HOW TO VALIDATE RESEARCH IN ENGINEERING DESIGN?

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ABSTRACT
This paper conducts a literature review of 71 publications from the past five years in the Journal of *Research in Engineering Design*. The goal is to look for correlations between types of research and the types of validation in hopes to improve the quality of research in engineering design and to aid researchers in the search for a common methodology. By analyzing the contents of each paper, a way of classifying the types of research and validation is developed. Due to a lack of application of research studies in real industrial settings, this paper also asks the question: is an industrial validation mandatory? The classification of papers in the field may provide clarification for understanding and potentially allow for some important distinctions in design methodology. The survey of the literature, combined with the results of this study, indicate that there is room for improvement in the field of research in engineering design, and this paper hopes to add support to that improvement.

Keywords: Design Research, validation

1 INTRODUCTION
People have been attempting to improve processes of engineering design as well as the quality of research design for centuries. It was not until the 1960s, however, that researchers became interested in design as a topic of research. This was when significant change began to occur in the design industry, as it increased in complexity and economic involvement, and there was a realization that the scope of design goes beyond applied science.
Rapid change in design research is evident. It can be considered that design research has evolved through three phases of development: Experiential, Intellectual, and Experimental; described in [1]. The Experiential phase consisted of designers writing about their product processes, but it was evident the field lacked a systematic theoretical framework. During the Intellectual phase in the 1960s, and continuing into the 1980s, researchers began seeking to establish a more logical and systematic approach to design, and they proposed a number of frameworks and methodologies. At the end of World War II, people were faced with social and economic problems and the design process began to be seen as a problem-solving and decision-making activity [2]. New theories, computational tools, concepts, increased interest in how teamwork is involved in design, and much other advancement in the field has now motivated the Experimental phase. Thus, more data-gathering observational methods are taking place to understand and improve the impact of new methods and tools on the design process. However due to the youth of the field, there is a great need for organization and common methodology.
Despite its exponential evolution, the field of engineering design lacks a significant amount of structure and commonality. It is a truly inter-disciplinary science attracting a wide variety of researchers from a wide variety of disciplines. Marco Cantamessa stated in [3], “It is no simple matter to define the contents, the research approach or the community behind research in engineering design.” Cantamessa adds that design research along with its methods and tools does not naturally link to or inherit from an existing academic discipline; this is largely due to the status of engineering design as a relatively new field of scientific research. The main issues of concern regarding the current status of design research as highlighted by Blessing and Chakrabarti in [4] are: (1) the lack of overview of existing research, (2) the lack of use of results in practice, and (3) the lack of scientific rigor. A lack of common terminology, benchmarked research methods, and above all, a common research methodology are the most outstanding problems in the field [1].

A research methodology relates research questions, provides support for the process to address them systematically, and also supports the validation of the research method used. Validation is essential to design theory and is best used by researchers to guide the development and evaluation of new methods. A number of different viewpoints and of studies that propose frameworks for validation exist. Daniel D. Frey and Clive L. Dym summarize these past-proposed views on validation in their survey of the literature [5].

This paper investigates past literature and seeks a correlation between different types of research and validation by classifying them into categories. It is also discussed whether or not an industrial validation is mandatory in design research. As a dataset, we have chosen to limit the domain of the literature review presented in this paper to publications in the international journal «Research in engineering design» from November 2005 to November 2009.

Section 2 is a proposal of a classification of the design research papers. Section 3 is a contribution on the engineering design validation based on a survey. It also touches on the question of whether or not an industrial validation is mandatory. The results of the classification of the 71 papers and the discussion on these outcomes are presented in section 4. Section 5 concludes with recommendations for future work.

2 ENGINEERING DESIGN RESEARCH CLASSIFICATION

The amount of existing literature in the field of research in engineering design is vast. As a result, there was significant difficulty associated with determining how to approach the classification of the publications from the Research in Engineering Design Journal into types of research. A reason for this difficulty is that there is not a common view regarding what exactly design research aims to investigate, or how to approach this investigation. Many different aspects of this field are explored in a vast number of different ways, and this was evident throughout the literature review conducted for this paper.

A number of publications in the past have attempted to categorize papers into broad overarching categories to provide some structure in the field of design research. Some classified past literature particularly dealing with product development ([6], [7]). Others tried to clarify the research methods necessary to study design ([8], [9]), and yet others made an attempt to determine overarching disciplines of the research in the field [10].

Marczyk et al. in [11] show a broader perspective, quite different from that of Finger and Dixon as well as Oxman and a great deal more general. This categorization of the types of research is used as a starting point to begin classification in this paper:

1. Experimental
2. Quasi-experimental
3. Non-experimental

This framework helped us to go further in the analysis of the papers to classify. Within each category there are more specific types of research that are commonly used. Within experimental for example, were types such as the commonly used randomized two-group design, and the factorial design. Within Quasi-experimental for example, were non-equivalent comparison group design or the interrupted time series design. Examples of types of research within the Non-experimental category were case study, field study, and ethnographic study. These categories from this text served as the initial basis for classifying articles into types of research.

In the literature review classification began with the broader categories, Experimental, Quasi-experimental, and Non-experimental, and then tried to place each paper into the more specific types of research within those groups. Based on the observations in this study of the literature, some more categories were developed to better fit the domain. Thus, the empirical observations combined with [11] led to the development of the following list of research categories structured in Table 1.

This classification turned out to be a sufficient start to classification because it allowed each article within the domain to fit into a category, although there is some overlap and it is not exhaustive.

Case study types were divided into more specific categories because there seemed to be a difference between the case studies that were chosen to study methodologies or frameworks (e.g. [12]) and case studies chosen to study tools, algorithms and methods (e.g. [13]). Also, a number of them involved students (e.g. [14]) while some were applications to virtual or real industrial settings.

Table 1. Engineering design research classification

Research Type	Research Sub-type
Experimental	Factorial
Non-Experimental	Case Study - methodology/framework
	Case Study - tool/algorithm/method
	Case Study with student participants
	Computational Simulation/Modeling
	Document Study
	Ethnographic study
	Field Study
	Interviews
	Literature Review
	Literature Review, Field Study
	Literature Review, Interviews, Case Studies
	Pilot Study
	Questionnaire using Likert scale
	Survey, Focus Group
	n/a
	Literature Review, Document Studies, interviews, observation
Virtual Experimental	Computational Simulation/Modeling
	Non-Equiv Comparison
Quasi-experimental	Case Study with student participants
	Computational Simulation/Modeling
	Non-Equiv Comparison
	Reversal Time-Series performed
N/a	n/a

It was necessary to create categories for articles that used a combination of research types, e.g., ‘Literature, Interviews, Case Studies’. This was done as an attempt to preserve the integrity of the articles; it was undesirable to classify a paper into simply the ‘Literature Review’ category if its results were also a result of interviews, field studies, case studies, etc. in addition to a literature review. For the articles that seemed to be equal-weighted types of research it seemed necessary to create a combined category. This presented difficulty because it is possible that different researchers might make different decisions at these crossroads throughout the review process. It was necessary to create a ‘Computational Simulation/Modeling’ category of research because many of the articles, with various constraints such as time and budget, gathered data by performing simulation iterations (e.g. [15]). It appears in different categories because this research type was used in a number of different broader categories. It seemed necessary to create a ‘virtual experiment’ broad category because some articles present experiments that they had performed with a software program that, for example, allowed the creation of different virtual scenarios with variables that could be controlled on the computer (e.g. [16]).

Lastly, it was necessary to create an ‘n/a’, or not applicable, category because a number of articles were preliminary and just presented a methodology. Such articles did not discuss any research or validation, or were evaluating known methods as a means of discussion and improvement of the field (like this paper).

3 ENGINEERING DESIGN VALIDATION

There has been variation in perspective with regards to validation as there has been with classifying research. Validation is required in research to evaluate new methods proposed by researchers and is rooted in epistemology. It deals with the justification of knowledge claims. In their survey of the literature [5], Frey and Dym outline three common contemporary views of the justification of knowledge: Foundationalism, Relativism, and Naturalistic epistemology. They observe that the foundationalist perspective “holds that some instances of knowledge are basic and that the remaining instances are justified by relating them to basic beliefs (e.g., by deduction from axioms).” They also observe that the relativist perspective "argues that knowledge cannot be validated in an objective way and that individual, subjective preferences and rules of fraternal behavior among scientists must be considered a part of validation processes," and that the naturalistic perspective "promotes empirical study of how subjects convert sensory data into theories." These perspectives represent the underpinnings of validation.

It is evident that there is a wide range of opinions on how to validate a scientific proposal. From the literature review conducted by Frey and Dym and also that of the present paper, none of these validation methods have been explicitly applied in the literature. The goal of the classification scheme presented in this paper attempts to develop categories that try to capture the way in which the proposal in each paper was validated.

This paper also tries to touch upon the question of whether or not an industrial validation is mandatory. Throughout the study, it was noted whether or not each paper applied their proposal to an industrial application in hopes to open up room for some discussion to address this question.

The same level of confusion and difficulty followed into developing categories of validation. The approach taken by many books and articles when discussing validation is a discussion of validity, e.g. internal validity, external validity, construct validity, statistical validity [11] or theoretical structural validity, empirical structural validity, empirical performance validity, and theoretical performance validity [17].

We must underline that the majority of papers in the field do not explicitly address validation.

As has been shown there are a number of different perspectives on validation, but the present paper focuses on a perspective of the types of validation that seems to describe the actual way an article was validated (e.g. by statistical analysis or by comparison of simulation data with real industrial data). No previous work found in this study did anything like this, so a scheme was developed from the observations in the literature review. This process proved to be very difficult and time consuming. A significant amount of articles in the literature were not explicit about their validation methods, so they had to be extracted empirically. The following scheme of validation types resulted from the analysis:

- Application
- Comparison
- Focus groups
- Questionnaire
- Simulation
- Statistical analysis
- None
- N/a

The analysis of the literature led to the development of these categories. The 'Application' category represents articles that attempted to validate their proposals by applying or implementing them into software for evaluation purposes [18], classical problems such as the cylinder or the cantilever beam (numerical application, eg. [19], development of a consumer product eg. [20]), and other various. The 'Comparison' group is another broad category that is meant to group articles that attempted to validate their proposals by comparing the results to alternative methods in the field [5], results from other varying case studies either in the past or within the article [21], benchmarked methods [22], and other various comparisons. The 'Focus Groups' category group only achieved one article and the authors [23] emphasize that validity is often difficult to show mathematically, but attempted to validate findings by discussing the research and noticing patterns over the course of the project with various attendees at meetings. Some articles attempted to validate their findings by presented pre- and post-test questionnaires (eg. [24]). The 'Simulation' category was developed because an article was observed to use stochastic modeling to attempt to show the potentiality of solving challenging design synthesis problems with simulation iterations. The 'Statistical Analysis' group consists of articles that used methods such as analysis of variance, or principal component analysis to explain variation in the data (eg. [25], [26]). The 'None' category groups the articles that had no validation, and the 'n/a', or not applicable, category includes articles that were, for example, just a clarification of a proposed methodology and a discussion of its potentiality with maybe an illustrative example, but not an application.

These categories served the purpose of grouping all the articles in the domain into categories of types of validation, as was part of the initial goal. However there is still significant overlap and again it seems as if they are ultimately a product of judgment. Nonetheless they provide a different perspective of an overview of research that opens up some discussion of the field, which was also part of the initial goal.

For each article included in the domain of the literature review conducted in this study, it was noted whether or not the authors demonstrated their proposal in an industrial setting. This is important because in order to improve design in practice, it is logical that the effectiveness of a scientific proposal in the field of research in engineering design should be demonstrated in an industrial setting. The possibility of an industrial application is possible for virtually all articles in the literature. This is not to be confused with the 'Application' category of validation because some articles that fall into that category do not have an industrial application. For example, a proposal that was applied to classical mathematical engineering problems such as the cantilever beam. It was noted whether or not an article had an industrial application if the research or validation was performed in a real industrial setting or was used to solve a real industrial problem. The question about whether or not this is mandatory is discussed in the next section.

4 RESULTS AND DISCUSSION

Classifying the research included in the domain of this study involved the need for structure and organization in the field of research in engineering design. Surveying the past literature showed that there is a virtually unlimited amount of different ways to interpret the literature. The lack of overview of existing research, lack of use of results in practice, and the lack of scientific rigor highlighted as the main issues of the field by Blessing and Chakrabarti in [1] became evident throughout this study. The lack of common terminology was clear, especially in referencing articles from other design journals. Terms such as 'function' and 'design' and 'validation' all found more than one definition from one article to the next. Overall, much has been accomplished in this field, and improvement and understanding in this field are necessary for its progression toward a common understanding. The results from this study need to be considered in light of what has been presented thus far in this paper.

Although the classifications of the types of validation and types of validation do not seem to be the optimal way of looking at an overview of the research in this field, an optimal way has not yet been developed. This paper provides another way of looking at an overview of the research published in the past five years in design research by the Journal of Research in Engineering Design.

The data collected on the types of research and validation as well as comments made throughout the study and whether or not there was an industrial application in each article were kept track of in a Microsoft Excel spreadsheet. The data was analyzed after using the PivotTable function of Excel to count up the number of articles in each classification category.

4.1 Classification examples

The process of classifying the articles was time-consuming. Presented here are a two examples of the classification process.

"The Design Guidelines (DGLs), a knowledge-based system for industrial design developed accordingly to ISO-GPS (Geometrical Product Specifications) concepts" [27] was classified in the 'Computational Simulation/Modeling' type of research and the 'Application' type of validation categories, and is an example of the difficulty encountered during the classification process. The authors conducted a study to test their proposed DGLs by optimizing human-computer interaction in Fused Deposition Modeling (FDM), a system controlled by a computer-aided manufacturing software. They use the computational tool in the study to make a manufacturing model by their proposed DGLs. In the article, they referred to this study as a field study as well as a case study. It seemed better grouped in the Computational Simulation/Modeling category within the Non-experimental broad category because the data they collected was a result of their computation modeling. Although it was a case study, this alternative placement seemed more meaningful. The fact that they referred to it in separate sentences as a field test as well as a case study demonstrates the lack of a common terminology. If this article were grouped into a case study category, then analysis of the data and conclusions would be affected. This article was placed in the 'Application' category because it seemed that the authors attempted to validate their research by evaluating the FDM computational model with a verification software instrument called Coordinate Measuring Machines (CMMs). They describe the basic functions of the evaluation software as consisting of the “measurement of the actual shape of a work-piece, its comparison with the nominal shape and the evaluation of the conformity to the requirements, in terms of dimensional and geometrical tolerances.” While the predominant type of validation seemed to be the ‘Application’ category, it was also possible to consider it in the ‘Comparison’ category, although they applied it to a software for evaluation, the results were compared by the software to the what they decided was the acceptable shape of the work-piece and to the dimensional and geometrical requirements. This is a prime example of how it ultimately came down to judgment when classifying a large number of these articles.

“Design evaluation by combination of repeated evaluation technique and measurement of electrodermal activity” [28] is an example of a paper that was categorized into the Reversal Time-Series Design category of the Quasi-experimental broad category. In the experiment the authors paid or gave course credit to two different groups of student volunteers to participate in two different reversal time-series experiments to analyze the dynamic effects of innovation and attractiveness. The authors made observations of electrodermal activity before during and after they presented stimuli to the participants during 25-minute individual experiments. It was easy to classify the type of research for this paper. The difficulty associated with this article was that the type of validation seemed to be predominantly statistical, but they also compared the results to the results of past studies. They performed a two-way repeated measurement ANOVA to interpret the variation of the collected data and emphasized the replication of original findings. This was best fit to go into the ‘Statistical Analysis’ category because it seemed to me to be the predominant type of validation. Again, this was the difficulty associated with a large number of papers in this study.

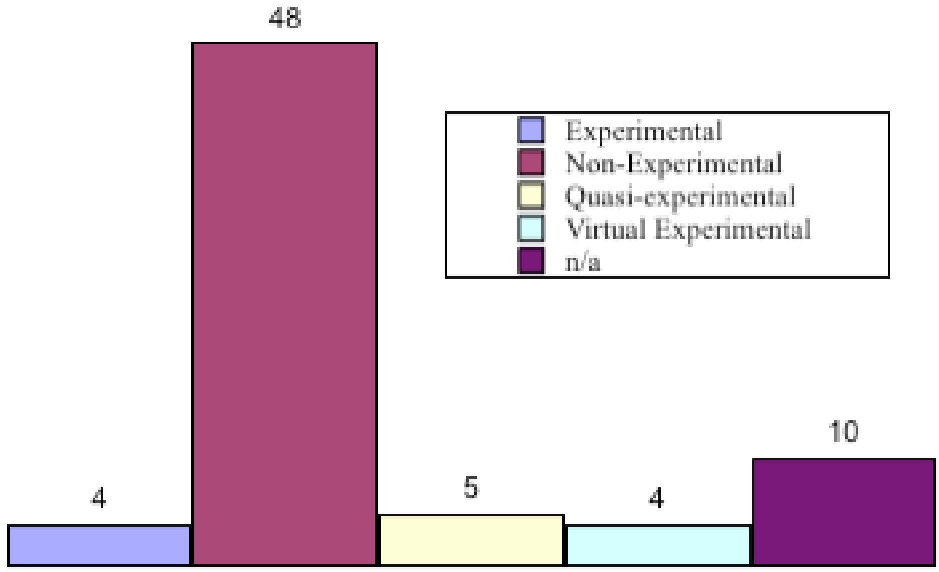
4.2 Results

The PivotTable function of Microsoft Excel counted up the classifications. This data is best viewed in light of the aforementioned difficulties. Looking at this data shows below a correlation between the types of research and the types of validation. The result of the classification of the 71 articles published in the international journal «Research in engineering design» from November 2005 to November 2009 is presented in table 2.

Table 2. Results of the classifications.

Count of Research Sub-type		Validation Type								
Research Type	Research Sub-type	Application	Comparison	Focus Groups	Questionnaire	Simulation	Statistical Analysis	None	n/a	Grand Total
Experimental	Factorial						4			4
Experimental Total							4			4
Non-Experimental	Case Study - methodology/framework	1	1			1		3		6
	Case Study - tool/algorithm/method	2	2					2		6
	Case Study with student participants							1		1
	Computational Simulation/Modeling	6	4					3		13
	Document Study							1		1
	Ethnographic study	1						2		3
	Field Study	1	1					1		3
	Interviews			1						1
	Literature Review		1					4		5
	Literature Review, Field Study				1					1
	Literature Review, Interviews, Case Studies		1							1
	Pilot Study							1		1
	Questionnaire using Likert scale						1			1
	Survey, Focus Group				1					1
	n/a								3	3
	Literature Review, Document Studies, interviews, observation							1		1
Non-Experimental Total		11	10	1	2	1	1	19	3	48
Virtual Experimental	Computational Simulation/Modeling	1					1	1		3
	Non-Equiv Comparison						1			1
Virtual Experimental Total		1					2	1		4
Quasi-experimental	Case Study with student participants							1		1
	Computational Simulation/Modeling		1							1
	Non-Equiv Comparison							2		2
	Reversal Time-Series performed						1			1
Quasi-experimental Total			1				1	3		5
n/a	n/a							3	7	10
n/a Total								3	7	10
Grand Total		12	11	1	2	1	8	26	10	71

From this matrix of the literature classifications of research and validation types, one might observe that Non-experiments make up the majority of the studies conducted in the field of research in engineering design, comprising 68% of the research observed (Figure 1). It must be emphasized that these results come from just one journal. The Non-experimental category did have the largest amount of papers without validation, however, Non-experimental studies made up over half of the total amount of papers in the domain of the literary analysis. There were many more Non-experimental studies than any others whose authors seemed to validate by application or comparison. This may be because it is difficult to quantify many of these studies to allow for statistical analysis.



Throughout the analysis of this matrix of results, one must keep in mind the dynamic process of deciding on a predominant category of classification for both research type and validation type.

Figure 1. Analysis of the types of research

The types within the Non-experimental broad category that had the highest count were the case studies and 'Computational Simulation/Modeling' categories. All of them were placed in the 'Application' or 'Comparison' or 'None' categories of validation. None of them were validated statistically.
The total number of papers that were grouped into the 'Statistical Analysis' validation category was 8. Of those, 7, or about 88% were associated with experimental or quasi-experimental types of research. This is most likely due to the inability to quantify a great deal of observations in the field of design such as product attributes or results from interviews and surveys. It seems that the majority of the validation is subjective and in many cases the question arises; if it works, does it need to be validated? The answer to this question is not simple. It is part of the ongoing discussion of the field. An industrial application however might provide some insight into answering this question. In the literature review, 46% of the papers had no industrial application.
In this study, 38% of the articles were validated qualitatively by methods such as application, comparison, questionnaires, and focus groups, 11% were evaluated statistically, 37% were not validated at all, and 14% did not apply to the types of research and validation categories. Due to the limited domain of this study, there may not seem to be sufficient evidence supporting any substantial correlations between types of research and the types of validation, but there are hints about correlations existing between Non-experimental types of research and qualitative types of validation. Statistical methods seem to be predominant in experimental, quasi-experimental, and virtual experimental categories. These categories often lead to quantitative empirical data, which is highly desired when it comes to validating results (Figure 2).
One can quickly see from the array that the largest number of papers without no validation is within the Non-experimental category. There is not sufficient data to conclude whether there is a correlation here.

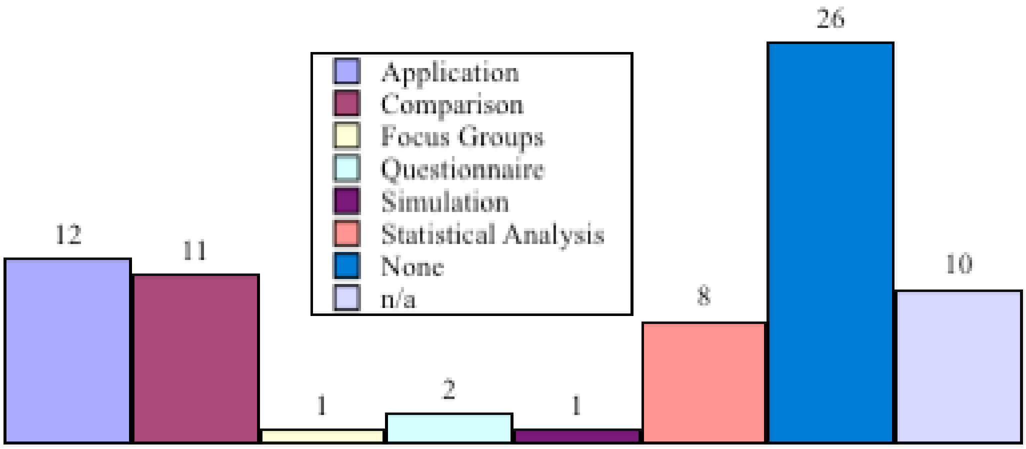


Figure 2. Analysis of the types of validation

4.3 Discussion

The widespread need for more organization in the field of design due to a lack of agreement regarding an overview of existing work is evident. The widely diverse and multidisciplinary nature of design makes it difficult to form classifications without significant overlap. The past approaches as well as this approach each provide different perspectives on an overview of existing literature and allow for discussion aimed at the improvement of the quality of research. Despite the limitations associated with classifying research, there is still a need for structure in the field.

What is gained or lost when you classify data? Cross et al. in [29] discuss answers to this question. Contained inside any methodology is a point of view, or a way of thinking about classifying the data, that limits other viewpoints. However what is gained by classification is “order over chaos [,]” because it allows us to “put a shape on the world and enables us to see that world in new ways.” It also includes the identification and interpretation of texts by finding patterns that lead to new interpretations. Cross et al. also made a particularly outstanding observation, which highlights the highly dynamic process of classifying research.

“Certainly, we grounded our study in fact by surveying journal articles for descriptions of different pedagogical practices. But sorting and classifying these practices was a highly dynamic process, infused with selection and interpretation at every step of the way. Arriving at the categories (or approaches), for example, was not so much a matter of discovery as it was a matter of constructing categories by privileging certain concepts over others. In our case, we privileged the concept of community, although it is only one of many concepts discussed in social theory. Privileging this term allowed us to then construct categories, interpreting different pedagogical practices as they might fit into various categories. Our decision to privilege the concept of community is a clear example of the value-laden activity implicit in the classification of data. Privileging a different concept would have led to alternate constructions – alternate lens for reading and classifying – pedagogic practices.”

5 CONCLUSIONS AND FUTURE WORK

As the results have shown, 37% of the articles reviewed did not have any validation. There needs to be more validation in the field of research in engineering design. It is paramount for its improvement, progression and generalization. The majority of the articles, even if they performed some type of validation, did not explicitly address validation. It would advance the field if the topic of validation was addressed and attempted in each article. This would best support the claims made by researchers and would provide more common structure to the field of research if each article was required to discuss validation.

There also needs to be more experimental research conducted in the field. The highest amount of statistical analysis was performed in experimental, quasi-experimental studies. Although there is not a significant amount of papers included in the domain of this research study, there is a need for more numerical empirical data and analysis. Being able to perform statistical analysis such as calculating the variability among datasets can be much more convincing than simply explaining the potential of results or demonstrating an example. Results of this study may hint that there is a need for more quantification of research.

While this study does not provide an conclusive answer to the question of whether or not an industrial validation is mandatory, more industrial applications are necessary. Less than half of the research papers in the conducted literature review applied their proposals to industrial settings or tried to solve real industrial problems. The overarching goal of this paper was to open up discussion in hopes of improving the quality of research. More industrial applications may be necessary to improve the quality of research. More research is necessary on whether or not studies, experimental or non-experimental, performed on students are relevant in the field of research in engineering design. A number of the papers reviewed in this study conducted studies involving students. In some studies, students were paid or given credit to participate in studies. Are results from these studies relevant to the improvement of practice in the industry?

It can be useful and important to seek correlations between types of research and types of validation. It has not been an explicitly well-studied area of interest, however if researchers collaborated on a more extensive literary analysis than the study conducted in this paper regarding the correlation between types of research and validation, this could potentially provide some substantial structure to design research. More common understanding is necessary in the field of research in engineering design. If a common methodology linking research and its validation is formalized, there can be great advancements in the field. Studying the correlations between types of research and types of validation seems to be a promising activity that may lead to a better overview of research and ultimately support the development of a common methodology.

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