INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.239

Testing in Engineering Design: What Are We Teaching

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Abstract

Although testing is critical in industries, the general approaches of testing in engineering design are under-represented in academia. This research investigates the current state of testing based on design textbooks. The findings suggest there is no clear definition of testing. Testing appears in different design stages with adjacent concepts such as prototyping, experimentation, verification, and validation. The processes of testing and its role within engineering design are ambiguous. Recommendations to design educators are provided, and the limitations of the study are discussed.

Keywords: design education, engineering design, product development

1. Testing practice/training in design

INDUSTRY: A potential design can be subject to mismatches with customer needs or technical design faults. Testing is necessary for identifying these faults. Testing can identify issues regarding the manufacturability and maintainability of the product (Qian *et al.*, 2010; Thomke, 2007). Testing is also necessary for verifying and validating the functionality, durability or reliability of engineered products to be competitive in the markets. Similarly, testing is one of the vital approaches for assessing and improving software quality (Orso and Rothermel, 2014). Testing, especially the "field testing", is the critical method for validation and reliability analysis of complex mechatronic systems (Millitzer *et al.*, 2019). Therefore, testing has become essential in product design development (PD). In industry practice, the product design process consists of numerous testing ranging from material and part testing to testing major functional components and subsystems. The whole system also needs to be tested against customer requirements. Different properties of an object such as functional performance, regulation compliance, reliability, durability are tested at different stages of the PD.

An empirical case study in UK-based manufacturing companies and in-depth analysis of their processes identified that testing is closely intertwined with design and analysis, playing a significant role in product development and manufacturing (Tahera *et al.*, 2019). For incrementally developed products, testing is focused on the changes and mostly on verification and validation, but for radically new products, the literature suggests, testing plays other significant roles such as exploration (Erat and Kavadias, 2008), experimentation, learning, demonstration (Thomke, 2007), and refinement (Camburn *et al.*, 2017). This is especially true when new technologies are introduced into the product. Introducing these technologies built in existing products or in the new product are tested thoroughly before release. Thus, the need for testing is growing; in fact, the testing scope, coverage, and rigour will only increase because of the pressure of improved quality.

The generic view of product development (PD), such as the sequential stage-gate process, represents testing as the tasks to be done towards the end of the product development process. This view of product development is far more simplistic and is not practical because delayed problem identification has huge cost penalties. The processes of design and development of mechanical products have faced a transformation from "design-build-test" to "design-test-build" to meet the target of "Build it Right the First Time" and reduce the lead time to market. (Tahera *et al.*, 2019) represents a model which shows how industries frontload testing using design-test-build cycle in each stage of the PD process. Similarly, (Cooper, 2019) reports that using build-test-feedback revise iterations in each phase of the PD provided the opportunity to design the product right earlier and make necessary changes long before formal product testing begins (Cooper, 2019). Their research also identifies testing as a key driver of new product development success. They report that top-performing businesses (27%) carry out concept tests well, and 49% of new product failures were due to deficient product testing. However, the cost of testing has increased significantly compared to other expenditures in research and development (R&D). Typically, testing costs now consume up to 50% of the total development cost (Tahera, 2014). Other research reports testing activities are usually time-consuming and can account for up to 30 to 50 per cent of the total development cost (O'Connor, 2002; Sudol and Mavris, 2018). Companies continuously try to reduce the cost of physical testing by using virtual analysis (i.e. computer simulation and modelling) and better integrating and organizing these activities throughout the PD process.

EDUCATION: While engineering design is becoming more distributed as an instructional topic in engineering curricula (Tolman and Jensen, 2021), it is still most commonly taught in capstone design programs (Ngo and Oh, 2019). As such, a review of capstone design programs and the inclusion of testing as a topic of instruction or an expected activity that is done by students provides some understanding with respect to how testing is viewed in undergraduate programs. In one program (Qattawi *et al.*, 2021), a one semester course has three defined milestones, including a Preliminary Design Review (PDR), a Critical Design Review (CDR), and a Final Design Review (FDR). Testing is explicitly expected as an element for both CDR and FDR milestones. Tests are used with simulation, finite element analysis (FEA), detailed costing, and standards evaluation to help select a "best" solution to be presented at the CDR. Implicit in this is that tests are physical as simulation and FEA are discussed separately. A final prototype is used to demonstrate satisfying the need for the FDR. This suggests that the tests are used for confirmation that the requirements have been met. In both situations, testing is used as a means to evaluate solutions, not as a means to identify requirements, elicit new information, or to justify additional testing. Testing as a knowledge, skill, or ability is not evaluated within the team rubrics. In a different, two semester program (Zhu, 2018), students complete all embodiment and detailed design in the first semester, reserving the construction and testing for the second semester. Implicit in this is that the testing is reserved for validation and acceptance of the final built solution. Following a similar model, it was found that "test engineer" activities were the least frequently identified role within a two semester (build-test second semester) program (Kotys-Schwartz *et al.*, 2018). The students self-reported that they wished that they knew to prioritize testing throughout the year (rather than being relegated to the final semester) and that they should expect some tests to fail. In a recent survey of capstone design programs (Howe and Goldberg, 2019), it was found that "prototyping/testing" as a topic is covered through lectures by 9%, individual assignments by 4%, team projects by 14%, and not explicitly covered or addressed by 73% of the surveyed programs (445 respondents). Testing is focused near the end of the project through design verification and validation. Ultimately, it appears that testing is relegated to a confirmatory activity after prototyping of a final solution has been completed.

A study designed to impart to students the relevance of testing, conducted on 456 undergraduate mechanical engineering students in "Innovation Project" at ETH Zurich project-based engineering design course, finds that artifacts being tested at different product development stages positively impacted the student's success (Türk *et al.*, 2014). (Marius, 2014) also reports factual feedback during engineering project-based course through extensive testing enhances the learning experience. A later survey conducted by the Product Development Group Zurich, ETH Zürich, Switzerland, identified that mechanical engineering graduate students spend an average of 32% of their project time with testing activities; however, they did not receive any substantial input during their studies about testing (Batliner *et al.*, 2018). They highlighted a lack of coherent frameworks or classifications of testing outside the verification and validation processes, making it challenging to address them in the engineering design curriculum (Batliner *et al.*, 2018).

QUESTIONS: With testing becoming increasingly important within the industry, the current state of testing in design education needs to be investigated. The primary purpose of this paper is to survey the teaching of testing within engineering design education. In this case, the scope of design education is limited to published and widely used engineering design textbooks. This allows for a preliminary analysis of the content, potentially identifying specific avenues of investigation which can be operationalized to facilitate a broader and deeper study of engineering design education. As such, two exploration questions are identified for the review of design textbooks.

- **ExQ.1**: To what extent is the concept of testing discussed in design textbooks?
- **ExQ.2**: In what context is testing discussed in design textbooks?

To address **ExQ.1**, objectives measures such as the frequency of the term "test" or "testing" in each textbook can be evaluated. Moreover, chapters and sections of a book dedicated to testing should be recorded. Discussions regarding how and when to conduct testing, and any formalized testing procedures also provides insight into the depth of discussion related to testing. Finally, a definition of testing (explicit or implicit) within the context of engineering design should also be recorded. With respect to **ExQ.2**, the design textbooks can be reviewed to identify the different stages of the design process where testing is discussed. Additionally, testing-adjacent concepts may be recorded to understand if testing is discussed alongside other aspects of the design process. If a textbook discusses different types of testing, such as material, standards, or user testing, these should also be recorded.

2. Design of the protocol

SOURCE MATERIAL: To select source material for analysis of where and how testing is taught as an element in engineering design, several textbooks were reviewed that are commonly marketed to capstone design programs. The citations to these books ranged from 13,000 to 130 citations. Further, an analysis of the larger mechanical engineering undergraduate programs by number of graduates annually was conducted to discern whether additional books should be considered. For Georgia Tech (#1), Iowa State (#2), and Purdue (#6), *The Mechanical Design Process* (Ullman, 2018) was listed as a primary source on course websites. For Virginia Tech (#4), *Product Design and Development* (Ulrich and Eppinger, 2016) was listed. For Texas Tech (#7), *Engineering Design* (Dieter and Schmidt, 2021) was listed. None of the other schools (#3 Texas A&M, #5 University of Central Florida, #8 Penn State, #9 Alabama, and #10 Arizona State) listed textbooks outside of course notes. Thus, filtering based on popularly marketed textbooks, frequently cited textbooks, and the most commonly required textbooks in the larger undergraduate programs in the US, a refined list of books is identified (Table 1). The books can be classified, broadly, by engineering design (ED), methods/principles (M), and product design and development processes (PDP). The number of times that a large US Mechanical Engineering program assigned the book is found in the final column.

Table 1. Selected Textbooks as Source Material

	Book	Citations[1]	Book Title	Focus	Frequency
1	(French, 1985)	985	Conceptual Design for Engineers	ED	None
2	(Dieter and Schmidt, 2021)	2338	Engineering Design	ED	1
3	(Dym and Little, 2004)	1207	Engineering Design: A Project-Based Introduction	ED	None
4	(Pahl *et al.*, 2013)	12911	Engineering Design: A Systematic Approach	ED	None
5	(Cross, 2008)	4139	Engineering Design Methods: Strategies for Product Design	M	None
6	(Jones, 1992)	3414	Design Methods	M	None
7	(Eder and Hosnedl, 2007)	252	Design Engineering: A Manual for Enhanced Creativity	M	None
8	(Hurst, 1999)	131	Engineering Design Principles	M	None
9	(Otto and Wood, 2001)	2547	Product Design: Techniques in Reverse Engineering and New Product Development	PDP	None
10	(Ulrich and Eppinger, 2016)	13258	Product Design and Development	PDP	1
11	(Ullman, 2018)	4842	The Mechanical Design Process	PDP	3

[1] https://scholar.google.com/ (2021.11.12)

https://doi.org/10.1017/pds.2022.239 Published online by Cambridge University Press

REVIEW PROCESS: Once source material was chosen, the research team searched for the term testing electronically (if possible) or manually if only physical copies were available. Unfortunately, some of the source material used in engineering design courses are only available as physical copies, which necessitates the varied approach to analysis. Despite the limitations, a formal process was used to assess whether or not the source materials mentioned testing and to record where and when it was mentioned. The team recorded the following information about the term testing: if it is mentioned in the text, if it is listed in the index, in which chapters it is mentioned, and on which specific pages. The team then recorded any formal definitions offered for testing as direct quotes and summarized how the source material presented an approach to testing in engineering design. If testing was present in the text, what portion of the engineering design process (Problem Definition, Conceptual Design, Embodiment Design, Detail Design, Production & Manufacturing) was recorded (Dieter and Schmidt, 2021; Ulrich and Eppinger, 2016). Further, it was noted how many times "testing" is mentioned alongside related terms: Validation, Verification, Experimentation, Prototyping, Simulation, and Modelling. Direct relevant quotes could be recorded during the analysis process for later clarification. Lastly, basic information was recorded about the source material such as the full author list, book edition, publication date, number of chapters, number of pages, and place of publication. All of the source material in consideration is published in the United States or the United Kingdom. This analysis approach was chosen to represent a broad range of possible ways the source material might present the idea of testing in engineering design. For example, by coupling the number of pages/chapters with the number of times testing is mentioned, it can be roughly determined how much emphasis the source material places on the idea of testing. As another example, recording in which stages of the engineering design process the term testing is discussed could show deviations in how different source materials present the concept of testing during engineering design.

3. Results

Observations from the eleven textbooks reviewed are presented in this section. While the books incorporate different aspects of addressing design requirements in general, and testing in particular, discussion in this paper will focus on the two exploration questions identified in Section 1.3. The exploration questions target the depth of testing related discussion from two perspectives: the extent and the context. In this case, extent refers to the presence of a definition, the discussion of testing approaches, and the different types of testing mentioned. Similarly, context refers to the design stages where testing is discussed, and the testing adjacent concepts present in the books.

DEFINITIONS: Reviewing the selected textbooks through a lens of testing in engineering design revealed that none of the books provide an explicit definition of the term testing. Moreover, discussions of testing frequently omitted clear description of what is meant by testing within an engineering design framework. Similarly, the purpose of testing is not often made explicit. Discussions of testing range from allusions to testing solutions concepts (Cross, 2008), to illustrative examples of test plans using design of experiments (Dieter and Schmidt, 2021).

Of the eleven textbooks reviewed, two books contain statements about testing that resemble a definition. In Engineering Design: A Project-Based Introduction, (Dym and Little, 2004) state that testing involves "establishing a formal means of determining whether or not the concept under consideration can reasonably be expected to meet the design requirements." In this case, the type of testing being discussed is proof-of-concept testing. Alternatively, in The Mechanical Design Process, (Ullman, 2018) discusses testing within the context of "Robust Design" and argues that the role of experimental testing is to "evaluate a proposed design" when mathematical and analytical models of the system do not exist or are insufficient. It should be noted that neither of these books present the statements as a definition of testing; rather they are provided as a description, explanation, and justification of testing. In other books, authors either assume that the concept of testing is understood by the readers or expect the context of the discussion to convey the appropriate meaning of testing.

The concept of testing appears in most of the books in the form of evaluating concepts or solution candidates. In Engineering Design: A Systematic Approach, (Pahl *et al.*, 2013) refer to testing as "checking and assessing" within "a step-by-step approach based on constant testing and evaluation" and "balancing of conflicting needs". In this case, a stronger emphasis is placed on evaluation of concept variants for the purpose of decision making. (Cross, 2008) discusses testing in a similar manner with the primary focus on evaluating alternatives concept proposals. (Ulrich and Eppinger, 2016) place a greater importance on testing by explicitly including a testing and refinement phase which "involves the construction and evaluation of multiple preproduction versions of the product." The authors describe this type of testing as concept testing, where "the development team solicits a response to a description of the product concept from potential customer in the target market."

Beyond definitions, explicit or implicit, the discussion of testing varies significantly between the selected textbooks. For example, (Dieter and Schmidt, 2021) identify several types of testing that are needed and employed in a design project. These include (but are not limited to) testing design prototypes, modelling and simulations, testing for failures modes (electrical and mechanical), and testing for supplier qualification. Similarly, in the final chapter of the Conceptual Design for Engineers, (French, 1985) provides guidance for "checking and evaluation" for various aspects of design including function, manufacturing, maintenance, and safety. The use of standardized tests such as material testing methods defined by NIST, ASTM, or Underwriters Laboratory (UL) is also identified (Ullman, 2018).

APPROACHES: Following a review of the definitions of testing, methods and approaches to testing identified in the textbooks are surveyed. Similar to definitions of testing, the methods and approaches described also vary from textbook to textbook. *Product Design and Development* provides a seven-step process for concept testing (Ulrich and Eppinger, 2016). Similarly, a five-step process for testing and analyzing data under "Robust Design Through Testing", as defined by (Ullman, 2018), is found in Figure 1.

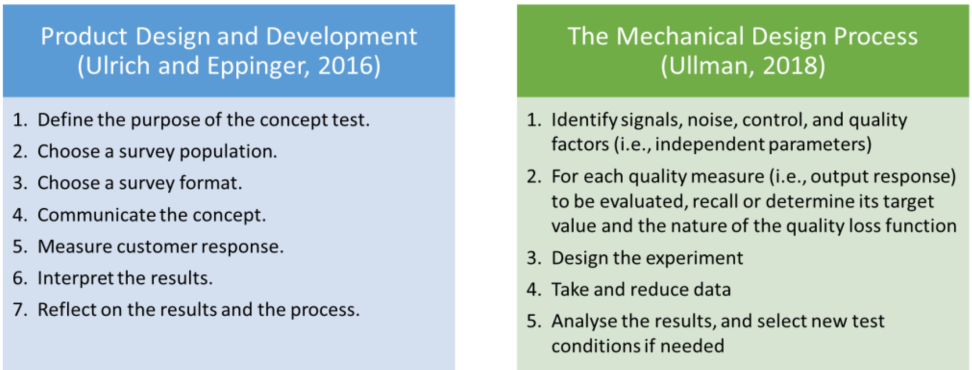

Figure 1. Testing approaches found in design textbooks

In *Product Design and Development*, the focus of testing leans towards evaluation of market opinion on proposed concepts. In this case, the concept may not necessarily be prototyed, but this concept test serves a means to get input from potential users before development is begun (Ulrich and Eppinger, 2016). Alternatively, in the five-step process of Figure 1, the emphasis is on evaluation of product function and performance. Both approaches provide explanation and justification for the steps outlined. In both cases, the purpose of the test is emphasized, along with careful analysis of the results. (Ullman, 2018) identifies the need for target values for test parameters and the use of a "quality loss function" to guide design improvements based on testing. On the other hand, (Ulrich and Eppinger, 2016) point out the need to select the appropriate population to sample and to communicate the alternative concepts in a consistent format to avoid representation bias. While the two approaches discuss testing approaches in a similar level of detail, the focus of testing is different.

In addition to the more step-by-step approaches for testing, other textbooks mention the use of design of experiments (Dieter and Schmidt, 2021), proof-of-concept testing (Dym and Little, 2004), acceptance testing (Hurst, 1999), and exploring design situation (Jones, 1992). Some of the books identify the need for developing a test plan, which can serve as a means to test whether a solution candidate meets the requirements (Dieter and Schmidt, 2021).

DESIGN STAGES: Following the approaches to testing, the design stages where testing is mentioned in each of the textbooks is analyzed. In this case, the design stages outlined by (Dieter and Schmidt, 2021) and (Ulrich and Eppinger, 2016) are used. A graphical representation of the presence of testing in the reviewed books based on the design stage is presented in Figure 2.

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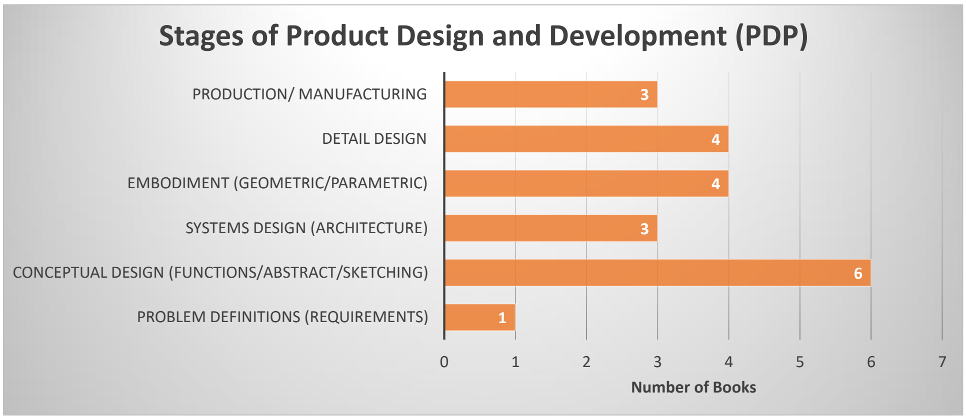

Figure 2. The concepts of "testing" by different design stages/phases

As seen in Figure 2, five of the books reviewed discuss testing in only one design stage. Two books mention testing in two design stages, and two books mention testing in three design stages. One of the books discusses testing in four design stages, and the final book touches on testing in five of the design stages. The concept of testing is frequently mentioned in Conceptual Design (seven books) and Embodiment Design (five books). Conversely, only one book identifies the role of testing in Pre-Design, and testing is virtually absent from Use, and Retirement/Recycling stages.

ADJACENT CONCEPTS: The textbooks are also surveyed for testing adjacent concepts or concepts that are often discussed alongside and in lieu of testing. Key terminologies that found to be used in such a manner are presented in Figure 3. It should be noted that this is not an exhaustive list of all testing adjacent concepts but a list of terms that were discovered in the survey of selected textbooks.

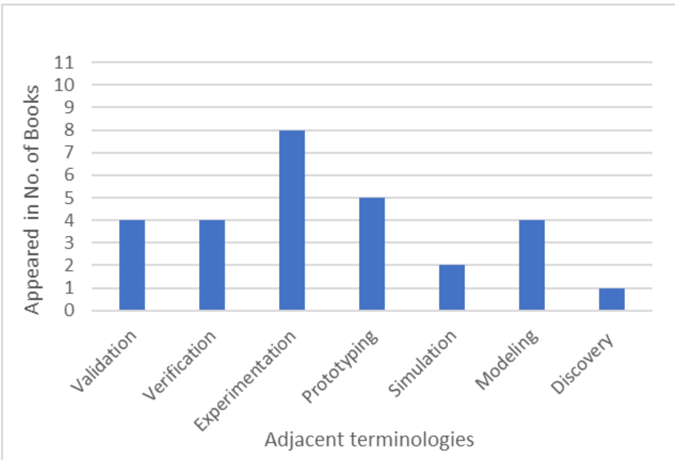

Figure 3. Adjacent terminologies appeared in books in relation to "testing"

As shown in Figure 3, review of engineering design textbooks identifies testing is discussed in relation to the following concepts: validation, verification, experimentations, prototyping, simulations, modelling, and discovery. Eight out of eleven books discussed testing with experimentation. This is primarily in the context of checking and/or assessing design ideas and evaluating design concepts at the early stages of the design process. An exception to this is found in Engineering Design (Dieter and Schmidt, 2021), where authors propose testing competitor products using experiments (benchmarking) in Pre-Design. Another common term used in relation to testing is prototyping, with five out of eleven books using the terms together. Verification, validation, and modelling are discussed alongside testing in four of the books, while simulation and discovery are observed less frequently.

To summarize, review of textbooks revealed that no accepted, explicit, or consistent definition of testing exists among commonly used design textbooks. Moreover, the methods and approaches described in the books suggest that different books have different views on the concept of testing, and the depth of discussion pertaining to testing varies between the books (**ExQ.1**). In terms of the context where testing is

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discussed, Conceptual Design is the most common design stage where testing is mentioned. Additionally, testing is discussed frequently in Embodiment Design and Detail Design. Besides the design stages, testing adjacent concepts were identified, chief among which is experimentation. Prototyping, modelling, verification, and validation were also frequently found in testing related discussions (**ExQ.2**).

4. Discussion

The eleven books surveyed in the study provide insight into how testing is portrayed in these design textbooks. Based on these observations, a working definition of testing is proposed, opportunities for design education are discussed, and limitations of the study are identified.

DEFINING: In reviewing the design textbooks, the primary question in mind was "what is testing?" On that subject, few books provide and answer, and none have a strong and independent definition that can be applied in design practice or taught in design education as inherently sufficient or universally applicable. However, the review of books conducted in this study suggests that there is not only a lack of agreement about the meaning, process, and purpose of testing, there is also a lack of definition. This is evident from the lack of a single clear definition of testing within commonly cited (in research) and frequently used (in teaching) books. To properly discuss the position and role of testing in engineering design education, a definition of testing is needed. Based on the material reviewed, a working definition of testing can be constructed as follows: ***testing is the process of evaluating a proposed design with respect to the design requirements***. Implied in this definition is that testing must have a purpose, with parameters in consideration identified in advance, and the procedure for testing documented. Depending on the design stage, testing may involve only some aspects of the design or the complete solution. Moreover, testing may involve virtual or physical prototypes, and may be conducted intermittently based on the information needed, or systematically based on a test plan.

CONTEXT: Similar to the lack of consistency in the extent of testing-realted discussion, the context of testing is also varied among the books. As previously mentioned, not all books mention testing in the same design stages. The testing adjacent terms used in the books are also inconsistent. Majority of the books discuss testing in the conceptual design phase, and many of them include experimentation in relation to testing. However, that does not show the complete picture of the context in which testing is considered in these books. Table 2 shows the testing adjacent terms used by the design textbooks separated by the design stage in which they are considered. For brevity, symbols have been used and a legend is provided.

Table 2. Testing adjacent concepts in design stages

Books	Pre-Design	Problem Definition	Conceptual Design	Systems Design	Embodiment Design	Detailed Design	Production
(Pahl *et al.*, 2013)			E, D		M		
(Eder and Hosnedl, 2007)					P, V, L		
(Cross, 2008)			V				
(French, 1985)			E				
(Ulrich and Eppinger, 2016)		P	E				L
(Dieter and Schmidt, 2021)	E		E		E	M, S, P	P, L
(Ullman, 2018)				E	E, P	E, V	
(Dym and Little, 2004)			E	V	E	M, V	
(Jones, 1992)				E			
(Hurst, 1999)			L	L			
(Otto and Wood, 2001)						E	
*E – experimentation; P – prototyping; D – discovery; V – verification; L – validation; M – modelling; S – simulation;							

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As shown in Table 2, discussion of testing and testing-related concepts is largely missing from Pre-Design, Problem Definition, and Production stages of the design process. While omitted from Table 2, it should be noted that testing related discussion is also not found in Use and Retirement/Recycling stages of the product lifecycle. This aligns with other observations that imply most of the testing related discussion in the selected books is about concept testing or testing for refinement. This is further supported by the presence of experimentation in Conceptual Design, Systems Design, and Embodiment Design stages. Discussions of experimentation in the books often involved testing aspects of the design to evaluate them against requirements. This is done either to compare alternative concepts or to check whether the design can meet certain requirements. The use of prototypes can also be seen in Embodiment Design and Detail Design stages. Early prototypes are built for checking and assessing the design idea, while later high fidelity (production intended) prototypes are built for testing the product's functionality, reliability, and durability. Along with physical prototypes, modelling and simulation is also discussed in these design stages. Finally, testing for verification and validation is discussed in throughout mid- to late-stages of the design process.

It is important to understand the difference between these concepts, especially for the design students to plan and conduct testing in design projects. (Dym and Little, 2004) state that "prototypes, models, and proof-of-concept testing have different roles in engineering design because of their intents and test environments. These distinctions should be borne in mind while planning for the design process". However, between the eleven books reviewed in this study, there is little agreement about the purpose of testing, types of testing, and methods for testing.

RECOMMENDATIONS: Through this study, it was found that no clear or consistent definition for testing is offered by literature commonly used in design classrooms. The authors suggest that instructors of engineering design courses spend time discussing a formal approach to testing in design with their students. One example might be to discuss that the purpose of creating a prototyping is for testing design concepts at various stages of development and to have students outline exactly for what they are testing (functionality, aesthetics, durability etc.) (Türk *et al.*, 2014). It is also clear that testing does not only occur at a specific point of the design process. Across the reviewed literature, it was found that testing is discussed alongside simulation, modelling, etc., which is an indication that testing might not only be limited to physical models. Testing occur virtually (such as a computer simulation) or physically (from a prototype). However, the relationship and information flow between these variations is not clear from the reviewed literature and work can be done to relate these terms in a more formal manner. Testing during embodiment design might look significantly different from the process during detail design.

The common design approach known as "design-test-build" includes the idea of testing, but it is unclear when, how, or why testing should be implemented. Testing could theoretically occur at all three stages of this approach depending on how it is defined. For example, during the first portion of the iterative process, "Design", designers are testing their concepts against requirements, stakeholder desires, and customer needs. Design educators should not assume that students inherently understand what testing means and how to do it. As an analogy, the scientific method is taught in grade school and during STEM undergraduate degrees at length, yet students still can struggle with the process. Students are exposed to "testing" a hypothesis, but the process of testing may not be entirely clear. Spending time on testing in design could help students understand what they can learn from different phases of the design process and how to achieve meaningful results from their models, simulations, and prototypes.

LIMITATIONS: This study has a few limitations. First and foremost, the reviewed source material is not all-encompassing. While the research team took considerable measures to ensure that that the reviewed literature provides a representative cross-sectional view of engineering design literature commonly taught in engineering design classrooms, some literature was undoubtedly overlooked. Further, course syllabi are increasingly harder to find since universities largely store them within learning management systems (LMS), which universities do not always make publicly available. Another limitation of this study is that synonyms of the term testing (i.e., experimentation, probing, analyzing, etc.) were not explicitly considered. This decision was made to appropriately scope this research but may have excluded content that is relevant to conceptual idea of testing as a practice in engineering design. To mitigate this, the research team recorded when testing was presented alongside related terminology (Validation, Verification, Experimentation, Prototyping, Simulation, and

Modelling). An unavoidable limitation was that some source material was only available as a physical copy. This greatly increased the effort required and may have increased the likelihood of making errors. While discussed as a limitation, this showcases the potential for computer based searching on material. Another underlying limitation of our approach to this study is the assumption that a formal approach to testing is indeed something that should be taught to undergraduate engineering students. It may be the case that testing is simply understood rhetorically and that there is not inherent value to explicitly defining it in an engineering design context. The authors of this work argue that there is value in explicitly defining the term testing. Evidence of improved design outcome or understanding by students that learn a formal approach to testing is left to future work.

FUTURE: Work presented in this paper is an investigation intended to understand how testing is taught within engineering design. While the design textbooks surveyed in this study represent an aspect of design education, there are several other avenues that need to be queried to better understand what and how design students are learning about testing. Two clear avenues of future work can be identified to further study this subject: an interview-based study to gain insight from design educators, and a case study approach to identify what students are learning from design practice. These three facets of design education can then be compared to identify the aspects of testing that permeate different modes of learning. Moreover, data from the different studies can be used to triangulate effective mechanisms for teaching testing in engineering design.

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