Chapter 2
Design Methodologies

Abstract Engineering design is a formal discipline within the field of engineering. The study of design methodologies is a sub-discipline and requires the use of unique modes of thought and the application of a number of specific features to ensure that designs are both repeatable and result in products that are useful for a specified period of service. A methodology is purposefully positioned in a formal hierarchy of scientific approaches, supported by a specific paradigm and philosophy while acting as the framework for more detailed methods and techniques. There are a number of unique engineering design methodologies, frameworks, and models that have evolved to provide the structural framework for the applicable design processes, methods, and techniques. The Axiomatic Design Methodology provides a systems-based framework for design that permits design alternatives to be evaluated based on quantitative analysis, eliminating the need for messy qualitative and cost-based models.

2.1 Introduction to Design Methodologies

This chapter will introduce a number of engineering methodologies that may be used to invoke repeatable processes for the purposeful design of *engineering systems*. The term *engineering systems* may be used either as (1) a noun—"systems that fulfill important functions in society" (de Weck et al. 2011, p. xi) or (2) a verb—"new ways of analyzing and designing them" (de Weck et al. 2011, p. xi). In the verb form *engineering systems* addresses technology and technical systems by harmonizing them with the organizational, managerial, policy, political, and human factors that surround the problem while allowing the stakeholder's needs to be met while not harming the larger society. The analysis and design efforts for engineering systems require formal methodologies in order to implement repeatable processes that both invoke proven engineering processes and are subject to efforts to improve those processes.

The chapter will begin by discussing the discipline of engineering design and its sub-disciplines of design theory and design methodology. The features and modes of thought that support engineering design endeavors are reviewed.

K.M. Adams, *Non-functional Requirements in Systems Analysis and Design*,
Topics in Safety, Risk, Reliability and Quality 28,
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The next section defines the terminology required to understand how a methodology is positioned in the scientific paradigm. The section that follows provides a formal hierarchical relationship between the terms.

This is followed by a section that presents seven historically significant engineering design methodologies. The basics tenets of each methodology, including the major phases, stages, and steps associated with each model are reviewed. References for further study of each methodology are provided.

The chapter concludes by presenting a formal methodology for accomplishing engineering technical processes, the Axiomatic Design Methodology. The Axiomatic Design Methodology provides the framework through which system functional and non-functional requirements are satisfied by design parameters and process variables in the system design.

The chapter has a specific learning goal and associated competencies. The learning goal of this chapter is to be able to identify describe engineering design, its position in the scientific paradigm and a number of specific methodologies for conducting engineering design endeavors. This chapter's goal is supported by the following objectives:

- Describe engineering design as a discipline.
- Differentiate between design theory and design methodology.
- Describe the desirable features of engineering design.
- Describe the double-diamond model of design.
- Construct a hierarchical structure that includes a paradigm, philosophy, methodology method, and technique.
- Differentiate between the seven historical design methodologies.
- Describe the major features of the Axiomatic Design Methodology.

The ability to achieve these objectives may be fulfilled by reviewing the materials in the chapter topics which follow.

2.2 Introduction to the Discipline of Engineering Design

The study of engineering design is a discipline within the broader field of engineering. The scholarly journals in the discipline that address transdisciplinary engineering design topics are presented in Table 2.1.

Design theory (or design science) and design methodology represent two academic subjects within the discipline of engineering design that each have their own unique viewpoints and research agendas. The two subject areas are simply defined as follows:

- Design theory—*is descriptive as indicates what design is* (Evbuomwan et al. 1996, p. 302).
- Design methodology—*is prescriptive as it indicates how to do design* (Evbuomwan et al. 1996, p. 302)

Table 2.1 Scholarly journals for engineering design

Journal (ISSN)	Description	Publication period/issues
Journal of Engineering Design (0954–4828)	Articles on research into the improvement of the design processes/practices in industry and the creation of advanced engineering products, and academic studies on design principles	1990-present, 4/year
Research in Engineering Design (0934–9839)	Research papers on design theory and methodology in all fields of engineering, focusing on mechanical, civil, architectural, and manufacturing engineering	1989-present, 4/year
Design Issues (0747–9360)	Examines design history, theory, and criticism. Provokes inquiry into the cultural and intellectual issues surrounding design	1984-present, 4/year
Design Studies (0142–694X)	Approaches the understanding of design processes from comparisons across all domains of application, including engineering and product design, architectural and urban design, computer artefacts and systems design	1979-present, 6/year
Journal of Mechanical Design (1050–0472)	Serves the broad design community as the venue for scholarly, archival research in all aspects of the design activity with emphasis on design synthesis	1978-present, 12/year
Journal of Research Design (1748–3050)	Interdisciplinary journal, emphasizing human aspects as a central issue of design through integrative studies of social sciences and design disciplines	2001-present, 4/year

This chapter is focused upon design methodology—the *how to* of design. More precisely, how does a specific engineering design methodology sequence and execute the technical processes of the design stage of the systems life cycle which were described at the end of Chap. 1? The purpose of each of the technical processes required for the design stage are established in *IEEE Standard 15288* (2008) and presented in Table 2.2 (repeated from Table 1.5).

The section that follows will discuss the features and properties that a design methodology must possess in order to effectively execute the eight processes in Table 2.2.

2.2.1 Features that Support Design Methodologies

> Self conscious design contains many well-known activities such as decision making, optimization, modeling, knowledge production, prototyping, ideation, or evaluation. However, it cannot be reduced to any one of them or all of these activities (e.g., decisions are made in design, but design is more than decision making). Thus, design theory is not about modeling everything that one can find in a design practice, its goal is to precisely

Table 2.2 Technical processes in the design stage

Technical process	Purpose
1. Stakeholder requirements definition	"Define the requirements for a system that can provide the services needed by users and other stakeholders in a defined environment" IEEE and ISO/IEC (2008, p. 36)
2. Requirements analysis	"Transform the stakeholder, requirement-driven view of desired services into a technical view of a required product that could deliver those services" IEEE and ISO/IEC (2008, p. 39)
3. Architectural design	"Synthesize a solution that satisfies system requirements" IEEE and ISO/IEC (2008, p. 40)
4. Implementation	"Realize a specified system element" IEEE and ISO/IEC (2008, p. 43)
5. Integration	"Assemble a system that is consistent with the architectural design" IEEE and ISO/IEC (2008, p. 44)
6. Verification	"Confirm that the specified design requirements are fulfilled by the system" IEEE and ISO/IEC (2008, p. 45)
7. Transition	"Establish a capability to provide services specified by stakeholder requirements in the operational environment" IEEE and ISO/IEC (2008, p. 46)
8. Validation	"Provide objective evidence that the services provided by a system when in use comply with stakeholders' requirements, achieving its intended use in its intended operational environment" IEEE and ISO/IEC (2008, p. 47)

> address issues that are beyond the scope of the classical models that accompany its constituent activities (decision making, prescriptive models, hypothetic-deductive model and others). The questions this goal raises are of course: What, then, are the core phenomena of Design? Is Design driven by novelty, continuous improvement, creativity, or imagination? (Le Masson et al. 2013, pp. 97–98).

There are a number of features (or properties) that should be possessed by each and every design methodology. The features are prominent elements characteristic of each and every successful engineering design endeavor. While most design methodologies do not formally address these features, they are unwritten elements that the both the methodology and team members must invoke during the design endeavor. The features are foundational to every engineering design methodology and ensure that the methodology effectively and efficiently executes the eight technical processes of the design stage. Ten features that support design methodologies are presented in Table 2.3 (Evbuomwan et al. 1996).

All of the features in Table 2.3 represent unique facets (i.e., one side of something many-sided) that the design methodology must contain in order to effectively and efficiently execute the technical processes of the design stage during the systems life cycle. The first letters of each of the features may be combined to create the acronym *ERICOIDITI*. The features are depicted in Fig. 2.1.

The next section will address the types of thought invoked during the execution of a design methodology.

Table 2.3 Desirable features that support design methodologies

Feature	Description
Exploratory	Design is a formal professional endeavor requiring specific knowledge, skills, and abilities
Rational	Design is rational involving logical reasoning, mathematical analysis, computer simulation, laboratory experiments and field trials, etc
Investigative	Design requires inquiry into the stakeholder's requirements and expectations, available design techniques, previous design solutions, past design failures and successes, etc
Creative	Design requires know-how, ingenuity, memory, pattern recognition abilities, informed solution scanning, lateral thinking, brainstorming, analogies, etc
Opportunistic	Both top-down and bottom-up approaches are used by the design team based upon the situation presented
Incremental	Improvements or refinements are proposed during the design process in order to achieve an improved design
Decision-making	Design requires value judgements. Courses of action and selection from competing solutions are based on experience and criteria provided by the system's stakeholders
Iterative	Design is iterative. Artifacts are analyzed with respect to functional and non-functional requirements, constraints, and cost. Revisions are based on experience and feedback mechanisms
Transdisciplinary	Design of engineering systems requires a transdisciplinary team
Interactive	Design is interactive. The design team is an integral part of the actual design

2.2.2 Thought in a Design Methodology

Design teams invoke different modes of thinking during execution of a design methodology. The particular type of thought is a function of the execution point in the methodology and the unique process being utilized. Two major modes of thought exist in most methodologies—divergence and convergence, which are inter-related and complementary. The sequence of divergence and convergence is represented by the *Double-diamond Model of Design* (Norman 2013) depicted in Fig. 2.2.

The idea behind the Double-diamond is that when a design idea is conceived, the first action is to expand the team's thinking (divergence) allowing the team to explore all of the issues related to the design idea. Once all of the ideas related to the design idea are surfaced and reviewed, the team may then focus their thinking (convergence) on what the design should do. After the team has decided what the design should accomplish, the team must once again expand their thinking (divergence) to review all of the possible solution alternatives for the system. Finally, once all of the solution alternatives have been identified and reviewed, the team may focus (convergence) on a single satisficing solution.

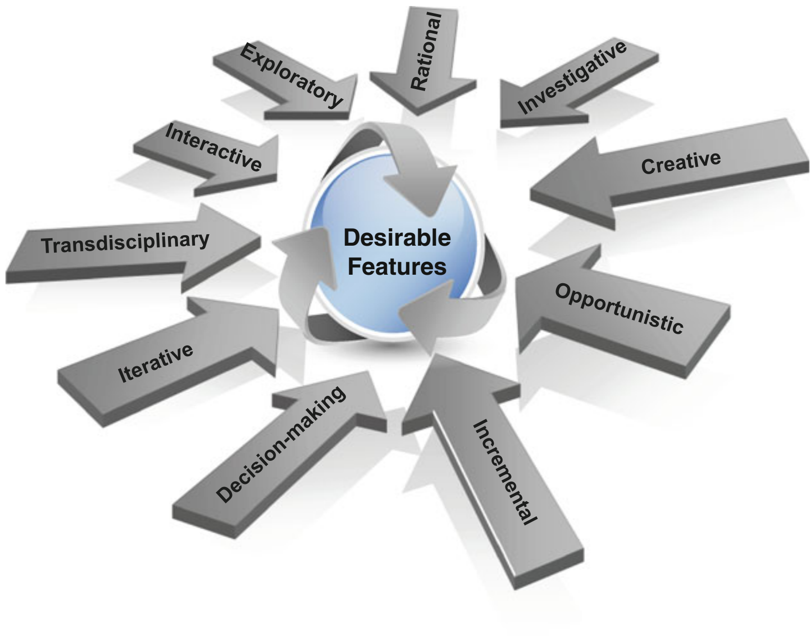


Fig. 2.1 Desirable features of engineering methodologies

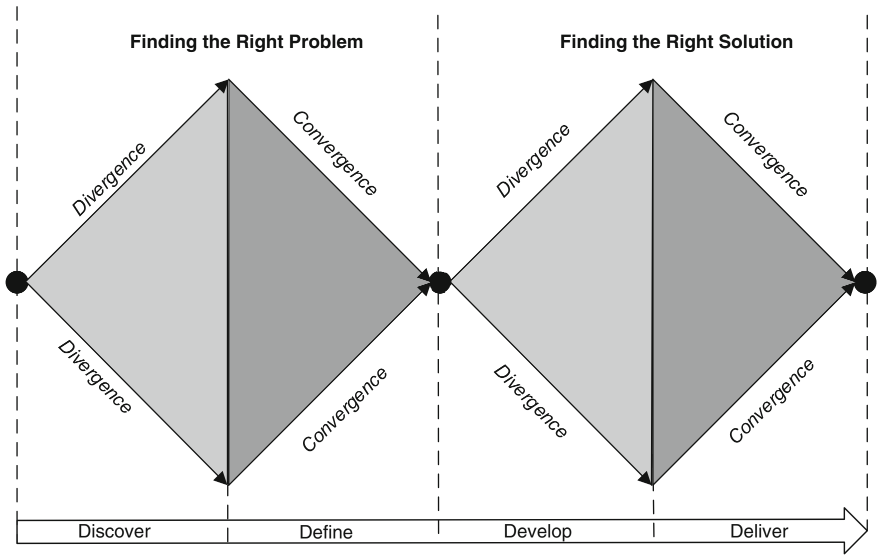


Fig. 2.2 Double diamond model of design

2.2.3 Synthesis of Thought and Features that Support All Engineering Design Methodologies

To be successful, the design team must invoke both the desirable features and the two modes of thinking as a matter of routine during the execution of the technical processes within the design methodology adopted for the design endeavor. The ability to apply thinking modes required for the technical processes and to include each of the desirable features provides a solid framework for the design effort. Figure 2.3 is a depiction of the synthesis of thought and desirable features that provide support for all engineering design methodologies.

The section that follows will review the terminology and relationships associated with a methodology.

2.3 Methodological Terms and Relationships

In order to better understand where a methodology fits in the scientific hierarchy, the next section will review and define key terms that include paradigm, philosophy, methodology, method, and technique. The section will also present a structured relationship between the terms.

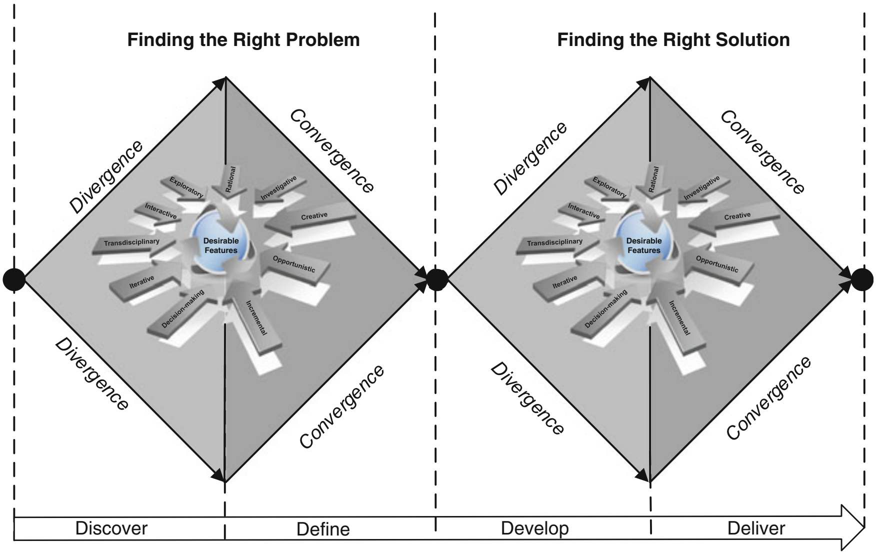


Fig. 2.3 Synthesis of features and thought

2.3.1 Paradigm

Paradigm is a term attributed to the physicist and modern Philosopher of Science Thomas Kuhn [1922–1996]. Two definitions for paradigm are presented in Table 2.4.

From these definitions a composite definition for paradigm is developed which states that a paradigm is *the whole network of theories, beliefs, values, methods, objectives, professional and educational structure of a scientific community.* As such the paradigm associated with the field of engineering and the discipline of engineering design requires the paradigm to contain:

- The network of beliefs and values,
- The professional and education structure, and
- The worldview for a scientific community.

2.3.2 Philosophy

Two relevant definitions of philosophy are presented in Table 2.5.

From these definitions a composite definition for philosophy states that philosophy is *the logical analysis of the concepts, propositions, proofs, theories of science, as well as of those which we select in available science as common to the*

Table 2.4 Definitions of paradigm

Definition	Source
"The entire constellation of beliefs, values, techniques, and so on shared by the members of a given community"	Kuhn (1996, p. 175)
"The whole network of theories, beliefs, values, methods, objectives, professional and educational structure of a scientific community"	Psillos (2007, p. 174)

Table 2.5 Definitions of philosophy

Definition	Source
"Philosophy deals with science only from the logical viewpoint. Philosophy is the logic of science, i.e., the logical analysis of the concepts, propositions, proofs, theories of science, as well as of those which we select in available science as common to the possible methods of constructing concepts, proofs, hypotheses, theories"	Carnap (1934, p. 6)
"The different ways in which we classify whatever the world, or any world, contains"	Proudfoot and Lacey (2010, p. 302)

possible methods of constructing concepts, proofs, hypotheses, theories. The application of the notion of *philosophy* to the field of engineering and discipline of engineering design requires the supporting philosophy to contain:

- The body of theoretical knowledge that underpins the worldview,
- Is at the highest level of abstraction, and
- Contains the systems laws, principles, theorems, and axioms used by the scientific community to address the world.

2.3.3 Methodology

Three relevant definitions of a methodology are presented in Table 2.6.

From these definitions a composite definition for methodology states that a methodology is *the systematic analysis and organization of the rational and experimental principles and processes which guide a scientific inquiry*. The application of the definition for methodology to the field of engineering and the discipline of engineering design requires the supporting methodology to be:

- It is one of the systemic approaches that is used to guide scientific endeavor, and
- Is a blend of more than one systemic methodology, becoming increasingly specific until it becomes a unique methodology.

2.3.4 Method or Technique

Both method and technique are terms that require definition in order to both differentiate them and provide for a common language for engineering design.

- **Method**: A systematic procedure, technique, or mode of inquiry employed by or proper to a particular discipline or art (Mish 2009, p. 781).
- **Technique**: A body of technical methods (as in a craft or in scientific research) (Mish 2009, p. 1283).

Table 2.6 Definitions of methodology

Definition	Source
"The philosophical study of the scientific method."	Honderich (2005, p. 598)
"A structured set of methods or techniques to assist people in undertaking research or intervention."	Mingers (2003, p. 559)
"The systematic analysis and organization of the rational and experimental principles and processes which guide a scientific inquiry, or which constitute the structure of the special sciences more particularly."	Runes (1983, p. 212)

The section that follows will provide a hierarchical relationship between each of the terms utilized in the description of an engineering methodology.

2.3.5 Relationship Between Scientific Terms

There is a distinct relationship between the terms paradigm, philosophy, methodology, method, and technique. Dr. Peter Checkland, acknowledged as a leader in the development of systemic methodologies states:

> I take a methodology to be intermediate in status between a philosophy, and a technique … a technique is a precise specific programme of action which will produce a standard result … A methodology will lack the precision of a technique but will be a firmer guide to action than a philosophy (Checkland 1999, p. 162).

The relationships between a paradigm, philosophy, methodology, method, and technique are depicted in Fig. 2.4.

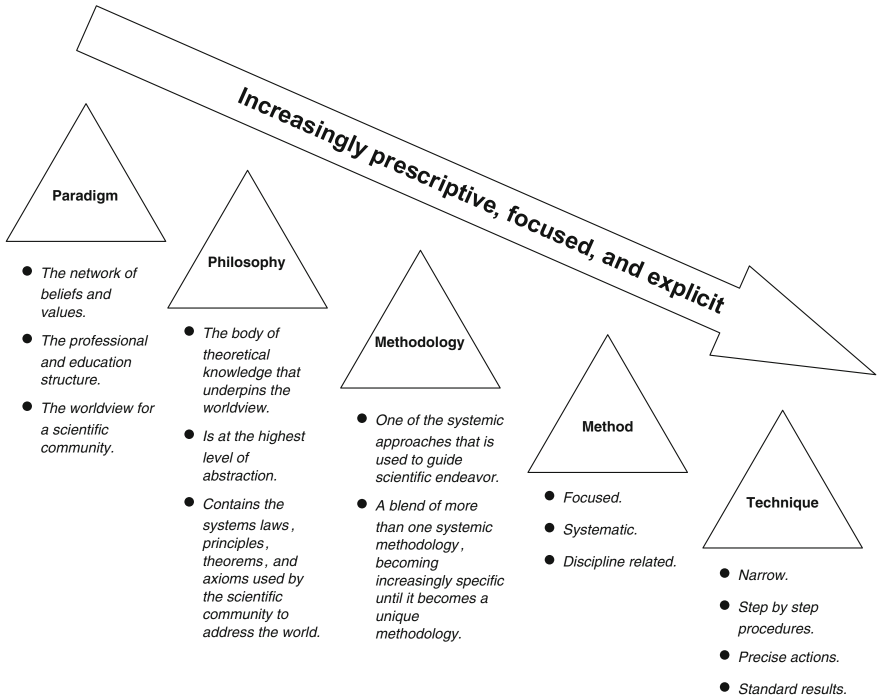


Fig. 2.4 Relationship between scientific terms

2.4 Hierarchical Structure for Engineering Design

Figure 2.4 provides the structure within which an engineering design methodology exists. Documents that support a methodology in engineering design will be discussed in the section that follow.

2.4.1 *Paradigm for Engineering as a Field of Science*

The top-level, the paradigm, that surrounds all engineering efforts is science, the scientific method and scientific community. The “sciences are organized bodies of knowledge” (Nagel 1961, p. 3) which at its highest level includes six major fields: (1) natural sciences; (2) engineering and technology; (3) medical and health sciences; (4) agricultural sciences; (5) social sciences; and (6) humanities (OECD 2007). Each science is guided by “the desire for explanation which are at once systematic and controllable by factual evidence that generates science” (Nagel 1961, p. 4). “Science is not a rigid body of facts. It is a dynamic process of discovery. It is alive as live itself” (Angier 2007, p. 19).

2.4.2 *Philosophy for Engineering*

The second-level, philosophy, serves to focus all engineering efforts and contains a guide to the theoretical body of knowledge that underpins the worldview for all engineers. There is an overarching body of knowledge that encompasses general engineering knowledge (NSPE 2013) and individual bodies of knowledge for each engineering discipline. For instance, the *Guide to the Systems Engineering Body of Knowledge* or SEBoK (BKCASE-Editorial-Board 2014) and the *Guide to the Software Engineering Body of Knowledge* or SWEBOK (Bourque and Fairley 2014). The body of knowledge acts as a guide to the specific knowledge areas required to effectively practice engineering in the discipline governed by the body of knowledge. Each body of knowledge endeavors to:

- To promote a consistent worldwide view of the engineering discipline,
- To specify the scope of, and clarify the relationship of the engineering discipline with other scientific fields and engineering disciplines,
- To characterize the contents of the engineering discipline,
- To provide a topical access to the body of knowledge in the extant literature, and
- To provide a foundation for curriculum development and for individual certification and licensing material in the discipline.

2.4.3 Methodology for Engineering Design

The third level, the methodology, serves to focus all engineering design efforts (a discipline of engineering) in achieving the technical processes required to design a man-made systems. The definition of a design methodology was provided in Chap. 1.

> A systematic approach to creating a design consisting of the ordered application of a specific collection of tools, techniques, and guidelines (IEEE and ISO/IEC 2010, p. 102).

A design methodology can be envisioned as a framework or model that focuses the actions of human beings that are attempting to define an object, device, process, or system in order to provide the details required to effect construction, assembly, and implementation for use.

> Design models are the representations of philosophies or strategies proposed to show how design is and may be done (Evbuomwan et al. 1996, p. 305).

The section that follows will present a number of formal methodologies that may be utilized during the design of engineering system.

2.5 Engineering Design Methodologies

This section will present a number of major engineering design methodologies. Each methodology will be reviewed at a very high-level, but will contain adequate references that may guide further investigation of the details of the methodology. It is important to remember that the methodology is a framework or model that guides the execution, tracking, and accomplishment of technical tasks required to accomplish the design of a man-made system. Seven select methodologies will be presented in chronological order of their appearance in the literature.

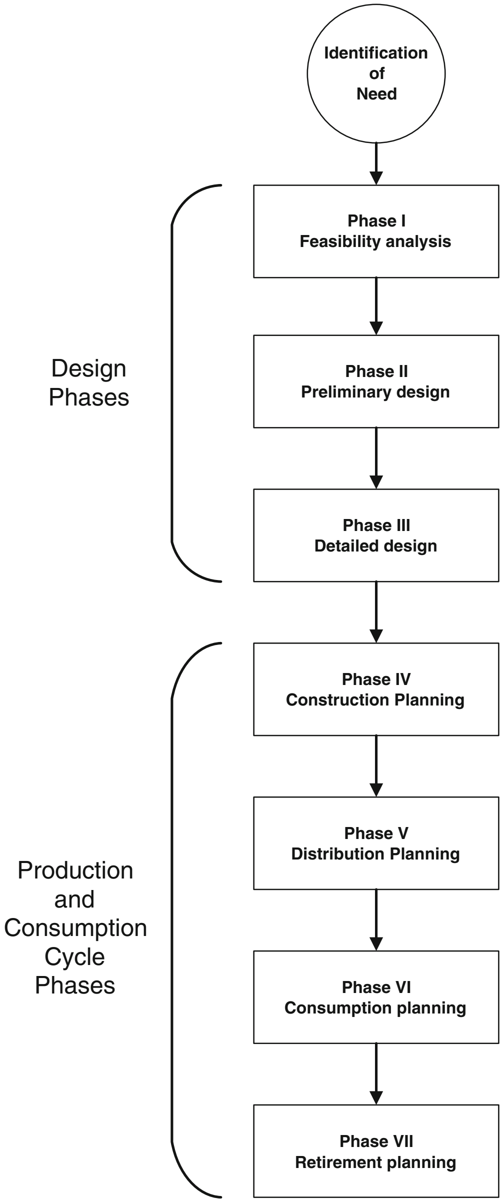
2.5.1 Methodology by Morris Asimov

Morris Asimow [1906–1982], a professor of engineering systems at the University of California at Los Angeles, developed the seven-phase linear chronological structure (i.e., morphology) for design projects depicted in Fig. 2.5. Asimow was the initial author to discuss morphology in engineering design and as such has the distinction of authoring one of the earliest texts on the topic.

Notice that Fig. 2.5 contains three phases identified as the design phases. The purposes of each design phase are as follows:

- Feasibility study—"to achieve a set of useful solutions to the design problem" (Asimow 1962, p. 12).

Fig. 2.5 Seven phases of a complete project [adapted from (Asimow 1962, p. 12)]



- Preliminary design—"to establish which of the proffered alternatives is the best design concept" (Asimow 1962, p. 13).
- Detailed design—"to furnish the engineering description of a tested and producible design" (Asimow 1962, p. 13)

This step-wise execution of design phases and the associated processes should be familiar to every engineer as it serves as the foundation for teaching the sequential path of activities involved in delivering products and systems. The details of each of the seven phases are presented as individual chapters in Asimow's text *Introduction to Design* (1962).

2.5.2 Methodology by Nigel Cross

Nigel Cross, an emeritus professor of design studies at The Open University in the United Kingdom and current editor-in-chief of the scholarly journal *Design Studies*, published the first version of the eight-stage model of design shown in Fig. 2.6 in 1984. This model is unique in that it permits the user to visualize how the larger design problem may be broken into sub-problems and sub-solutions which are then synthesized into the total solution.

The three stages on the left hand side of the model and the one stage in the bottom middle establishes objectives, functions, requirements, and characteristics of the problem. The three stages on the right hand side of the model and the one in the upper middle generate, evaluate, and provide improvements to alternatives and identify additional opportunities that may be relevant to the problem's design solution. The right hand side responds to and provides feedback to the left hand side. The details of this model are presented in Cross' text *Engineering Design Methods* (Cross 2008), which is now in its 4th edition.

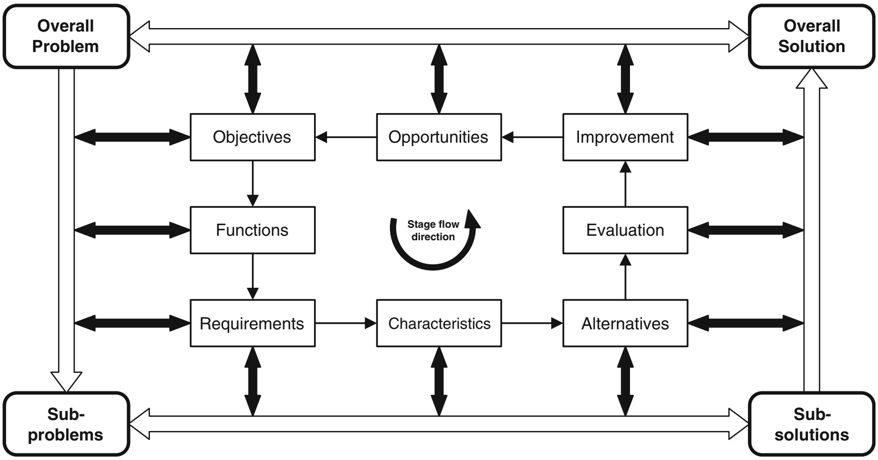


Fig. 2.6 Eight stages of the design process [adapted from (Cross 2008, p. 57)]

2.5.3 Methodology by Michael J. French

Michael J. French, Emeritus Professor of Engineering Design at Lancaster University proposed a block diagram of total design in his text *Conceptual Design for Engineers* in 1985. His four-phase model is depicted in Fig. 2.7.

The details associated with this model of design are presented in his text *Conceptual Design for Engineers* (French 1998) which has recently been reissued in its 3rd edition.

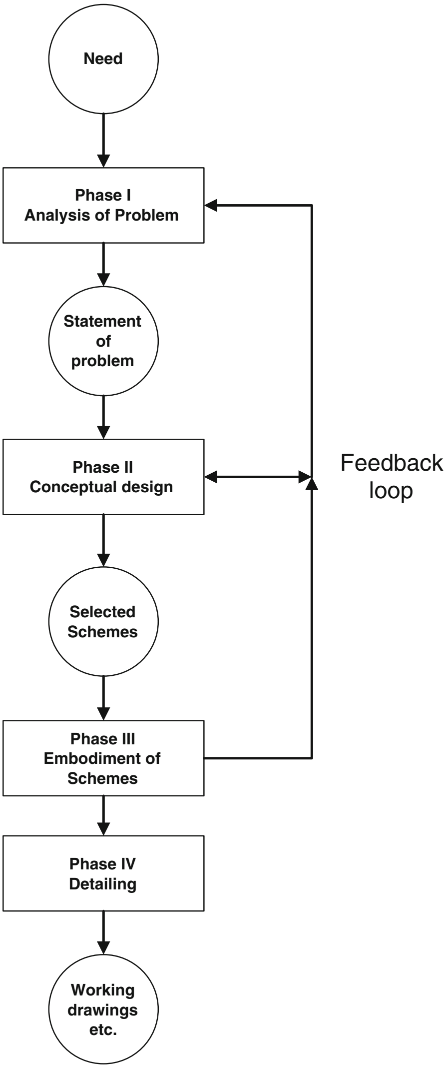


Fig. 2.7 Block diagram of the design process [adapted from Fig. 1.1 in (French 1998, p. 2)]

2.5.4 Methodology by Vladimir Hubka and W. Ernst Eder

Vladimir Hubka [1924–2006] was the head of design education at the Swiss Federal Technical University (ETH) in Zürich from 1970 until 1990. His area of expertise was design science and the theory of technical systems. Hubka proposed a four-phase, six step model that addressed elements of design from concept through creation of assembly drawings. A simplified depiction of Hubka's design process model that represents the states of the technical processes during the design phases is depicted in Fig. 2.8.

This is a unique model in that specific design documents are identified as deliverable objects upon completion of the various steps. The details of this innovative approach to design are described in the text *Design Science: Introduction to the Needs, Scope and Organization of Engineering Design Knowledge* (Hubka and Eder 1995). Hubka's long-time colleague W. Ernst Eder provides an excellent compilation on Hubka's legacy, which includes his views on both engineering design science and the theory of technical systems, providing a glimpse into a number of fascinating views on these subjects (Eder 2011).

2.5.5 Methodology by Stuart Pugh

Stuart Pugh [1929–1993] was the Babcock Professor of Engineering Design and the head of the Design Division at the University of Strathclyde in Glasgow, Scotland from 1985 until him untimely death in 1993. During his time at Strathclyde he completed his seminal work *Total Design: Integrated Methods for Successful Product Engineering* (1991). Pugh was an advocate of participatory design using transdisciplinary teams. Until Pugh fostered this idea in both his teaching and consulting work, most engineers focused on technical elements of the design and rarely participated in either the development process or the commercial aspects associated with the product. Pugh's use of transdisciplinary teams ensured that both technical and non-technological factors were included in what he labeled *Total Design*.

Pugh's *Total Design Activity Model* has four parts. The first part is the *design core* of six phases: (1) user need; (2) product specification; (3) conceptual design; (4) detail design; (5) manufacture; and (6) and sales. The six phases of the design core are depicted in Fig. 2.9. The iterations between the phases account for changes to the objectives for the product during the period of design.

The second part of the *Total Design Activity Model* is the product design specification (PDS). The PDS envelopes the design core and contains the major specification elements required to design, manufacture and sell the product. The major elements of a PDS are presented in Table 2.7.

When the PDS is placed on the design core the *Total Design Activity Model* is represented by two of its four parts as depicted in Fig. 2.10. The lines that radiate

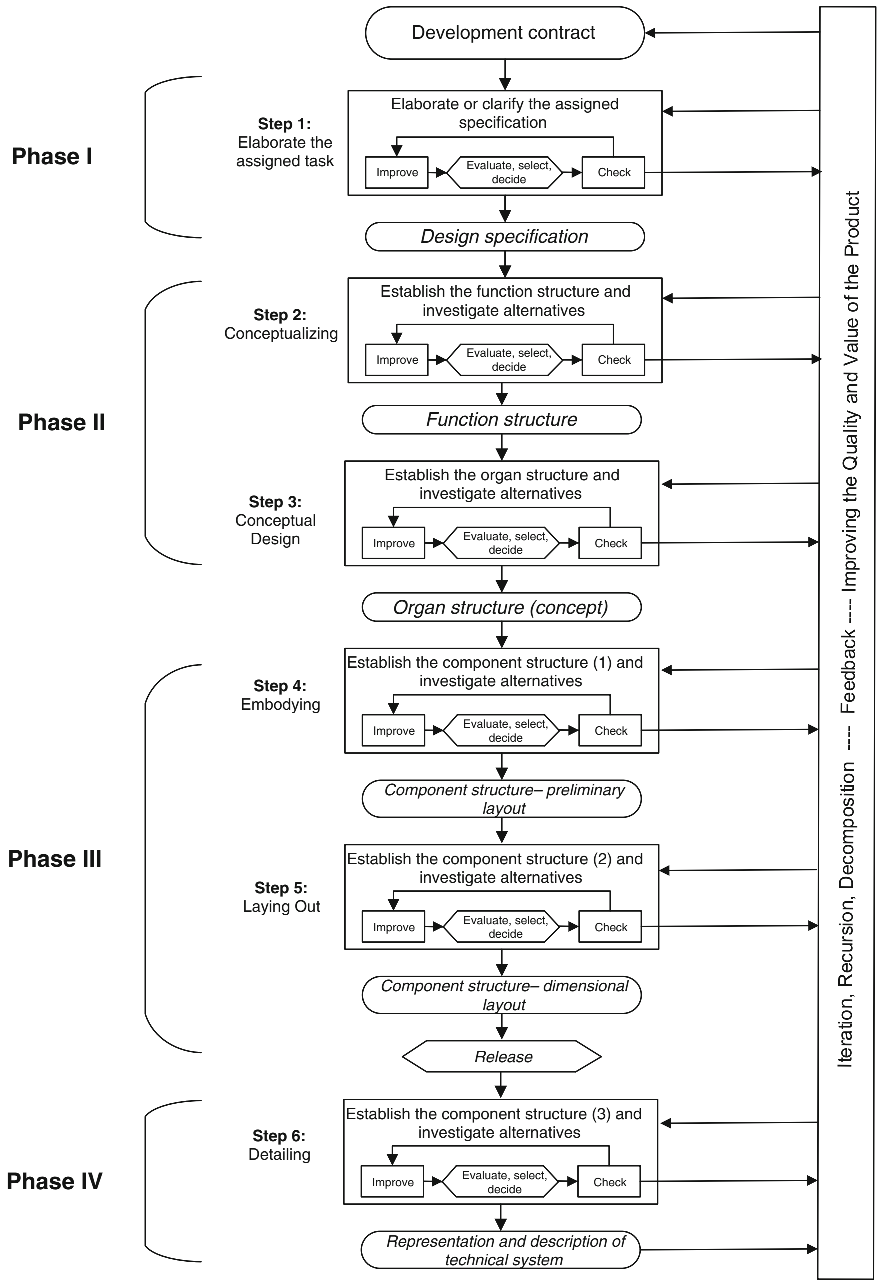


Fig. 2.8 Depiction of Hubka's design model [adapted from Figs. 7–13 (Hubka and Eder 1995)]

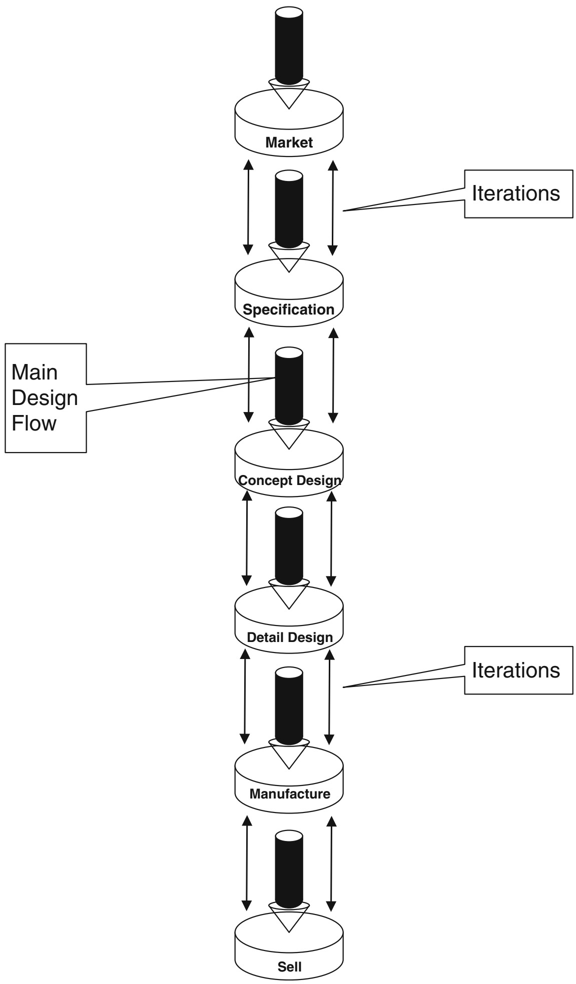


Fig. 2.9 Main design core [adapted from Fig. 1.4 in (Pugh 1991, p. 6)]

Table 2.7 Elements of the product design specification

Customer	Processes	Size	Shipping	Performance
Disposal	Aesthetics	Politics	Installation	Weight
Maintenance	Competition	Packing	Reliability	Shelf life storage
Patents	Environment	Testing	Safety	Legal
Documentation	Quality	Product lifespan	Materials	Ergonomics
Standards specifications	Manufacturing facilities	Market constraints	Company constraints	Life in service
Product cost	Time scale			

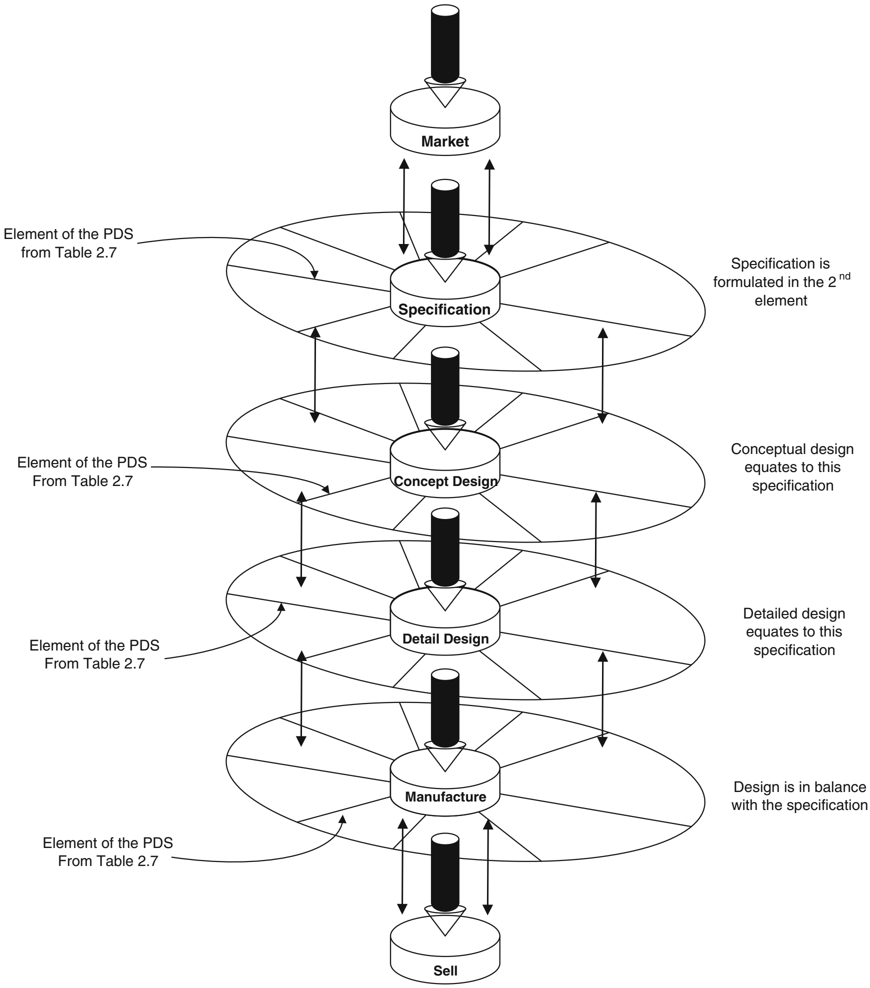


Fig. 2.10 Design core and surrounded by PDS [adapted from Fig. 1.5 in (Pugh 1991, p. 7)]

from and surround the core phases are the elements of the PDS relevant to the particular product's design.

The third part of the *Total Design Activity Model* are the inputs from the discipline independent methods required to execute the design core. These include both the desirable features of engineering design and the two modes of thought as depicted in Fig. 2.3 and many others. The fourth and final part of the *Total Design Activity Model* are the inputs from the technology and discipline dependent sources. Many discipline specific methods are required to execute the elements of the PDS that surround the design core. Examples include stress and strain analysis, welding,

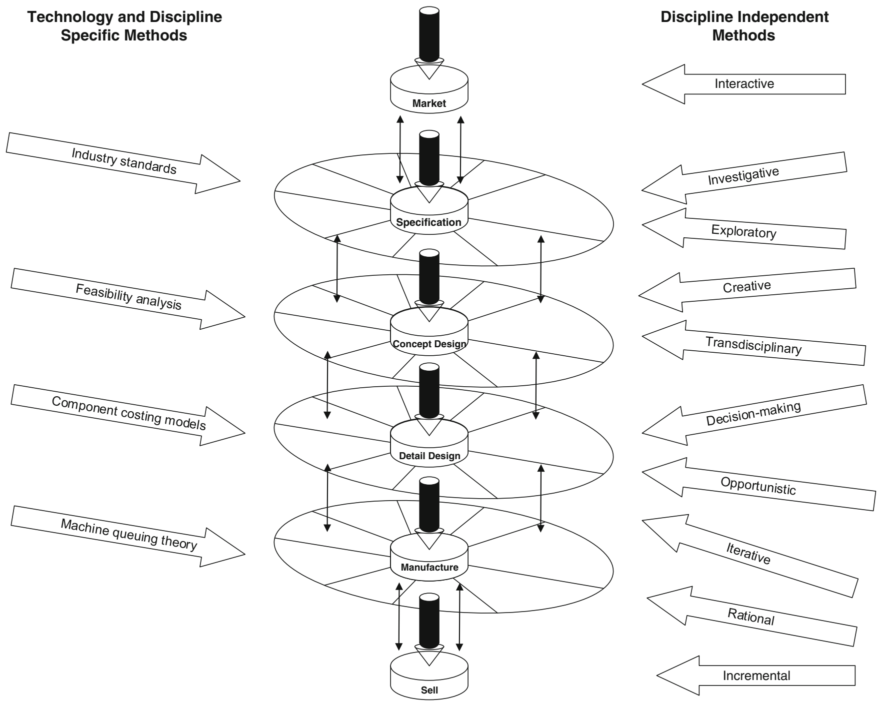


Fig. 2.11 Total design activity model

electromagnetic surveys, heat transfer studies, etc. The completed *Total Design Activity Model* is depicted in Fig. 2.11.

The *Total Design Activity Model* depicted in Fig. 2.11 includes examples of both technology and discipline specific methods and discipline independent methods to be illustrative of the inputs to the model. Real-world implementation of this model would involve many more methods. The details of this detailed model for to design are described in Pugh's seminal text *Total Design: Integrated Methods for Successful Product Engineering* (1991).

2.5.6 Methodology by the Association of German Engineers (VDI)

In Germany, the Association of German Engineers (VDI) has a formal guideline for the Systematic Approach to the Design of Technical Systems and Products (VDI 1987). The guideline proposes a generalized approach to the design of man-made systems that has wide applicability within a wide range of engineering disciplines. This approach is depicted in Fig. 2.12.

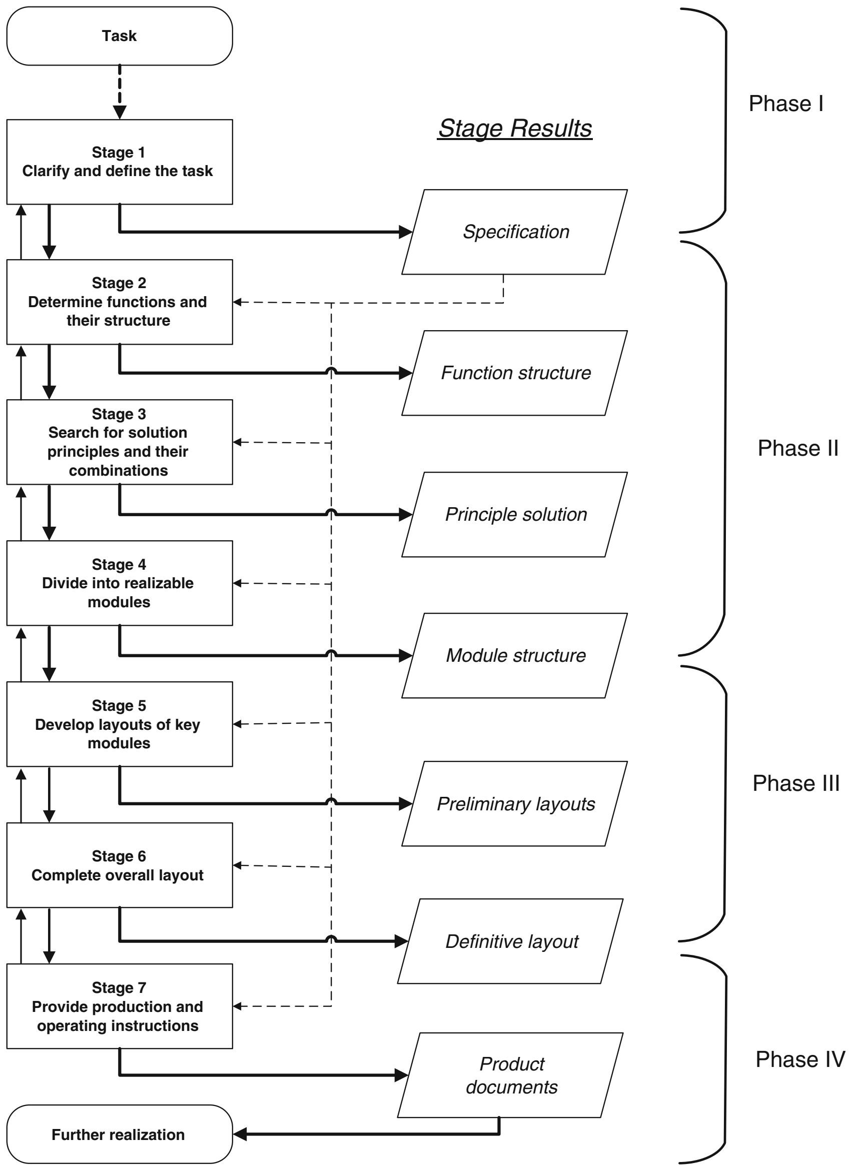


Fig. 2.12 General approach to design [adapted from Fig. 3.3 in (VDI 1987, p. 6)]

The model has four phases made up of seven stages and a specific result is associated with each stage. The approach in Fig. 2.12 should be "… regarded as a guideline to which detailed working procedures can be assigned. Special emphasis is placed on the iterative nature of the approach and the sequence of steps must not be considered rigid" (Pahl et al. 2011, p. 18).

2.5.7 Methodology by Pahl, Beitz, Feldhusen, and Grote

The team of Gerhard Pahl, Wolfgang Beitz, Jörg Feldhusen, and Karl-Heinrich Grote have authored one of the most popular textbooks on design, *Engineering Design: A Systematic Approach* (2011). In this text they propose of model for design that has four main phases: (1) planning and task clarification; (2) conceptual design; (3) embodiment design; and (4) detailed design. The simple nature of the model does not warrant a figure, but each of the phases are described in the following:

- Task Clarification—the purpose of this phase "is to collect information about the requirements that have to be fulfilled by the product, and also about the existing constraints and their importance" (Pahl et al. 2011, p. 131).
- Conceptual Design—the purpose of this phase is to determine the principle solution. "This is achieved by abstracting the essential problems, establishing function structures, searching for suitable working principles and then combining those principles into a working structure" (Pahl et al. 2011, p. 131).
- Embodiment Design—the purpose of this phase is to "determine the construction structure (overall layout) of a technical system in line with technical and economic criteria. Embodiment design results in the specification of a *layout*" (Pahl et al. 2011, p. 132).
- Detailed Design—the purpose of this phase is to finalize "the arrangement, forms, dimensions, and surface properties of all the individual parts are finally laid down, the materials specified, production possibilities assessed, costs estimated, and all the drawings and other production documents produced. The detailed design phase results in the *specification of information* in the form of *production documentation* (Pahl et al. 2011, p. 132).

The details of each of the phases in this model are presented in their text *Engineering Design: A Systematic Approach* (Pahl et al. 2011) which is now in its 3rd edition.

The section that follow will discuss an eighth design methodology—Axiomatic Design.

2.6 The Axiomatic Design Methodology

The *Axiomatic Design Methodology* is given special treatment in this chapter because it not only satisfies the Technical Processes in Table 2.2, but it also meets nine critical attributes that ensure a methodology remain sustainable (Adams and Keating 2011). The nine (9) critical attributes and how the Axiomatic Design Methodology satisfies these are presented in Table 2.8.

It is important to note that one of the most unique features of the *Axiomatic Design Methodology* (ADM) is its ability to not only satisfy the Technical

Table 2.8 Critical attributes of the axiomatic design methodology (ADM)

Critical Attribute	Attribute description and satisfaction in the ADM
1. Transportable	*A methodology must be capable of application across a spectrum of complex engineering problems and contexts.* The ADM has been successfully applied to a wide variety of design problems is multiple domains
2. Theoretical and Philosophical Grounding	*A valid methodology must have a linkage to a theoretical body of knowledge as well as philosophical underpinnings that form the basis for the methodology and its application.* The theoretical body of knowledge for the ADM is systems theory
3. Guide to Action	*A methodology must provide sufficient detail to frame appropriate actions and guide direction of efforts to implement the methodology.* The ADM provides clear guidance on how to transform customer requirements to functional and non-functional requirements to design parameters and process variables
4. Significance	*A methodology must exhibit the holistic capacity to address multiple problem domains, minimally including contextual, human, organizational, managerial, policy, technical, and political aspects.* The ADM addresses functional and non-functional requirements and systems constraints
5. Consistency	*A methodology must be capable of providing replicability of approach and results interpretation based on deployment of the methodology in similar contexts.* The ADM mathematical rigor ensures consistency of results
6. Adaptable	*A methodology must be capable of flexing and modifying the approach, configuration, execution, or expectations based on changing conditions or circumstances.* The ADM may be applied in a variety of conditions and circumstances subject to compliance with the axioms of systems theory
7. Neutrality	*A methodology attempts to minimize and account for external influences in application and interpretation*. The ADM is sufficiently transparency in technique to eliminate bias, surface assumptions, and account for limitations during execution of the methodology
8. Multiple Utility	*A methodology supports a variety of applications with respect to complex systems to include new system design, existing system transformation, and assessment of systems problems.* The ADM may be applied across multiple problem domains and applications
9. Rigorous	*A methodology must be capable of withstanding scrutiny with respect to: (1) identified linkage to a body of theory and knowledge; (2) sufficient depth to demonstrate detailed grounding in relationship to the theory and knowledge; and (3) capable of providing transparent, replicable results with accountability for explicit logic used to draw conclusions and interpretations.* The ADM's grounding in systems theory, application of axioms for information entropy and independence, and its mathematical rigor ensure replicable results that use common logic for the development of conclusions

Processes for design presented in Table 2.2, but its ability to invoke specific axioms of systems theory in order to develop quantitative measures for evaluating systems design endeavors. None of the seven design methodologies reviewed in Sect. 2.5 demonstrated that ability.

The sections that follow will introduce the basic elements of the ADM. The central focus will be on its ability to selection the best design alternative based upon a quantitative evaluation of the design's ability to satisfy its functional and non-functional requirements. The elimination of qualitative evaluation parameters and cost is a major shift from every other design methodology. As such, the Axiomatic Design Methodology is positioned as the premier methodology for systems design endeavors.

2.6.1 Introduction to the Axiomatic Design Methodology

The Axiomatic Design Methodology was developed by Professor Nam P. Suh while at the Massachusetts Institute of Technology. Professor Suh's design framework is founded upon two axioms of systems theory, that he titles the *independence axiom* and the *information axiom*. Suh uses these axioms, in conjunction with the concept of domains to develop a framework where customer attributes are transformed into process variables in a completed design. The basic idea of an axiomatic design framework was envisioned by Dr. Suh in the mid-1970s and was first published in 1990 (Suh 1990) and updated in 2001 (Suh 2001). The sections that follow will provide a high-level description of the Axiomatic Design Methodology.

2.6.2 Domains in the Axiomatic Design Methodology

A key concept in axiomatic design is that of domains. In the design world there are four domains: (1) the customer[1] domain, which is characterized by customer attributes that the customer and associated stakeholders would like to see in the their system; (2) The functional domain where the customer's detailed specifications, specified as both functional requirements (FR) and non-functional requirements (NFR) or what Suh describes as constraints (C) are specified; (3) The physical domain where the design parameters emerge; and (4) The process domain where process variables enable the design. Figure 2.13 is a depiction of the four domains of the design world.

[1]This chapter will adhere to Dr. Suh's term *customer*. However, note that this term is too narrowly focused. Therefore, the reader is encouraged to substitute the term stakeholder, which includes the larger super-set of those associated with any systems design.

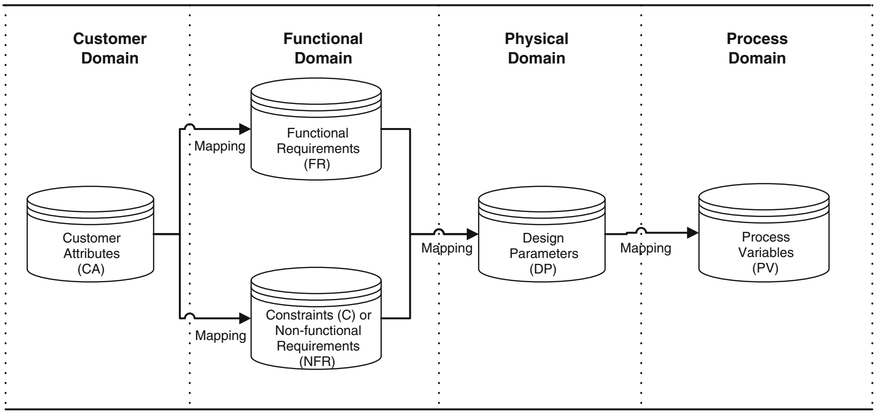


Fig. 2.13 Four domains of the design world

2.6.3 Independence Axiom

A second key concept of axiomatic design is the *independence axiom*. The independence axiom states:

> Maintain the independence of the functional requirements (Suh 2005b, p. 23).

Simply stated, each functional requirement[2] should be satisfied without affecting any other functional requirement. During the conceptualization process the functional requirements are transformed from the functional domain where they state *what,* to the physical domain where they will be met by *how*. The mapping should be one design parameter (DP) to one functional requirement (FR). Mathematically this can be related as two vectors, the FR vector [*FR*] and the DP vector [*DP*] as shown in Eq. 2.1.

Equation for Functional Requirements

$$[FR] = [A][DP] \tag{2.1}$$

where [*A*] is the design matrix which relates FRs to DPs and is:

Equation for Design Matrix

$$[A] = \begin{Vmatrix} A11 & A12 & A13 \\ A21 & A22 & A23 \\ A31 & A23 & A33 \end{Vmatrix} \tag{2.2}$$

[2]Only functional requirements will be addressed in this description, but the concept also applies to the non-functional requirements that act as constraints on the system design.

Using the design matrix in Eqs. 2.2 and 2.1 may be written as Eq. 2.3.

Expanded Equation for Functional Requirements

$$\begin{aligned} FR_1 &= A_{11}DP_1 + A_{12}DP_2 + A_{13}DP_3 \\ FR_2 &= A_{21}DP_1 + A_{22}DP_2 + A_{23}DP_3 \\ FR_3 &= A_{31}DP_1 + A_{32}DP_2 + A_{33}DP_3 \end{aligned} \tag{2.3}$$

This satisfies the general relationship in Eq. 2.4.

General Equation for Functional Requirements

$$FR = \sum_{i=1}^{n} A_{ij}DP_j \tag{2.4}$$

where i = the number of Design Parameters (DP).

The independence axiom may be used to evaluate design complexity. Most systems exhibit complexity as a result of excessive interaction between components within the system design. Design complexity may be measured by observing system coupling, i.e., where the number of DPs is less than the number of FRs. In this case the design has added complexity because DPs are satisfying more than one FR, or the FR has not been satisfied.

The relevance of the independence axiom has additional utility in that individual designs may be evaluated, not qualitatively, but quantitatively, based on the relationship to an *ideal design*. The ideal design is one where the number of DPs are equal to the number of FRs, where the FRs are kept independent of one another. All design alternatives may be evaluated against the concept of an ideal design.

2.6.4 The Information Axiom

The information axiom is one of the seven axioms of systems theory (Adams et al. 2014). The Information Axiom states:

> Systems create, possess, transfer, and modify information. The information principles provide understanding of how information affects systems (Adams et al. 2014, p. 119).

The information axiom's principle invoked by Suh (1990, 2001) in his formulation for Axiomatic Design is the principle of information redundancy. Information redundancy is "the fraction of the structure of the message which is determined not by the free choice of the sender, but rather by the accepted statistical rules governing the use of the symbols in question" (Shannon and Weaver 1998, p. 13). It is the number of bits used to transmit a message minus the number of bits of actual information in the message.

The Axiomatic Design Methodology's information axiom makes use of Shannon's generalized formula for information entropy,[3] which is a measure of the uncertainty of the information, or the unpredictability of information content, as presented in Eq. 2.5.

Shannon's Equation for Information Entropy

$$H = -\sum p_i log p_i \tag{2.5}$$

where:

H information entropy

p_i probability of the information elements

The reformulated equation for information content (I), as related to the probability (p_i) of a design parameter (DP_i) satisfying a functional requirement (FR_i) is presented in Eq. 2.6.

System Information Content

$$I_{sys} = -\sum_{i=1}^{n} log_2 p_i \tag{2.6}$$

The information axiom, when used in this context, states that the system design with the smallest I_{sys} (i.e., the design with the least amount of information) is the best design. This is perfectly logical, because such a design requires the least amount of information to fulfill the design parameters.

The Axiomatic Design Methodology's utilization of Shannon's information entropy is remarkable because a system's design complexity, most often expressed as a qualitative assessment, may be represented as a quantitative measure based on the information entropy required to satisfy the design parameters.

2.6.5 Constraints or Non-functional Requirements

The design goals include not only the functional requirements (FR_i), but constraints (C_i) which place bounds on acceptable design solutions. Axiomatic design addresses two types of constraints: (1) input constraints, which are specific to the overall design goals and apply to all proposed designs; and (2) system constraints, which are specific to a particular system design.

[3]Information entropy is sometimes referred to as Shannon Entropy. For more information on Information Theory the reader may review either Ash (1965). *Information Theory*. New York: Dover Publications, or Pierce (1980). *An Introduction to Information Theory: Symbols, Signals and Noise* (2nd, Revised ed.). New York: Dover Publications.

> Constraints affect the design process by generating a specific set of functional requirements, guiding the selection of design solutions, and being referenced in design evaluation (Suh 2005a, p. 52).

The specific set of functional requirements generated by the constraints will be labeled *non-functional requirements.* Non-functional requirements (NFR) are addressed within the Axiomatic Design Methodology in the same manner as functional requirements. A discussion and nominal taxonomy for non-functional requirements will be presented in the next chapter.

2.7 Summary

In this chapter engineering design has been defined and positioned within the larger scientific paradigm and the engineering field. Desirable features and two modes of thought used in of engineering design were addressed. Terminology relating a methodology within a hierarchy of scientific approaches has been provided. Finally, seven historical and one preferred methodology for system design endeavors were presented.

The next chapter will review the definition for non-functional requirements and the role they play in every engineering design of man-made systems. It will also develop a notional taxonomy for identifying and addressing non-functional requirements in a system design endeavor.

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