NAVIGATING THE COMMON APPROACHES TO PRODUCT DEVELOPMENT

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Abstract

Many design approaches are used and taught in industry and academia, and it is difficult even for seasoned design professionals to know which to use. These design approaches were developed in different disciplines with a unique purpose or application in mind. To help practitioners, educators, and students navigate these approaches, a new way to communicate the similarities and differences and the strengths and weaknesses of common design environments, processes, and methods is needed. This study presents a review of some common approaches used in product development: design thinking, systems thinking, total quality management, agile design, waterfall process, engineering design process, spiral model, Vee model, axiomatic design, value driven design, lean manufacturing, six sigma, theory of constraints, and decision based design. This review revealed a set of key criteria for differentiating these approaches from one another, and a visual representation is proposed to identify the key characteristics of each approach and how they compare and overlap with one another. This analysis and representation can be used to help designers and students choose the best approach for a project.

Keywords: Design engineering, Design education, Design methodology, New product development

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1 INTRODUCTION

Product development is a complex, interdisciplinary process, and a number of prescriptive approaches have been developed to systematically guide designers. These approaches stem from different disciplines and therefore seek to address different types of design problems and different issues that may affect product success. Nevertheless, the approaches developed for mechanical engineers, systems engineers, industrial engineers, management science, and other fields exhibit similarities and overlaps. This paper presents a literature review of fourteen well-established approaches to identify their key characteristics. Synthesizing those key characteristics, a number of metrics are then established to aid educators, students, researchers, and practitioners in understanding the differences among the approaches and selecting the most appropriate approach to their needs. The approaches are then sorted according to those metrics to visually represent how the approaches compare and contrast, and the implications of such a classification system are discussed.

While other studies have compared different approaches to product development, and some design experts argue that such an endeavour is unnecessary and designers should simply use the approaches they are most familiar with, the authors were unable to find a compilation of the scope presented in this paper. Cross (2008) discussed several distinct descriptive and prescriptive design process models, all of which fall under the umbrella of "engineering design processes," which in this paper represent a single high-level approach. Estefan (2007) provided an overview of different Model-Based Systems Engineering (MBSE) methodologies, drawing distinctions among MBSE design processes, tools, methodologies, and environments. However, this review only considered systems engineering approaches, and it focuses on several company-specific approaches rather than their higher-level counterparts. An analysis by Jones (2014) considered a variety of high-level design principles, including design science, design theory, and systems theory, and their usage towards simplifying complex systems. This work discussed the commonalities and complementarities of these approaches and how they can be leveraged to address complex social systems and the mitigation of problems that commonly arise in these scenarios, and was thus about combining systemic approaches rather than distinguishing them. From a more philosophical perspective, a recent workshop involving many of the world's foremost design researchers resulted in the publication of an anthology of design theories and models (Chakrabarti and Blessing, 2014). This compilation focuses on the distinction among theories and models along with requirements and evaluation criteria from a philosophical, rather than applied, perspective.

The present study reviews and analyses a broad array of high-level approaches to product development from various engineering and management disciplines, taking an application-oriented perspective to help designers make sense of these methodologies. The results of this study provide an initial classification of the fourteen approaches across six identified key criteria, and this information is presented in a novel graphical format for ease of interpretation. It should be noted that this is not intended to be a complete list or a final ranking across the criteria, and others may prefer to add or modify according to their expertise. The value of this study lies primarily in the method of organizing and sorting these approaches to engineering design.

2 BACKGROUND

A comprehensive literature review of systematic approaches to product development revealed fourteen well-established design approaches, which were classified into three categories according to Estefan's (2007) framework, shown in Figure 1: environments, processes, and methods. At the highest level, environments enable processes and methods by prescribing appropriate surroundings and conditions under which product development teams should best operate. Processes prescribe task sequences that should be followed to achieve design objectives. Finally, methods provide techniques to aid designers in determining how they will perform design tasks. Estefan (2007) also includes "tools" as a fourth category, which are specific instruments for efficiently implementing methods; while tools were initially considered, they are excluded from the present analysis to allow a greater focus on higher-level approaches that span multiple phases of design. Explanations of the fourteen identified approaches are grouped by classification and provided in the following subsections.

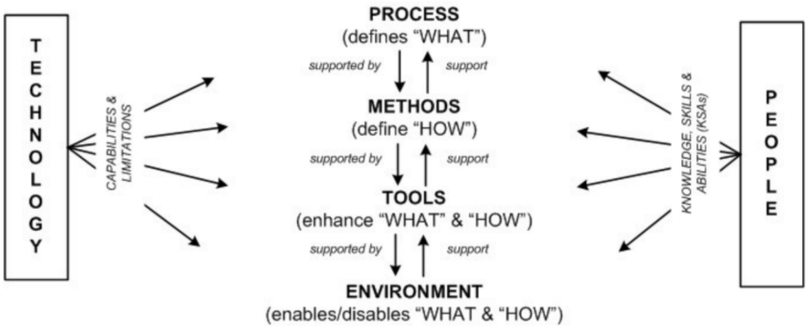


Figure 1. Organization of processes, methods, tools, and environments (Estefan, 2007)

2.1 Environments

Design thinking is a product development environment that has been championed by IDEO and the Institute of Design at Stanford that suggests a thought process in four parts: "divergent thinking" to consider alternatives outside the current reality, "convergent thinking" to organize options and choose the best, "analysis" by which patterns are broken down, and "synthesis," which is used to identify meaningful patterns (Brown, 2009). Similarities are easily drawn between design thinking and the engineering design process, which will be described later, but this approach requires a more human-focused perspective. Design thinking forces everybody involved in the design process to closely consider the end user on a personal level, as evidenced by its focus on empathy. The steps Stanford uses to teach design thinking are shown in Figure 2.

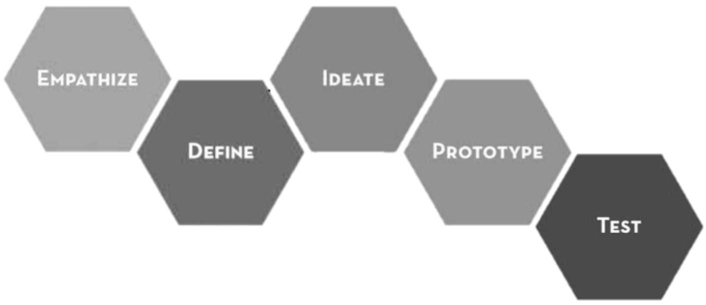


Figure 2. Stanford design thinking process (Institute of Design at Stanford, 2012)

Systems thinking is similar to design thinking in that it forces designers to consider the problem from a particular perspective, in this case, a holistic perspective. There is not a specific “systems thinking process,” but it is generally described as considering how each element of a system interacts with all other elements of that system (Aronson, 1996). In other words, it prescribes that designers consider the big picture when designing a product or a system component. This can help avoid unintended consequences resulting from interactions among different system components, and it can result in single solutions that fix multiple problems.

Total Quality Management (TQM) is a management perspective that encourages constant improvement of design and manufacturing processes in an effort to achieve higher customer satisfaction. As with the other environments, this perspective is ideally held by all members of an organization, including employees and management, in order to ensure that high quality is assured in all aspects of a project. Although this approach was originally developed exclusively for manufacturing processes, it has since been adopted for many other management applications and is now taught to many engineers in product development contexts (Porter and Parker, 1993).

Agile design is a highly iterative approach typically used in software development, particularly within the context of managing teams of developers working on a large project. The main emphasis in agile design is on communicating, interacting, and reducing resource-intensive intermediate stages of development (Cohen et al., 2003). The focus on iteration allows teams to react quickly to changing requirements, and the focus on communication enables teams to make decisions quickly and learn from mistakes. These practices make agile design very adaptable, and much of the software development industry has embraced this approach over the past 2-3 decades (Rigby et al., 2016).

2.2 Processes

The waterfall process is a linear sequence of design tasks most frequently used in software development. This process is ideal for situations where the requirements and specifications of the design problem are well-defined and not subject to change. The components of this system generally follow a sequence that begins with setting requirements and ends in operationalizing and maintaining a product (Royce, 1970). The waterfall process is often used because of its easy implementation and clear milestones, but it has obvious drawbacks in the context of dynamic projects, as it does not specifically account for feedback loops or iterations, seen in Figure 3.

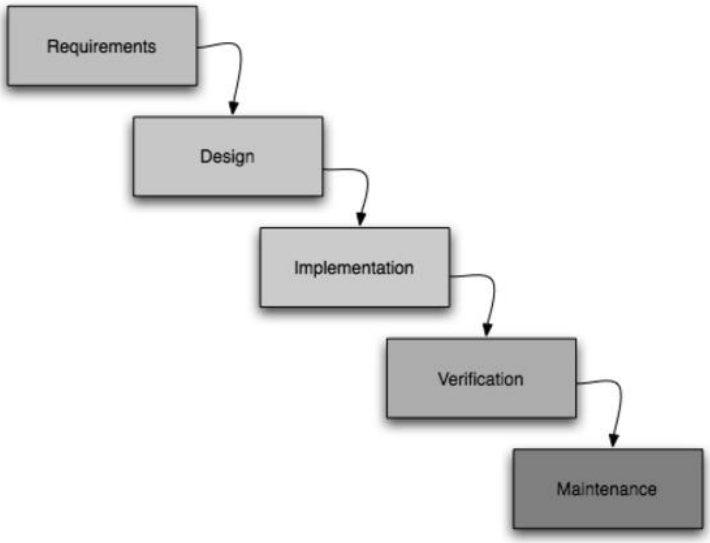


Figure 3. Waterfall design process (Royce, 1970)

The engineering design process is perhaps the most commonly taught systematic design process in traditional engineering disciplines, and it comes in many forms and levels of complexity (Dominick et al., 2001). It can comprise as few as three phases (design, build, test) and as many as eight (e.g. from Figure 4: identify need, research problem, generate alternatives, select a solution, construct a prototype, test and evaluate, communicate, redesign), but it typically accounts for iterative loops through these prescribed steps to allow for continuous improvement (Wheelwright and Clark, 1994).

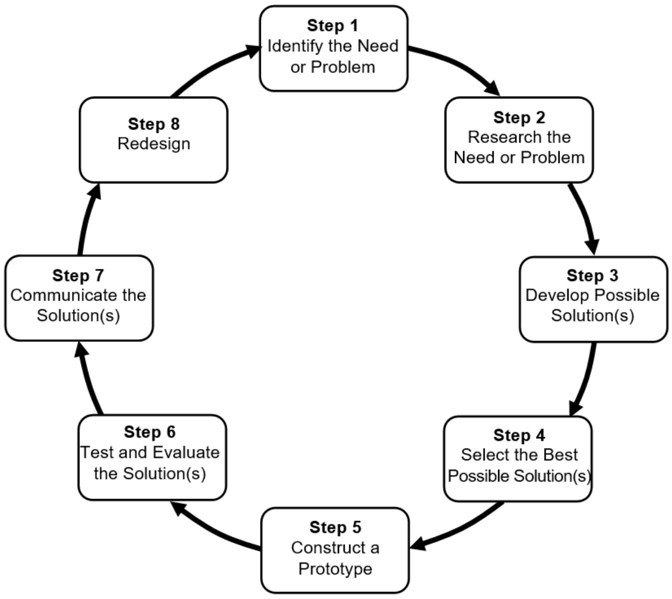


Figure 4. Typical engineering design process (Massachusetts Dept. of Education, 2006)

The spiral model is a process developed in 1988 to address design problems while specifically accounting for risk (Boehm, 1988). This model is, like the waterfall process, most commonly used in software engineering applications. Its value in high-risk situations comes from its interpretation stages, represented in Figure 5, which are used to decide whether to continue the development process. Though it is possible to implement this type of frequent assessment of risk with many of the other methods, the spiral model is the only one that requires risk assessment through a series of iterative loops.

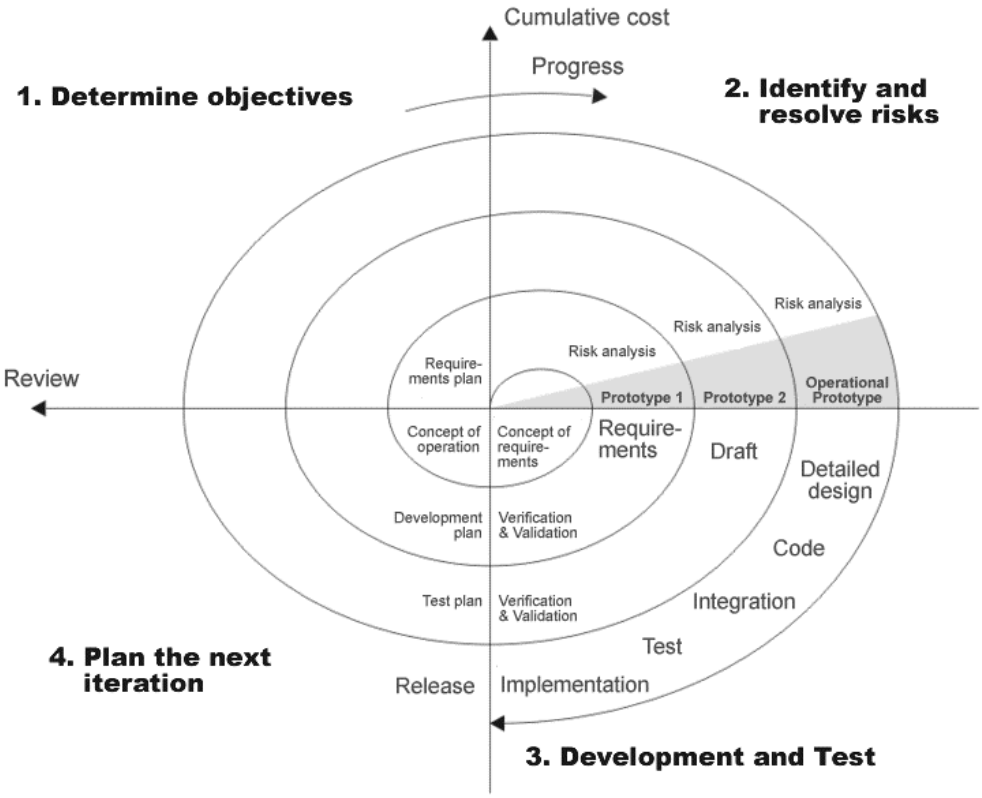


Figure 5. Spiral model (Boehm, 1998)

The Vee model is most often taught in systems engineering for the design of complex products with many sub-systems. Its two prongs, sometimes referred to as streams, are the decomposition and definition stream and the integration and verification stream (Forsberg and Mooz, 1994). The Vee model includes steps to understand user requirements, develop a system concept and validation plan, develop a system performance specification and system verification plan, decompose the problem into hierarchical sub-systems down to the individual component level, design and implement the components, assemble and verify sub-systems, verify and validate the system, and operationalize and maintain the system (Forsberg and Mooz, 1994). This model is not explicitly iterative, but it does stipulate that the steps in the testing stream must verify back to the corresponding steps in the specification stream, which is represented by the horizontal arrows in Figure 6. This process is similar to the waterfall process in its simplicity, but it explicitly builds in decomposition and verification. It is most appropriate for the design of complex products that are best designed and analysed with decomposition and subject matter expertise.

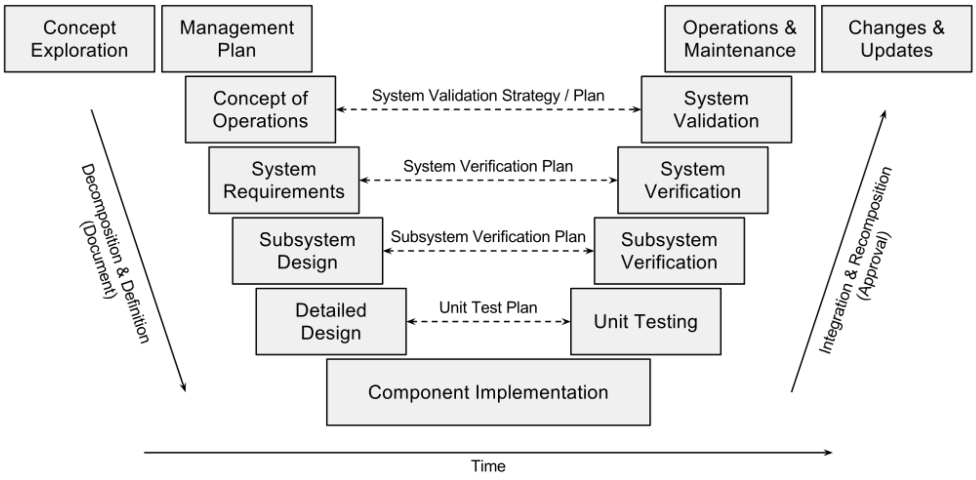


Figure 6. Vee model (Esfahbod, 2013)

2.3 Methods

Axiomatic Design is a popular systems planning methodology that transforms customer needs into functional requirements using matrices. This process defines four main design domains: customer, functional, physical, and process. (Martin and Kar, 2001) Any decision made in a preceding domain directly maps to the next, transforming "whats" to "hows", as shown in Figure 7. This alteration is represented mathematically by performing matrix operations between the functional requirements and design parameters in adjacent domains. For systems containing complex architectures, this method proves especially useful for the elimination of erroneous design alternatives.

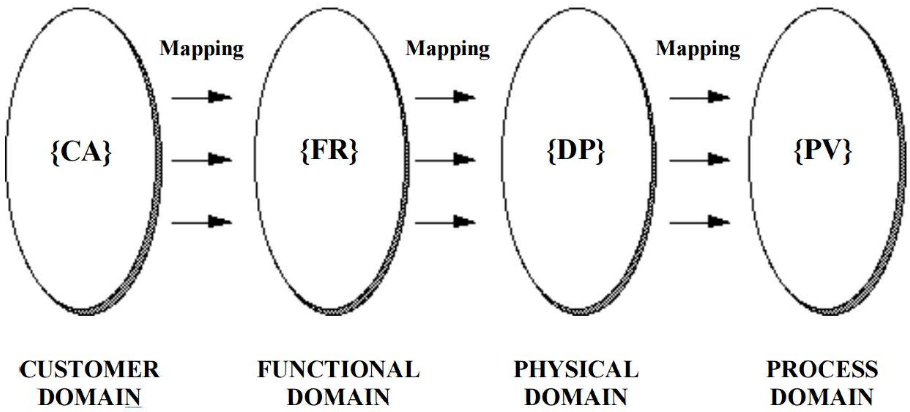


Figure 7. Axiomatic design process (Suh, 1998)

Value Driven Design (VDD) is a design perspective that was created in a collaborative effort by the American Institute for Aeronautics and Astronautics (AIAA) to optimize the attributes of a product or a system while delivering the highest value to its stakeholders. This optimization occurs via the creation of a single mathematical function that considers only the objectives of a system. In doing so, VDD does not explicitly consider performance requirements, potentially jeopardizing the efficiency of the resulting system. (Curran, 2010) However, following this perspective provides engineers with a single "score" for each potential design, which can help streamline the selection process.

Lean manufacturing is a methodology used in the design of manufacturing systems to eliminate waste within each respective process. Lean manufacturing encourages designers to develop more efficient processes to produce the same or better results than those of existing methodologies. This helps designers identify which elements of a manufacturing process add value, and subsequently, which elements should be reduced or eliminated completely (Shah, 2003).

Six Sigma is a manufacturing methodology that aims to improve the quality of a product by reducing the variability in the manufacturing process and by removing the causes of product defects (Harry, 1998). This methodology encourages the proper assignment of employees to well-defined projects that directly impact the company's bottom line. Furthermore, this methodology emphasizes the DMAIC (Define, Measure, Analyse, Improve, Control) problem solving approach.

The Theory of Constraints (ToC) is a management perspective that mainly focuses on identifying a single limiting factor in a particular design or production process. Once identified, a scientific approach is followed to alter the process in a way that either improves this limiting constraint or eliminates it altogether (Goldratt, 1990). This theory was developed under the ideology that every complex system consists of co-dependently linked processes, and any instance of inefficiency will limit the system as a whole. This perspective also lends itself to be iterative, as new constraints are likely to arise throughout the entirety of a design or production process.

Decision Based Design (DBD) is an analytical approach that highlights the decision making process and its applicability to engineering design. Specifically, this approach highlights the importance of considering customer preferences in design decisions, and the necessity of performing consistent economic modelling across each decision associated with a design process. All of these considerations are intended to be made with the mind-set that the maximum number of interests of both the producer and customers are to be maintained throughout the design process, as represented in Figure 8. This approach is generally followed with the consideration of profit being the driving factor in a given engineering project. Thus, any decision made during this process must consider the relative impact on total profit, regardless of the point in the process in which the decision is made (Hazelrigg, 1998).

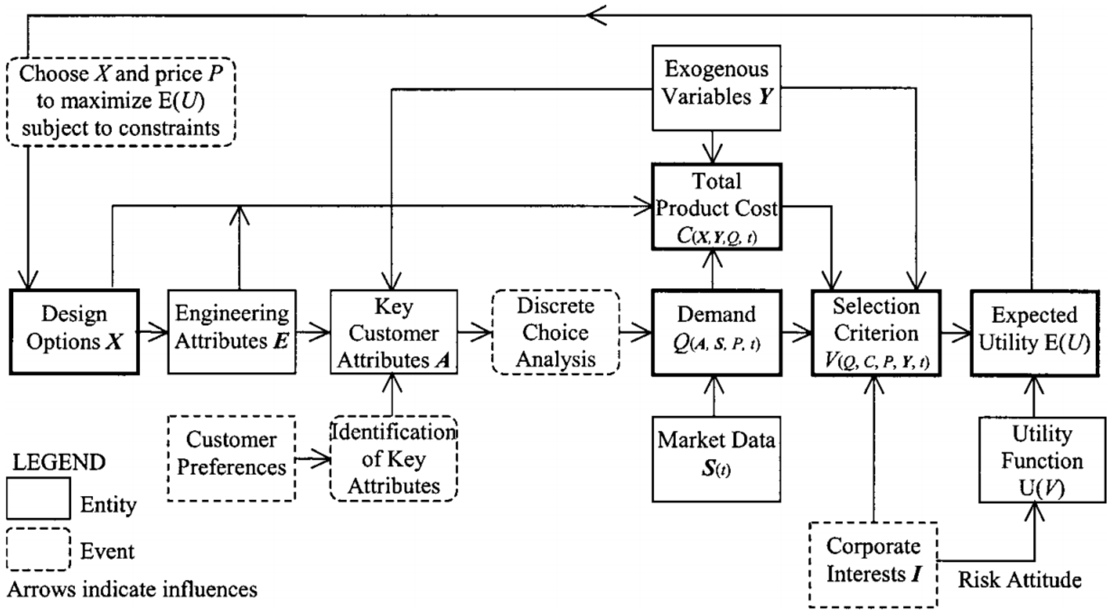
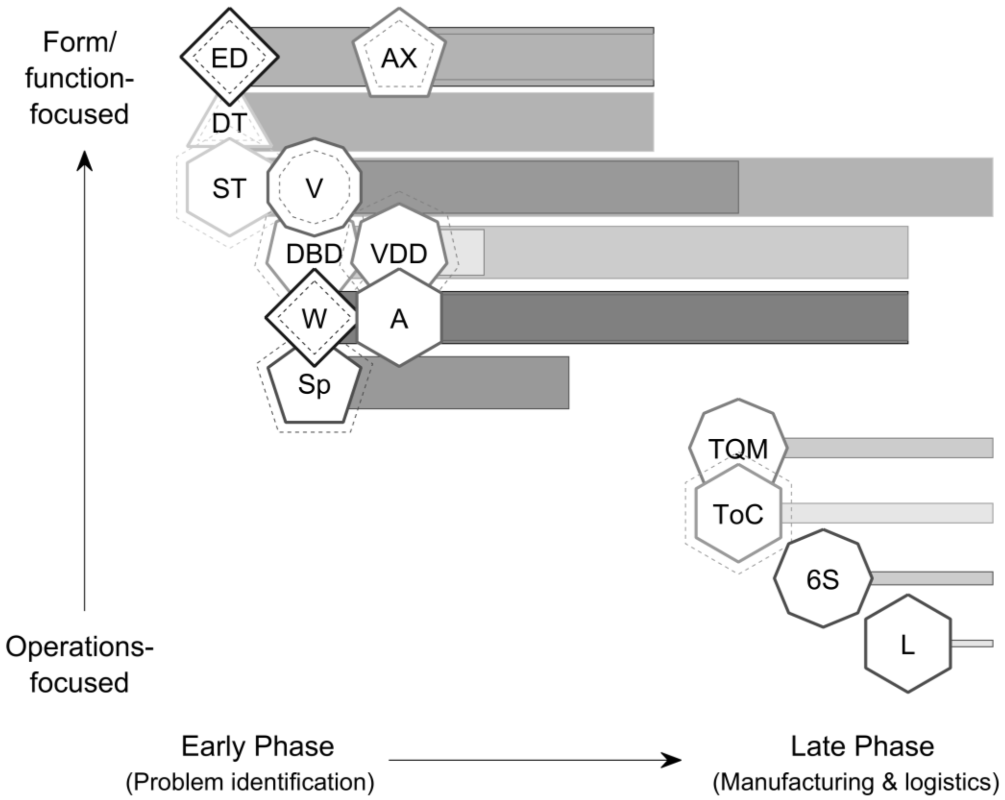


Figure 8. Decision-based design (Wassenaar, 2005)

3 ANALYSIS

Following the literature review, the authors identified several key criteria associated with the fourteen design approaches. Originally, eleven metrics were considered, and each approach was placed on a scale of one to ten within those metrics. Next, the eleven scales were reduced to the six most informative criteria that describe the design approaches, which showed the most significant differentiation across the criteria. The selected criteria include: the phases of the design process covered, the focus on manufacturing and operations versus product form and function, the complexity of the design problem the approach is intended to solve, whether the approach specifically addresses problems within a product (inside) or addresses external factors such as consumer or environmental interaction (outside), the level of guidance offered by the approach, and the objective of the approach, which may focus on improving cost, profit, viability, risk, or time. Other metrics were discarded because they were strongly correlated with the selected metrics and therefore did not provide new information, which included: whether the approach is qualitative or quantitative in nature, whether the approach is linear or iterative, whether the approach is innovative or incremental, whether the approach focuses on details or abstract concepts, and whether the approach is emotional or technical.



Legend	
Horizontal position	Phases of design covered
Vertical position	Focus on manufacturing and operations or product form and function
Number of polygon sides	Complexity of problem addressed
Inner/outer dashed line	Primary focus on product (in)/external factors (out)
Darkness of outline	Level of guidance provided
Darkness of bar fill	Objective: cost (lightest), profit, viability, sustainability, risk, time (darkest)

Acronyms			
ED	Engineering Design	VDD	Value Driven Design
V	Vee Model	W	Waterfall Process
Sp	Spiral Model	A	Agile
AX	Axiomatic Design	TQM	Total Quality Management
ST	Systems Thinking	ToC	Theory of Constraints
DT	Design Thinking	L	Lean Manufacturing
DBD	Decision Based Design	6S	Six Sigma

Figure 9.Graphical representation of design approaches and criteria

With these six key criteria established, preliminary ratings were assigned to each approach, and a graphical representation of this information was constructed, as shown in Figure 9. The horizontal axis represents the continuum of the design process from the earliest phases, beginning with problem identification and definition, to the latest phases, ending with manufacturing ramp-up and logistics. The vertical axis represents the range between operations and form/function-focused approaches. The locations of the shapes along these two axes show where they lie on each scale, and the bar following each shape shows the range of design phases spanned. (The height or thickness of the bars corresponds with the starting phase so as to not confound overlapping approaches.) The number of sides of each shape is representative of the level of complexity of the problems the approaches intend to address. The presence of a dashed outline or inner shape represents whether the approach is more outwardly or inwardly focused. The darkness of the shape and bar outline is indicative of the amount of guidance each approach offers, with darker colours representing a higher level of guidance. Finally, the darkness of the bar itself indicates the objective of the approach; the lightest of these is cost, followed by profit, viability, risk, and time, which is the darkest.

4 DISCUSSION

This classification approach and visual representation can be useful in both educational and industrial settings. Educators and students can use this to aid in selecting the best approach for use in classroom design projects, as this representation can concisely communicate the breadth of established design approaches. It can also be used this way in industry, as product developers may want to use the most appropriate approach or combination of approaches for the design problem that they are facing. While Figure 9 presents a limited number of design approaches that is not entirely comprehensive, the approach used to create it can be applied to any number of design environments, processes, methods, and even tools. The authors recognize that this representation includes some subjective assessments, and the value of Figure 9 is less about the specific ratings and placements of the approaches as it is the intent and means of representing the ratings. The organization of information and ways that it communicates perceived similarities and differences among these distinct approaches to design can add value to education and industry, and any subjectivity can be mitigated in future work by consulting with experts in the field to confirm or redirect the ratings themselves.

For the purpose of this analysis, the authors limited the scope of this consideration to well-defined and relatively high-level approaches to engineering and systems design. From an academic perspective, these are the approaches that the authors found to be most commonly taught in business and engineering design courses. Tools, which are more specific, guided approaches than methods or processes, were excluded from the present analysis, but a similar analysis could be done to compile a list of design tools and organize them in a meaningful way.

The six criteria that are presented in the analysis are a subset of the originally-identified characteristics of design approaches, which included qualitative vs. quantitative, emotional vs. technical, and others. These were ultimately omitted from this analysis because of perceived overlaps among criteria and a desire to show only the most meaningful classifications. These supplementary ranking criteria can be considered in future iterations of this analysis, which would also allow for the consideration and ranking of additional design approaches.

One anticipated extension of this work will be to apply the resulting categorization schemes to a decision-making tool, which can be used by academics and practitioners to gauge the key characteristics and needs of their projects and determine the best design approach or combination of approaches. This would require a series of questions to elicit information about the project, as well as a decision tree or mathematical matching algorithm to recommend the most suitable means for conducting the design project.

5 CONCLUSIONS

This study presents a unique approach to classification and visual representation of the similarities and differences among common approaches to product development. Though the scope is limited and the classification of approaches is subjective, the method and organization is of value in both educational and industrial settings in helping to identify the most suitable design formalisms for any given product development task. This type of evaluation may be expanded to include other types of environments, methods, processes, as well as tools, and it can be supplemented with additional objective and subjective information to enhance the list of criteria and the evaluations of the approaches.

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