Elements of Teaching Design under Uncertainty

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Abstract

Uncertainty is unavoidable in engineering design. Engineers with knowledge of Design Under Uncertainty (DUU) are able to easily design flexible products with decreased sensitivity to uncertain events. While significant research is being undertaken on DUU, the topic of uncertainty has not been given comparable attention in the area of teaching design. The goal of this paper is to contribute to the enhancement of teaching engineering design. To this effect, the following research question was developed: Is incorporating uncertainty in engineering design important? To solicit the reaction of the stakeholders in this regard, a survey instrument was designed. The survey instrument addresses three aspects of teaching engineering design: the importance of considering uncertainty, the current practice of teaching engineering design, and the way forward. This survey was sent to the design faculty of ABET accredited 89 of the top 100 Graduate Mechanical Engineering schools in the USA. A Power Analysis was performed to estimate statistical significance of the results obtained. Results show that the majority of design faculty in the nation agree that it is important to incorporate the topic of uncertainty in teaching design and that industry will benefit from it. Although many agree on the importance of uncertainty in design education, the majority of educators are still hesitant to integrate uncertainty in teaching design. For this reason, a roadmap of the elements of teaching DUU was constructed and presented. This roadmap is believed to avoid the dilemma and help design faculty to incorporate uncertainty in teaching design. Moreover, while Probability and Statistics courses are usually taught prior to teaching design, there is a need to revitalize students' knowledge of Probability and Statistics in light of teaching uncertainty.

1. Introduction

1.1. Background

Teaching and learning engineering design is rather unique since the necessary skills are difficult to attain directly from conventional teaching-learning processes. Unlike other engineering courses, which mostly require science and mathematics to solve mainly close-ended problems, engineering design demands additional skills of solving open-ended problems, decision making and effective communication in design teams. Designers are expected to be team players to solve engineering problems in an iterative manner while always keeping in mind the main design objective and the concept of uncertainty. Dym[1] indicated that one of the attributes that designers exhibit in their design thinking is the ability to assume the world as not fully deterministic and to incorporate uncertainty in the design process.

Definition of uncertainty is widely different and is greatly influenced by context and discipline [2]. It refers to lack of definition, lack of knowledge or lack of trust in the knowledge[3]. Uncertainty is prevalent in engineering design[4]. Designers who address uncertainty in their design have one attribute of a good designer, which is considering uncertainty. Other attributes of a good designer include: tolerating ambiguity, keeping the big picture in mind, being able to make decisions, communicating in many languages of design and being able to work in teams[1]. What might be interesting is that most of these attributes are influenced by uncertainty. Communication skills, for example, are mentioned to be affected by imprecise expressions which may lead to uncertainty[5]. On the other hand, Wood[6] argues that uncertainty should be considered in design decision making.

Considering uncertainty helps not only to assess several options during the design process but also to design in such a way that the design could be less influenced by uncertain parameters [4,7]. These options in design will make the design process less difficult than the deterministic approach where changes at a later stage may be difficult or expensive. The importance of DUU is also directly proportional to the complexity of the design[7]. . Uncertainty is not only an important feature throughout the design process[4], but it is also a factor in the prediction of the manufactured product's market scenario[4,7]. In order to alleviate the effect of uncertainty in product design, it is necessary to identify the sources first. According to Chalupnik et al.[4], there are two major sources of uncertainty: exogenous process uncertainty (caused by the environment) and endogenous process uncertainty (caused by the process). Exogenous uncertainty entails uncertainties that are caused by factors affecting the product after it is deployed into the market and is out of the hands of the maker of the product. These sources could be categorized into three main types: use context, market context, and political/cultural context. If the product is affected by operational environment due to unexpected weather conditions, the source of uncertainty is referred to as *use context exogenous uncertainty*. On the other hand, a market could be a source of uncertainty. A product could easily be the victim of a dynamic market condition where the product could be replaced by a newly emergent competitor. The demand for a product can also change depending on several reasons such as environmental changes. Market could also be influenced by political and cultural factors, which can encourage the design and operation of approved product types with certain standard criteria. Endogenous uncertainty is uncertainty that arises mainly from where the product is designed. The sources could be in the context of product or corporate. Product context encompasses sources of uncertainty emanating from product design and development. A component may not work equally effectively when used in different systems, as a result of the changes in operating conditions which may require different demand. Unforeseen interactions between components of a product could also be a source of uncertainty. Corporate context uncertainties arise from the business context of product design. Companies can easily impact product design since it manages important aspects of the operation such as design resources and contractual agreements[4,7]. Since a deterministic design approach defines requirements, the approach could be risky in areas where there is no absolute certainty or definite knowledge[7]. Therefore, understanding sources of uncertainty helps to protect the system from risks of unanticipated failure by mitigating the sensitivity of the system to uncertainty[4]. This is possible if the type of uncertainty is reducible or could be mitigated. However, some uncertainties are irreducible[4]; in this case, knowledge of uncertainties and their sources helps to make the product flexible enough to alleviate the risk of product failure or malfunction[3]. Uncertainties, which are reducible, are known as epistemic. Epistemic uncertainty, also known as imprecision, refers to uncertainty that emanates from insufficient knowledge (inaccuracies in our representation, prediction and estimation of reality)[3,4,8]. Several other names used to refer to these types of uncertainty are listed in the reference by Thunnissen[5]. Uncertainties which are irreducible are known as aleatory. Aleatory uncertainty is the result of innate randomness in the system[3,4,8]. It is also sometimes referred to as stochastic [2,3] or objective uncertainty[3].

In the past two decades, tremendous research have been conducted in the area of uncertainty in engineering[5]. Moreover, the concept of DUU is currently being used in industries such as aerospace [3,9], structural[10,11] and systems and control[12]. de Weck et al.[7] provide real-world industrial examples where the effect of uncertainty was observed. The effects were observed in low earth orbit satellite constellations, automotive manufacturing plants, military equipment in Iraq, and fashion and customer products.

Despite the undergoing researches and their importance in industries, the concept of uncertainty is not well known among engineering graduates. This is not because theories of uncertainty are not numerically represented but because they are not usually included in a typical engineering curriculum[7]. For the special issue of the *ASME Transaction: Journal of Mechanical Design* dedicated to the topic of Design Under Uncertainty (DUU) [13], the editors indicated that no paper on "teaching design under uncertainty" and "theoretical foundations and frameworks for DUU" was received or accepted. In addition, they have pointed out that the papers collected do not necessarily provide a unified theoretical view of DUU.

1.2. Motivation

Chen et al.[13] claimed that uncertainty is ubiquitous in engineering design while Chalupnik[4] emphasized that uncertainty is prevalent in product development. Several design educators[14] argue that the ability to handle uncertainty is one of the six skills that good designers must have for design thinking. Wood[6] underlines that uncertainty analysis techniques, such as six sigma design and robust design, are used widely in industry where uncertainty is recognized and managed throughout the design process. Chalupnik[4] also concluded that industry will benefit from engineers who have better understanding of uncertainty, how it impacts projects, and how processes could be made less sensitive to the effects of uncertain events. According to the above claims and others, it has become extremely apparent that the concept of uncertainty is unavoidable in the area of engineering design. Hence, there is a need to train engineers with an appreciation of uncertainty in the design process and for DUU to be part of the undergraduate engineering curriculum.

Thunnissen[5] indicated that in the last two decades, research in uncertainty in the field of engineering has been significant. Nonetheless, Chen et al.[13] pointed out that '*Teaching DUU*' was one of the solicited topics that have not been addressed by any of the over 60 technical papers submitted to be published in a special issue publication on DUU. This shows that there is a disconnection between research and pedagogy in the topic of uncertainty. The recent developments of DUU attained via extensive research need to be tapped and added to the pedagogy of undergraduate program of engineering. The authors of this current paper believe that there is an urgent need to address the topic of uncertainty in teaching design.

1.3. Research Question and Scope of Work

The goal of this paper is to contribute to the enhancement of teaching of engineering design. For this reason the following research question was developed: Is incorporating uncertainty in engineering design important? To help answer the research question the following specific aims are formulated:

1. Assess the importance of incorporating the topic of uncertainty in engineering design.
2. Assess the current practice of teaching uncertainty in engineering design.
3. Propose elements of teaching uncertainty in engineering design

The scope of work is to:

- develop a survey instrument to address the stakeholders pertaining to three aspects of teaching and learning engineering design: importance of the topic of uncertainty in design, the current practice of teaching design and the way forward.
- identify top, ABET accredited Mechanical Engineering schools and the design faculty of these schools

- execute the survey and analyze the results
- construct a roadmap of the elements of teaching DUU.

2. Methodology

2.1. Survey Instrument

As indicated in the motivation of this study, the authors find the stakeholders' input concerning uncertainty in teaching design very important. For this reason, a survey instrument addressing three aspects of teaching engineering design was designed: it addresses the importance of uncertainty, the current practice of teaching engineering design, and the way forward. The survey was designed using the widely used survey software called Qualtrics[15]. The survey instrument includes Likert-type (aka Likert Scale or rating scale), Yes/No (dichotomous), multiple choice, open-ended and demographic questions.

The survey follows the postal questionnaire method[16] that involves sending questionnaires to a large sample of people located in a wide geographical area and who do not have any previous contact with the authors. The response rate is usually as low as 20%. Thus, the survey was sent to 266 design educators of 89 of the top 100 Graduate Mechanical Engineering programs (with ABET accredited undergraduate programs) in the US to ensure that the demographic profile of respondents reflect the design faculty population in the nation. The design faculty included a Dean, Full Professors, Associate Professors, Assistant Professors, Adjunct Faculty, Visiting Assistant Professors, and Emeritus Professors. The design faculty were communicated, via their institutional emails, to voluntarily participate in the survey.

As can be seen in Appendix 7.1, some of the questions (Q4.1.1, Q4.1.2, Q4.2.1, Q4.2.2, Q5.1, Q6.1 and Q7.1) are designed to have a *Display Logic*, i.e. they are displayed based on the answer selected in prior questions. For example, Q7.1 '*Do you think industry will benefit from incorporating the topic of uncertainty in design courses at undergraduate level?*' will be active if the respondent answered a 'Yes' to Q7 '*Have you had a research and/or design project from industry or have you been affiliated with industry in the past five years?*'. This is due to the authors' belief that design professors who have had industrial attachment in the past five years will be in a better position to answer if industry will benefit from the incorporation of the topic of uncertainty in the undergraduate teaching of design.

Responses are presented using bar charts and tables. The written feedback of the respondents is also presented as packs of responses relevant to each result category. The results of the survey are analyzed qualitatively as well as quantitatively, using different statistical methods, including Power Calculation.

2.2. Power Analysis

The power of a statistical test is the probability of correctly rejecting a false null hypothesis[17]. It is a useful tool to estimate the precision of inferences that one expects to achieve with a given sample size, or to estimate the sample size required to attain a certain precision.[18] In this survey, the sample size necessary to attain a certain precision or statistical significance level was not determined before the survey was actually carried out. Hence, a measured proportion of a survey result is used to specify the probability that a particular estimate or inference is statistically significant, i.e. to ensure that the confidence interval excludes the null value. That is, given the recorded p-values, classical Power Analysis[17–19] is used to calculate the sample size needed to validate the precision of inferences drawn from this study. For this purpose, confidence level of 95% or $\alpha = 0.05$ and a power of 80% or $\beta = 0.20$ (conventional level in sample size calculation) are considered.[18,19]

3. Results

The results are based on what is collected from 54 voluntary design faculty respondents, i.e., the expected 20% feedback that one can expect from the Postal Questionnaire type survey. The survey results are grouped into three categories and are presented in each category as shown below.

3.1. Importance of the topic of Uncertainty in Design

The responses of the design faculty pertaining to Q1 '*Do you think it is important to incorporate the topic of uncertainty in teaching design*' and Q7.1'*Do you think industry will benefit from incorporating the topic of uncertainty in design course at undergraduate level?'* is presented in Figure 1 and Figure 2, respectively. Out of the 53 respondents, Figure 1 shows that approximately 79 % (62.26% responded 'Very Important' and 16.98% responded 'Extremely Important') believe that it is important to incorporate the topic of uncertainty in teaching design. Furthermore, Figure 2 shows that out of 47 respondents, approximately 83% (48.94 % responded 'Likely' and 34.04% responded 'Very Likely') believe that industry will likely benefit if the topic of uncertainty is incorporated in design courses at the undergraduate level. As indicated in section 2.1, the respondents of the second question are fewer since the question was only active for design faculty who had a research and/or design project from industry or those who have been affiliated with industry in the past five years.

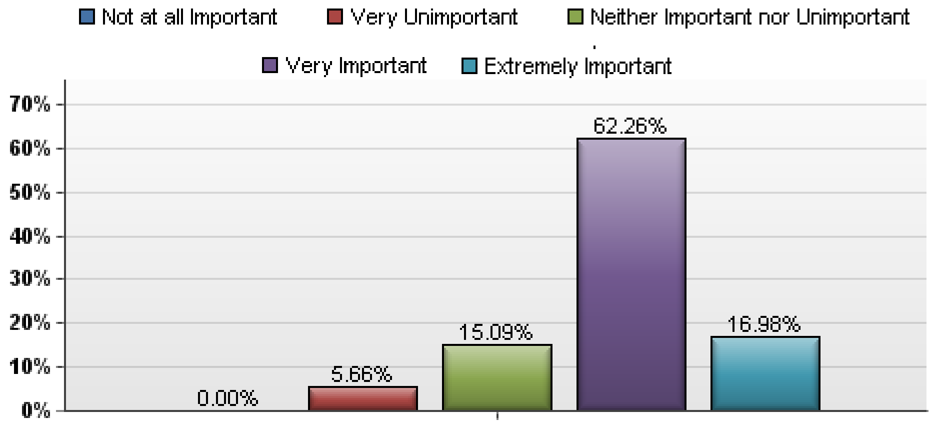

Figure 1. Is it important to incorporate the topic of uncertainty in teaching design?

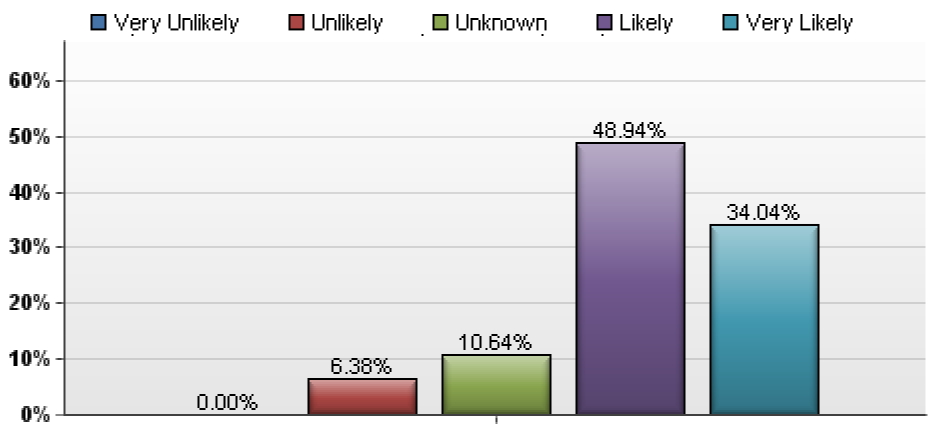

Figure 2. Will industry benefit from incorporating the topic of uncertainty in design course at undergraduate level?

Classical Power Analysis, explained in section 2.2, is used to justify if the recorded proportion (percentage) values from the sample sizes, 53 for the first and 47 for the second case, are statistically significant. To justify the claims that '*incorporating the topic of uncertainty in design is important*' and that '*industry will be benefited if topic of uncertainty is incorporated in undergraduate design course*' are supported by more than 50% of the population (design professors in the nation), a conservative standard error (standard deviation) of $s.e. = \frac{0.5}{\sqrt{n}}$ is considered. Furthermore, a confidence level of 95% or $\alpha = 0.05$ and a power of 80% or $\beta = 0.2$

(conventional level in sample size calculation: choose n such that 80% of the possible 95% confidence intervals will not include 0.5, i.e. an 80% chance that the sample proportion, $\hat{p}$ will be more than 1.96 standard deviations away from 0.5)[18] are also considered. Using the recorded p-values of 79% and 83% as the population proportions, sample sizes of $n = 23$ and $n = 18$, respectively, are required. Considering the actual sample sizes of $n = 53$ and $n = 47$, the results show that there is more than 80% chance that the 95% confidence interval will be entirely greater than 0.5.

Furthermore, some of the respondents of the survey also demonstrated their support by writing a feedback to Q8 '*Finally, please provide your valuable feedback if the topic of uncertainty could be considered in teaching and learning of engineering design.*' as shown below:

- R8.1: "Not only do I feel it is important to incorporate elements of technical uncertainty as it impacts functionality and failure modes, design and manufacturing costs, etc., but based on my extensive experience in product design, manufacture and marketing, uncertainty in the area of market acceptance is a critical element that must be fully embraced if the market is to accept products that otherwise have gone through a sound and competent engineering design process."
- R8.2: "Certainly uncertainty is important in engineering design."
- R8.3: "Uncertainty and ambiguity are both important components of any real design problem."
- R8.4: "This is becoming an essential component of any advanced design, especially for structurally critical components."
- R8.5: "This is an extremely important topic."

- R8.6: “The topic is very useful as some of the assumptions used in design maybe be based on probability. Ex. designing a product for Africa may rule out completely extremely cold and freezing temperatures. Would the device still operate effectively if some climatic changes occur to the point of dropping the temperatures to freezing values (even temporarily)? This had happened in the past.”
- R8.7: “Uncertainty management is critical in the success of engineering projects.”
- R8.8: “Uncertainty is an inherent component in any real engineering design problem. Coupled with ambiguity, these topics provide the greatest conceptual problems for students.”
- R8.9: “Engineering design should include managing risk, which naturally requires thinking about uncertainty.”
- R8.10: “I am a firm believer in incorporating uncertainty in design education. I cover it extensively in my graduate class which is new this year.”
- R8.11: “It is an important topic and both students and Industry will benefit from it.”

On the other hand, only three out of 54 respondents indicated that “uncertainty” was not defined in the survey instrument. These are:

- R8.27: “The survey did not define uncertainty. While the questions imply that you are considering probability such as used in statistical tolerancing, this is not the only area of uncertainty. There can be significant amount of uncertainty relating to performance of new design concepts that have nothing to do with probability.”
- R8.28: “It is profoundly unclear what teaching 'uncertainty' really means. It's pretty uncertain.”

- R8.29: “The further I got in the survey, the less sure I felt that we were using uncertainty in the same context.”

3.2. Teaching Uncertainty in Engineering Design – Current Practice

This section summarizes responses of design faculties to Questions Q2, Q3, Q4, Q4.1.1, Q4.2.2, Q5, Q5.1 and Q6 (see Appendix 7) are summarized. Based on the responses to Q2 and Q3, while approximately 85% of the respondents believe that students come to their design class already exposed to the concepts of Probability and Statistics, the following evaluation was also reported regarding the level of their exposure. As per the recorded data, approximately 35% of the respondents believe that students have higher level understanding, and approximately 37% believe that students have average level of understanding of the concepts of Probability and Statistics. Accordingly, a total of 72% of respondents believe that students have the prerequisites to learn the concepts of uncertainty in design class. Figure 3 below displays the observations of 54 design faculty to Q3 ‘*How do you describe the level of exposure (of your students) to the concepts of Probability and Statistics*’ summarized above.

The survey also solicits respondents, via Q4, if they already have incorporated the topic of uncertainty into their design course/courses. Out of the 53 respondents, 68% answered ‘Yes’ while 32% answered ‘No’. The 36 respondents who answered ‘Yes’ were again asked Q4.1.1 ‘*How is the topic of uncertainty incorporated into your design Course*?’ Table 1 below and the list presented following the figure explain how currently uncertainty is incorporated in design classes.

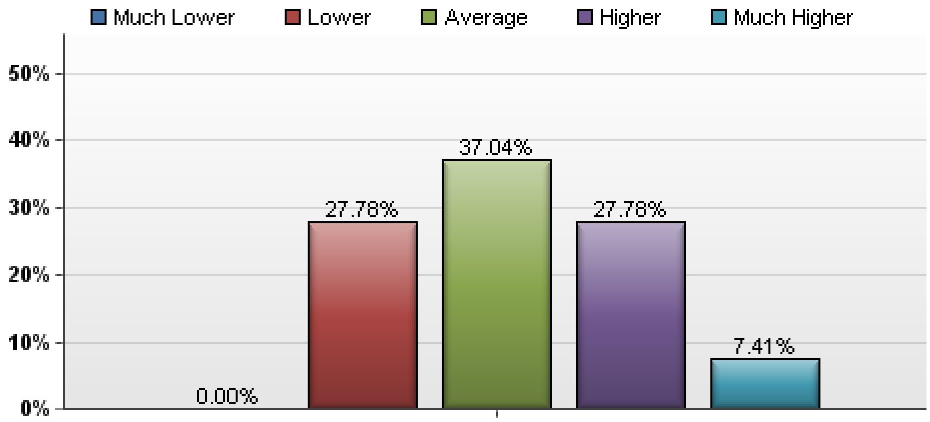

Figure 3. What is the level of exposure of students to the concepts of Probability and Statistics?

Table 1. The way currently uncertainty is incorporated in design classes

#	Answer	Bar Chart	%
1	As an independent Chapter/Chapters.		17%
2	As a sub-chapter in every design topic covered.		6%
3	As a sub-chapter in few chapters.		22%
4	As a brief introduction.		39%
5	Other		17%

The 17% respondents who answered 'Other' in Q4.1.1 have indicated the way uncertainty is incorporated in their design classes as a response to Q4.1.2 as follows:

- R4.1.2.1: "Assignments and projects"
- R4.1.2.2: "Students are expected to have knowledge of *p*-values coming into most of my courses. I hold them accountable for these concepts by requiring that they apply the correct statistical analysis to their testing results."
- R4.1.2.3: "Each design course has a project. In that project we emphasize the open-ended aspects of every design problem. Uncertainty in a statistical sense is introduced to the

sophomores in lab (probability distributions) and then again in the CAE course under the idea of tolerances and then again in the junior labs as well as the materials engineering course (under the material properties topic).”

- R4.1.2.4: “Integrated across topics and projects.”
- R4.1.2.5: “Several lectures with exercises where they process raw data. We start them with Excel and then move them to JMP.”

The respondents who have not incorporated the topic of uncertainty into their design course/courses were again asked in Q4.2.1 to briefly describe their reason as to why they are not currently addressing the topic. The responses are categorized in three groups as follows:

Design Prerequisite

- R4.2.1.1: “It is addressed in other courses but is often considered in the design course”
- R4.2.1.2: “There is no a lot of room in the didactic part of our design courses to include topics. My feeling is that uncertainty is best introduced in courses that come before the capstone design course and then students use it, if needed, in their design project.”
- R4.2.1.3: “Students should have already been exposed to it as part of a sequence of courses on measurements - probably a better fit than in my machine elements course.”
- R4.2.1.4: “We have 3 courses in design. One of them incorporates Probability and Statistics. One I teach does not.”
- R4.2.1.5: “It is addressed directly in a Probability and Statistics course and in our senior lab class.”

Time Constraints

- R4.2.1.6: "The design course is taught in a condensed time frame, and this is one of the things that was cut. Other courses taught with design as a backbone, is taught at a sophomore level."
- R4.2.1.7: "Too many more important topics, Time constraint"
- R4.2.1.8: "Time is always an issue. I state it is not addressed, I mean as a standalone topic. The concept in discussed during various other topics, however, not in depth."
- R4.2.1.9: "Limited credit hours, lack of knowledge"

Advanced Concept

- R4.2.1.11: "This is an undergraduate design course. Uncertainty is considered an advanced graduate-level topic."
- R4.2.1.12: "I think mixing the safety factor and uncertainty will be confusing for undergraduate students."
- R4.2.1.13: "Focus remained on basic phenomena and principles."
- R4.2.1.14: "The course is a project-based capstone design course. Very little new material is introduced."
- R4.2.1.15: "There is no reason. Uncertainty should be a course itself. If so, there is no need to include in design course. I would consider uncertainty is a continuation of a design course."

To understand the current practice fully, the design faculty were also asked Q5 '*Do you teach a separate course on Design Under Uncertainty (DUU) or any other course with a topic of uncertainty?*' Out of 53 respondents, 9 responded that they do have an independent Course.

Table 2 below presents the responses of the 9 design faculty to Q5.1 '*Please provide the course name, at what level it is taught and whether the course is given as an elective or regular course.*'.

Table 2. Separate Course on DUU

Courses on Uncertainty	Level	Cr. Hrs	Regular or Elective
Design of machine Elements	….	3	Regular
Mechanical Reliability	Junior	3	Regular
Statistics, Quality and Reliability	Junior	4	Regular
Introduction to Design	Junior	3	Regular
Probabilistic Engineering Design	Senior	3	Elective
Systems Engineering	Grad	4	Regular
Models, Data, and Inference	Grad	4	Regular
Decision-based Design	Grad	3	Elective
Manufacturing Processes and Design	Grad	4	Elective

As shown in Table 2, five of the courses are at the upper undergraduate level while four are at the graduate level.

The current practice on how (capstone) design projects are handled is also solicited via Q6 '*Do your (capstone) design projects consider the topic of uncertainty?*'. Out of 53 respondents, 74% said their (capstone) design Projects consider the topic of uncertainty.

Respondents of the survey also presented their additional reflection on the status quo as part of the response to Q8; their comments are listed in two groups below:

Existing Approaches (Design of Experiments, GD&T Analysis)

- R8.12: "I added a Design of Experiments module to our design class this year, complimenting what was already being done in the context of reliability."

- R8.13: “The required laboratory courses (Sophomore, Junior, Senior) emphasize statistics and uncertainty analysis in Design of Experiments. Students in the Junior level Machine Design course are taught to consider the variability of materials, manufacturing processes, and unpredictable factors of products in service such as variable loading, and the necessity for a factor of Safety. They analyze the empirical nature of fatigue analysis, and apply fundamental concepts of uncertainty in designing components.”
- R8.14: “We focus on teaching them how to deal with uncertainty through prototyping and experimentation/analysis (aka risk reduction).”
- R8.15: “Uncertainty is typically a minor aspect in our Capstone/Industry Sponsored projects. It typically affects tolerances and GD&T analysis, but in and of itself, it has not been a critical issue in any project over the last ten years.”

New Approaches

- R8.16: “Uncertainty and ambiguity are both important components of any real design problem. Dealing with both is something that we try to incorporate into our core design course sequence.”
- R8.17: “This is becoming an essential component of any advanced design, especially for structurally critical components.”
- R8.18: “Our Course is a Sophomore course. In addition capstone has some of uncertainty in design.”
- R8.19: “I cover it extensively in my graduate class which is new this year.”

3.3. Teaching Uncertainty in Engineering Design – The way forward

In this study, the authors also tried to understand the future plans of the design faculty who have not currently incorporated the topic of uncertainty into their design course. Thus, respondents who answered "No" to Q4 '*Have you incorporated the topic of uncertainty into your design course/courses?*' were asked Q4.2.2 '*Would you consider incorporating the topic of uncertainty in future design course?*'. Despite the overwhelming response in favor of the importance of incorporating uncertainty in teaching design (as presented in section 3.1: results from Q1, Q7.1 and Q8), few faculty responded positively to the question of incorporating the topic into their design class in the coming two or more years. Only two out of 17 respondents said it is likely that they will consider incorporating uncertainty within one year and 2 out of 16 responded they will consider within two years or more.

It is also worth mentioning here that out of 54 respondents, 83% responded that they do not have an independent course in DUU (see Table 3) when responding to Q5 '*Do you teach a separate course on Design under Uncertainty (DUU) or any other course with a topic of uncertainty?*'.

Table 3. Separate course on design under uncertainty

#	Answer	Bar Chart	%
1	Yes		17%
2	No		83%

Similarly, to the 14 faculty who answered "No" to Q6 '*Do your (capstone) design Projects consider the topic of uncertainty?*', Q6.1 '*Would you consider incorporating the topic of uncertainty in future (capstone) design projects?*' was activated. Two said they will likely incorporate the topic of uncertainty into their future (capstone) design projects 'Next Year' and four said 'In two years or more'.

Apart from the response to these questions, the participants have given their feedback, as part of Q8 '*Finally, please provide your valuable feedback if the topic of uncertainty could be considered in teaching and learning of engineering design*'. These are:

- R8.20: "Our students take a course in probability and statistics, but, unfortunately, it stands alone, and they do not necessarily see its relevance to other engineering topics. In engineering design, topics from probability arise naturally in the study of bearing life, for example, but could enter virtually everywhere."
- R8.21: "It certainly can be included in the context of uncertainty in the properties of materials and components, geometric tolerancing, and the uncertainty as to the environment in which a design operates. These topics are semi-quantitatively included in the form of risk analysis of the successfulness of design itself. However, I would not want to make it a major focus of our capstone design course as there are other concepts of importance that already are difficult to find the time for in the course."
- R8.22: "I don't think it can only be taught 'theoretically' in a design course as a chapter/topic - seems as though it would need to be brought in and emphasized through real-world projects/problems."
- R8.23: "Students should be aware of uncertainty, but I do not believe the methods to deal with uncertainty can be taught at the undergraduate level. They should take uncertainty into consideration, modify weights, scales, and see the effects before making decisions."
- R8.24: "I'd broaden it to experimental design and uncertainty. Also, we need to be teaching them how to do ANOVA, multiple linear regression, etc, not so much propagation of error."

- R8.25: “Uncertainty should be considered earlier in the curriculum in a design methods class.”
- R8.26: “I would like to now start incorporating it in the undergraduate curriculum.”

4. Discussion

4.1. Importance of the topic of Uncertainty in Design

The results of power calculation show that there is 80% chance that the 95% confidence interval will be entirely greater than 0.5. This conclusively confirms the claims that more than 50% of design faculty consider the topic of uncertainty important and should be incorporated in teaching design. The supporting statements (R8.1-R8.11) listed in section 3.1 fully corroborate with the aforementioned statistical results and claims. Furthermore, de Weck and co-workers[7] provide four examples from industries where crucial forms of uncertainty were not considered and the systems were negatively impacted once they had been deployed in the field. The authors argue that by ignoring uncertainty in the design process, the produced engineering systems did not have built-in flexibility to adjust to the true nature of the field and market conditions. Chalupnik et al.[4] observe that industry could benefit from an enhanced understanding of how uncertainty impacts the product development process and how the process could be made more insensitive to the effects of uncertainty. Dym[1] listed the ability to accommodate uncertainty as one of the qualities required in design thinking.

While widely different definitions of uncertainty exists and are greatly affected by context and discipline[2], the survey instrument sought a common denominator not to constrain the respondents by a narrow definition. It was preferred that the design faculty have their respective definition of uncertainty in mind and respond to the importance of incorporating the topic of uncertainty in engineering design.

4.2. Teaching Uncertainty in Engineering Design – Current Practice

According to the survey, while 85% of design faculty members believe that their students come to their design class having been exposed to the concept of Probability and Statistics, 72% of the respondents believe that their students have high and average level knowledge of Probability and Statistics to learn DUU. This is a positive indication that incorporating uncertainty into the existing design curriculum is feasible. Nevertheless, while capitalizing on the importance of the prior knowledge of Probability and Statistics for learning uncertainty in design, Dym[1] indicated that some design educators believe that the undergraduate curricula do not emphasize on explaining the role of Probability and Statistics in Engineering. Wood[6] further argues that Probability and Statistics often focus on the scientific mode of statistical hypothesis testing rather than on the characterization of data and the use of these characteristics for predictive behavior. These results show that while students come to design classes with high or average knowledge of Probability and Statistics, this knowledge needs to be revitalized in light of teaching uncertainty in design.

While 68% of the respondents included the topic of uncertainty in their design courses, there is no consistent framework or outline on how the topic of uncertainty is incorporated. This shows the need for a clear roadmap as to how uncertainty should be taught in design. The remaining 32% respondents have not included uncertainty and their reasons are presented into three groups: design prerequisite, advanced concept and time constraint (see section 3.2). The authors of this paper believe that considering uncertainty as an advanced concept may have its own risk; i.e. students graduating with their first degree will not acquire the necessary knowledge of uncertainty in design process. Wood [6] noted that industry is taking the lead in addressing the issue of uncertainty in design process and that the education curriculum does not yet properly address this knowledge gap. Accordingly, it is apparent that the undergraduate engineering curricula needs to include DUU. Lack of time is another factor mentioned. Surveys conducted on the status of teaching design in the years 1994, 2005 and 2009 clearly show that the duration of capstone design courses is increasing[20]. In the year 2009 most universities teach the course in the duration of two semesters with the theory and practice in parallel[20]. And yet one of the factors that hinder design faculties from integrating the concept of uncertainty is time constraint. Thus, increasing the credit hours of the capstone design or offering DUU as a separate required or elective course could be considered as an alternative, as is being practiced by some professors.

4.3. Teaching Uncertainty in Engineering Design – The way forward

The conflict that is visible in the results and feedbacks presented above shows that even though the majority of design faculty believe that it is important to incorporate the concept of uncertainty into teaching and learning design, there is hesitation to start implementing it. Some of the reasons could be the lack of time, knowledge, curriculum, text books and examples on how to incorporate uncertainty into the teaching of design in undergraduate program. Accordingly, a roadmap to incorporate uncertainty in teaching and learning design in the undergraduate program of engineering education, as presented in Figure 4, is proposed. The roadmap presents five elements of teaching DUU as questions to be answered, in the sequence they appear, when teaching design:

- What is a Product Design Process? [1,6,21]
- Why is considering uncertainty important? [4,7,13]
- What is the classification of uncertainty? [5–7,14]
- What are the sources of uncertainty? [3,7] and
- How do you manage (mitigate) uncertainty? [3,4,6,7,13].

A DUU curriculum that is designed to answer these five questions and their sub-questions (see Figure 4) is believed to train our engineers in the critically important skill of understanding and mitigating uncertainty in the product design process. These elements of teaching DUU can be presented at the top level within two classes or in detail as a three-credit elective course.

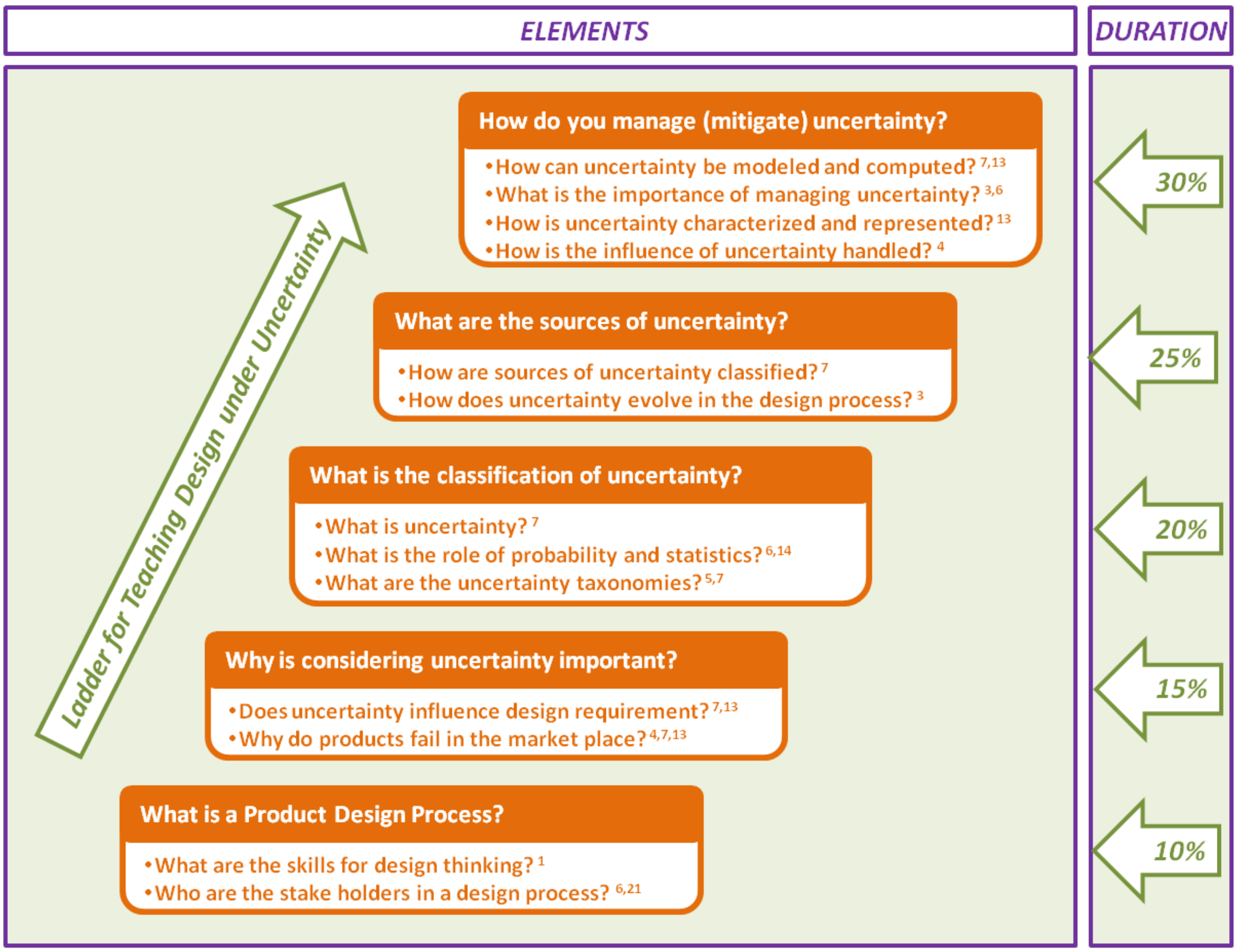

Figure 4. Elements of Teaching Design Under Uncertainty

5. Conclusion

A survey instrument has been designed and conducted to design faculty of 89 of the top 100 ABET accredited Mechanical Engineering schools. Results show that the majority of design faculty members in the nation agree that it is important to incorporate the topic of uncertainty in teaching design and that industry will be benefited from it. Besides, several studies conclusively prove that consideration of uncertainty in product design process is critical.

Despite the significant consensus on the importance of incorporating uncertainty in teaching and learning design, survey results show that only few have incorporated the topic. In addition, it is observed that there is lack of consistency in the implementation. On the other hand, the majority of the design faculty, who have not incorporated the topic, yet do not see themselves teaching design under uncertainty in the coming two or more years. This shows that there is a dilemma in addressing uncertainty despite the aforementioned evident agreement on the importance of incorporating the topic of uncertainty in teaching design. For this reason, a roadmap of the elements of teaching DUU is designed and presented. The roadmap, or the ladder of teaching DUU considers a stepwise approach in answering the following question: 'What is a Product Design Process?', 'Why is considering uncertainty important?', 'What is the classification of uncertainty?', 'What are the sources of uncertainty?' and 'How do you manage (mitigate) uncertainty?'. This roadmap is believed to avoid the dilemma and to help design faculty to incorporate uncertainty in teaching design. Furthermore, while Probability and Statistics courses are usually taught prior to teaching design, there is a need that the knowledge be revitalized in light of teaching uncertainty.

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7. Appendix: Survey Instrument

Q1. Do you think it is important to incorporate the topic of Uncertainty in teaching Design?

	Not at all Important	Very Unimportant	Neither Important nor Unimportant	Very Important	Extremely Important
Please provide level of importance.	○	○	○	○	○

Q2. What is the likelihood that your students are exposed to the concepts of Probability and Statistics?

	Very Unlikely	Unlikely	Unknown	Likely	Very Likely
Please provide the likelihood.	○	○	○	○	○

Q3. How do you describe the level of their exposure to the concepts of Probability and Statistics?

	Much Lower	Lower	Average	Higher	Much Highe
Please provide the level.	○	○	○	○	○

Q4. Have you incorporated the topic of Uncertainty into your Design Course/Courses?

- ○ Yes
- ○ No

Display This Question:
If Have you incorporated the topic of Uncertainty into your Design Course/Courses? **Yes** Is **Selected**

Q4.1.1. How is the topic of Uncertainty incorporated into your Design Course?

- ○ As an independent Chapter/Chapters.
- ○ As a sub-chapter in every design topic covered.
- ○ As a sub-chapter in few chapters.
- ○ As a brief introduction.
- ○ Other

Q4.1.2. Please tell us how the topic of Uncertainty is incorporated into your Design Course.

Display This Question:
If Have you incorporated the topic of Uncertainty into your Design Course/Courses? **No** Is **Selected**

Q4.2.1. Please briefly describe your reason for not addressing the topic of Uncertainty in to your Design Course?

Display This Question:

If Have you incorporated the topic of Uncertainty into your Design Course/Courses? **No Is Selected**

Q4.2.2. Would you consider incorporating the topic of Uncertainty in future Design course?

	Very Unlikely	Unlikely	Unknown	Likely	Very Likely
Next Year	○	○	○	○	○
In two years or more	○	○	○	○	○
Never	○	○	○	○	○

Q5. Do you teach a separate course on Design Under Uncertainty or any other course with a topic of Uncertainty?

- Yes
- No

Display This Question:

If Do you teach a separate course on Design Under Uncertainty or any other course with a topic of Uncer...
Yes Is Selected

Q5.1. Please provide the course name, at what level it is taught and whether the course is given as an elective or a regular course.

	Course Name	Level taught	Credit Hrs	Regular or Elective?
	Please Type all courses on uncertainty			
1				
2				
3				

Q6. Do your (Capstone) Design Projects consider the topic of Uncertainty?

- Yes
- No

Display This Question:
If Do your (Capstone) Design Projects consider the topic of Uncertainty? **No** Is **Selected**

Q6.1. Would you consider incorporating the topic of Uncertainty in future (Capstone) Design Projects?

	Very Unlikely	Unlikely	Undecided	Likely	Very Likely
Next Year	◯	◯	◯	◯	◯
In two years or more	◯	◯	◯	◯	◯
Never	◯	◯	◯	◯	◯

Q7. Have you had a research and/or design project from industry or have you been affiliated with industry in the past five years?

◯ Yes

◯ No

Display This Question:
If Have you had a research and/or design project from industry or have you been affiliated with industr...
Yes Is **Selected**

Q7.1 Do you think Industry will benefit from incorporating the topic of Uncertainty in Design courses at undergraduate level?

	Very Unlikely	Unlikely	Unknown	Likely	Very Likely
Please tell us the likelihood.	◯	◯	◯	◯	◯

Q8. Finally, please provide your valuable feedback if the topic of Uncertainty could be considered in teaching and learning of Engineering Design.