to prescribe or describe the process in terms of outputs or activities.

It becomes evident from this that descriptive models tend to use activities to distinguish the different phases of the design process. Most prescriptive models provide both output and activity; this is also quite typical of flow chart and the stage gate models such as the IIP process (shown in table).

Whilst several design activities such as 'generate' and 'evaluate' can also be found in the creative process, the outputs described are not, as the creative processes tend to only describe activities or cognitive phases. Though the design outputs can also be deemed information inputs to following phases, Black [1] is the only author that donates the input of 'inspiration', which is directly linked to the creative process and occurs at a specific point relative to the design process. Interestingly this actually refers to a textile fashion design process rather than an engineering design process.

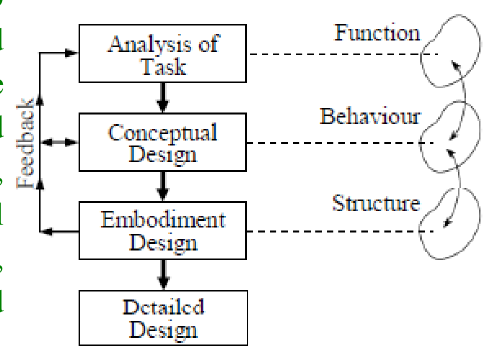
1. Black, S. The Fashion and Textile Design Process. London Collage of Fashion, University of the Arts London, 1999).

Market or Technology

The sequence of stages, activities and outputs will be subtly different from project to project.

The types of generic design process models try best to encompass these subtle changes through the broad headings of stages, thought there will always be exceptions. In all of the process models evaluated (Table), processes proceed in the same direction, moving from a need or analysis of task to conceptual design. For the majority of cases this may be true, where 80% of projects are driven by a realised problem or market space [1].

However there are also cases of design projects driven by the available technology. Though not usually stated in literature, the design process for a technology driven project has a variety of differences, particularly at its starting point. To emphasize this, consider Gero's FBS framework [2] which represents the core elements of Mechanical Engineering Design.



1. Ullman, D. The Mechanical Design Process. (McGraw-Hill International Editions, 1997).
2. Gero, J.S. Situated function–behaviour–structure framework. Design Studies, 2004, 25(4), 373.

Market or Technology

The Function (F) of a product will be decided early on in an ideal market driven process (Figure 1); were functional requirements are formed in the 'Analysis of Task Phase'. During the 'Conceptual Design Phase' the designers will produce concepts which have Behaviours (B) that will hopefully satisfy the functional requirements. During the 'Embodiment Design Phase' the physical Structures (S) of these concepts are realized.

In contrast, technology driven projects (Figure 2) are based around the use of behaviors exhibited by other structures. This may be a company trying to exploit one of its patents, or an inventor attempting to make use of an interesting shape or mechanism. Here the projects' begin in the conceptual design phase where the behavior of a known technology is taken. In a seemingly random sequence, a function is derived from the behavior to fit a particular market space, whilst a structure is developed by which the behavior can be embodied.

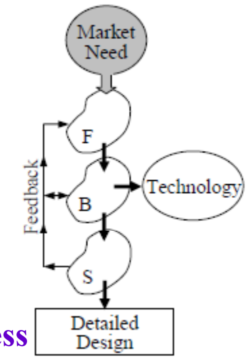


Figure 1.
Market driven process

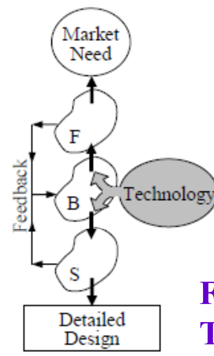


Figure 2.
Technology driven process

The four stage Creative process

This is the most recognized of all creative process models and detailed a four stage creative process of: Preparation – Incubation – Illumination – Verification. This is a linear process and contains no feedback loops.

Preparation:

This regards the information and knowledge inputs into the process, but also the problem structuring and sense making. This is the somewhat overlooked stage of the process that this research hopes to improve. Its relevance is obvious in engineering design as it parallels the common, Problem Definition/Clarification of task stage of the renowned systematic processes.

Incubation:

A relatively unexplained cognitive process where information is left for a period of time to either: remove mental bocks (e.g. writers block) resulting in the assimilation of an adequate association (illumination), and/or, waiting for stimulating information (e.g. waiting for inspiration) to arise and spark an adequate association [1]. This stage of the creative process does not always occur, or may occur but instantaneously. The incubation period may be the difference between producing creative solution and producing routine solutions.

1. Howard, T.J., Culley, S.J. and Dekoninck, E. Information as an input into the creative process. In 9th International Design Conference DESIGN 06. Dubrovnik. 549-556

The four stage Creative process

Illumination:

This is not so much a stage of the creative process but rather an output, when a promising idea has been realized. It is associated with a feeling of excitement and accomplishment. This is often referred to as the 'Eureka' or 'Ah ha' moment. In the authors [1] experience this is not always so clear cut. Often the Ah ha feeling can come later when understanding an idea. It is difficult to distinguish between the illumination experience that occurs in a creative process (when something is created i.e. a concept) and the illumination when gaining understanding i.e. when solving a logic puzzle, a maths problem or understanding a problem structure or evaluation method.

Validation:

This is where the solution from the illumination phase is checked for its appropriateness. This phase is less important with regards to this research as it lies after the process of idea generation. The validation, evaluation and testing of idea/concepts is easier and less mystical than the process of producing them.

1. Howard, T.J., Culley, S.J. and Dekoninck, E. Creativity in the engineering design process. In International Conference on Engineering Design, ICED'07/887. PARIS..

Creative process vs Design process

Paradoxically the confusion between the design process and the creative process is more than understandable given their similarity. The following will highlight several key crossovers and differences between the two processes, before suggesting how they may fit together forming an integrated descriptive process model.

Similarities:

- There are several commonalities between the two processes, in particular the notation or the form that the models are presented.
- The literature regarding both Creative and Design processes mainly consists of linear type models. This is done in attempt to formalize these quite erratic processes which both contain a substantial cognitive element.
- Furthermore, the literature regarding both processes also describes two other main types of process model, one involving divergent-convergent processes, the other describing information spaces (design) and, problem and solution spaces (creativity).
- Another notable similarity between the processes is the need for information and its analysis and understanding at the start of the process (analysis of task phase).

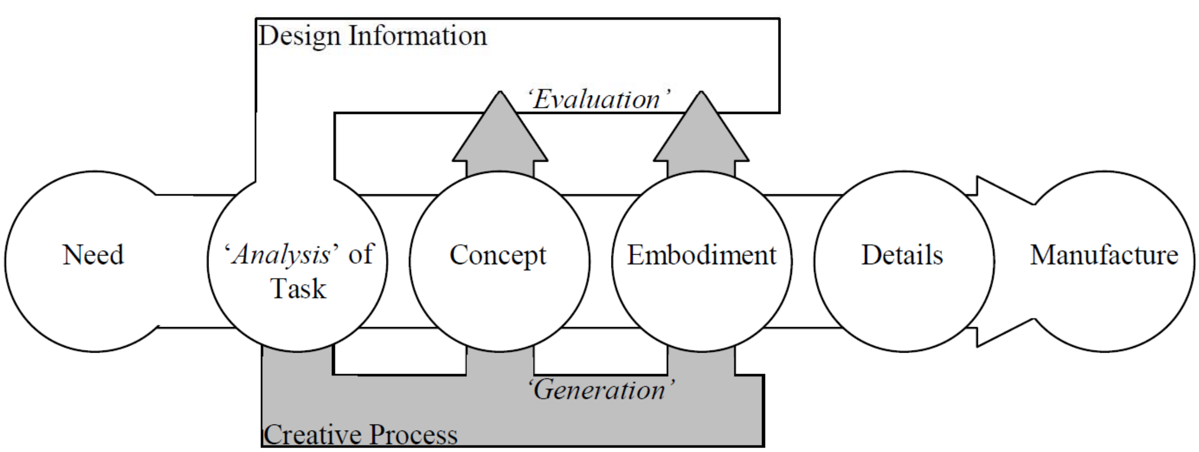
Creative process vs Design process

Differences:

- The embodiment design phase is defined by noticeably different activities and outputs to the equivalent stage of the creative process. Preceding the embodiment phase would be an evaluation and selection of a concept of which to embody, this phase is therefore all about adding the physical form to the concept. This phase of the creative process is simply the evaluation of the idea/solution generated.
- Following this stage is the detailed design phase which produces formal communication documents for manufacture/implementation, unlike the creative process where this stage does not always exist and involves the less formal externalizing of the idea.
- It is thus argued that the main difference between the design process and the creative process is seen within the scale and scope of the processes.
- In the completion of a successful design process, plans of the product or process would be laid out for the user, manufacturer, assembler, etc. Its process steps will consist of logical assumptions, evaluation, decisions and rejected solutions on route the final recommendation. The creative process simply addresses the generation and validation of single ideas.

Integrated creative-design process model

It is clear from the previous analysis that the creative process is a vitally important subset of the design process. Figure suggests how the creative process may be integrated into the market driven design process. Here the processes are joined at the common first phase – the 'analysis of task' phase. It is emphasized that the creative process manifests in both the conceptual design phase and the embodiment design phase. Each loop of the creative process within these phases will first generate information as an idea, and then evaluate it which adds to the design information and may re-clarify the task.



The Design process

“Design a safe ladder”

- It's not a big surprise that a whole bunch of questions immediately come to mind. Typically, design projects start with a statement that talks about a client's intentions or goals, the design's form or shape, its purpose or function, and perhaps some things about legal requirements.
- That statement then leads to the designer's first task: to *clarify* what the client wants in order to translate those wishes into meaningful *objectives* (goals), *constraints*(limits), and *functions* (what the design has to do). This clarification task proceeds as the designer asks the client to be more precise about what she really wants.
- Asking questions is an integral part of the design process. Aristotle noted long ago that knowledge resides in the questions that can be asked and the answers that can be provided. By looking at the kinds of questions that we can ask, we can articulate the design process as a series of design tasks.

“Design a safe ladder”

For example, with regard to designing a ladder, we *establish a client's objectives* when we ask questions such as:

- Why do you want another ladder?
- How will the ladder be used?
- What market we are targeting?

identify the constraints that govern the design with questions such as:

- What does “safe” mean?
- What's the most you're willing to spend?

establish functions that the design must perform and suggest *means* by which those functions can be performed with questions such as:

- Can the ladder lean against a supporting surface?
- Must the ladder support someone carrying something?

establish specifications for the design with questions such as:

- How much weight should a safe ladder support?
- How high should someone on the ladder be able to reach?

"Design a safe ladder"

generate design alternatives with questions such as:

- Could the ladder be a stepladder or an extension ladder?
- Could the ladder be made of wood, aluminum, or fiberglass?

model and *analyze* the design with questions such as:

- What is the maximum stress in a step supporting the "design load"?
- How does the bending deflection of a loaded step vary with the material of which the step is made?

test and *evaluate* the design with questions such as:

- Can someone on the ladder reach the specified height?
- Does the ladder meet OSHA's safety specification?

refine and *optimize* the design with questions such as:

- Are there other ways to connect the steps?
- Can the design be made with less material?

document the design process and *communicate* the completed design with questions suchas:

- What is the justification for the design decisions that were made?
- What information does the client need to fabricate the design?

"Design a safe ladder"

- Thus, the questions we asked about the design establish steps in a process that move us from a problem statement through increasing levels of detail toward an engineering solution. The idea is to translate a client's wishes into a set of *specifications* that state in engineering terms how the design is to function or behave. These are benchmarks against which we can measure a design's performance.
- With specifications in hand, we generate different *concepts* of how the design might work or look, that is, we create *design alternatives*. Then we choose one concept (say, a stepladder) and *build and analyze a model* of that concept, *test and evaluate* that design, *refine and optimize* some of its details, and then *document* the justification for the stepladder's final design and its fabrication specifications.
- Some of the early clarification questions clearly connect to later tasks in the process. We make choices, analyze how competing choices interact, assess trade-offs in these choices, and evaluate the effect of these choices on our top-level goal of designing a safe ladder.
- For example, the ladder's form or shape and layout are strongly related to its function.
- Similarly, the weight of the ladder has an impact on how it can be used.
- The material of which a ladder is made affects not only its weight, but also its cost and its feel.

"Design a safe ladder"

- Some of the questions in the later design tasks can be answered by applying mathematical models such as those used in physics. For example, Newton's equilibrium law and elementary statics can be used to analyze the stability of the ladder under given loads on a specified surface. We can use beam equations to calculate deflections and stresses in the steps as they bend under the given foot loads. *But there are no equations that define the meaning of "safe," or of the ladder's marketability, or that help us choose its color*. Since there are no equations for safety, marketability, color, or for many of the other issues in the ladder questions, we must find other ways to think about this design problem.

- It is clear that we will face a vast array of choices as our design evolves. In our ladder design, we have to choose a *type* of ladder. We then have to decide how to fasten the steps to the ladder frame. These choices will be influenced by two things: (1) the desired behavior (e.g., although the ladder itself may flex, we don't want individual steps to have much give with respect to the ladder frame); and (2) manufacturing or assembly considerations (e.g., would it be better to nail in the steps of a wooden ladder, use dowels and glue, or nuts and bolts?). Note that we may decompose the ladder into its components to select among particular design choices.

"Design a safe ladder"

- As we work through these design questions and tasks, we are always communicating with others about the ladder and its various features. When we question our client about the ladder's desired properties, or the laboratory director about evaluation tests, or the manufacturing engineer about the feasibility of making certain parts, we are interpreting aspects of the ladder design in terms of *languages* and parameters that these experts use in their own work: We draw pictures in *graphical languages*; we write and apply formulas in the *language of mathematics*; we ask verbal questions and provide *verbal descriptions*; and we use *numbers* all of the time to fix limits, describe test results, and so on. Thus, the design process can't proceed without recognizing different design languages and their corresponding interpretations.
- This simple design problem illustrates how we might *formalize* the design process to make explicit the design tasks that we are doing. We are also *externalizing* aspects of the process, moving them from our heads into a variety of recognizable languages to be able to communicate with others. Thus, we learn two important lessons from our ladder design project:
- *The designer must fully understand what is needed from the final design.*
- *The designer must be able to translate the client's wishes into the languages of engineering design (e.g., words, pictures, numbers, rules, formulas, and properties) in order to model, analyze, test, evaluate, refine, optimize, and finally document the design.*