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Impact of team size on requirement quantity

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ABSTRACT: This paper presents and experimental study that compares the performance of teams of one, three, and six in terms of generation of requirements from given design prompts. Team size has not been fully explored in the literature in comparative experimental studies for requirements generation. The study was conducted with 116 teams of one, 86 teams of three, and 92 teams of six composed of pre-service engineers in an introductory engineering course. Two prompts were used for the in-class activity. Results indicate that the size of the team did not have significant influence on the number of requirements generated. However, this suggests that there is a difference in efficiency of generating requirements. Analyzing the variety, novelty, and completeness of the requirements generated is reserved for future work. This work helps to lay the foundation for justifying team size.

KEYWORDS: teamwork, collaborative design, requirements, design education

1. Motivation: collaboration in engineering design

Collaboration is a fundamental aspect of engineering design, enabling the integration of diverse perspectives, expertise, and skills to solve complex problems (Kleinsmann et al., 2012a; O'Shields & Summers, 2018; Ostergaard & Summers, 2009). Engineering design is described as a complex social activity, the complexity of which is mitigated through the systematic sequencing of activities and the integration of many actors to ensure coverage of view (collaboration) (Milne & Leifer, 1999). Engineering design is inherently social, systematic, and creative, thus effective teamwork is essential throughout the stages of problem-solving, from identifying needs to implementing solutions (Dym & Little, 2004; Otto & Wood, 2001; Pahl et al., 2013; Ullman et al., 2024). While the significance of collaboration is widely recognized, the understanding of how team size influences collaborative design remains limited, especially in the context of requirements generation (Weiss & Hoegl, 2016). Team size, when combined with various mechanisms, influences team creativity, output quality, and efficiency, three key dimensions of team performance (Weiss & Hoegl, 2016). Further, team size can have distinct impacts on the performance of teams engaged in innovative tasks.

What is not fully understood is how team size relates to performance for engineering design activities. Team size was studied as a factor in a large design competition (Robots to the Rescue) with 101 teams of sizes ranging from 4 to 32 participants (Deng et al., 2022). It was found that team size had an influence on points garnered. The team size correlated with the number of actions and the occurrences of individuals opening an already open CAD document, both of which can be explained simply by the increase in the number of individuals on the team. The Wisdom of Crowds suggests that with a well-designed crowd (diverse, independent, and large), collective understanding and decision making can be improved against an individual's actions (Surowiecki, 2005).

The objective of this paper is to investigate the relationship between team size and the quantity of requirements generated during the early stages of engineering design. By examining how variations in team size impact the collaborative process, researchers seek to provide insights into optimizing team composition for effective requirement generation. Specifically, the research will explore how team size influences factors such as communication, coordination, knowledge sharing, and decision-making, which are critical for generating comprehensive and high-quality requirements. Understanding these dynamics will enable engineers and project managers to make informed decisions about team size and structure to maximize the effectiveness of collaborative design efforts

2. Background

Requirements ensures designs with stakeholder needs but capturing clear and comprehensive requirements is often challenging. This section discusses the considerations of team size and how requirements are written.

2.1. Team size

Collaborative design plays a pivotal role in engineering complex systems, yet it also introduces significant challenges (Grogan & de Weck, 2016). Research shows that while increasing team size could theoretically improve performance, perspectives from fields such as psychology, economics, and management suggest that larger teams may face diminishing returns due to communication overhead and other challenges (Bernerth et al., 2023; Grogan & de Weck, 2016; Jacobs et al., 2019; Mao et al., 2016; Staats et al., 2012). Larger teams tend to encounter difficulties such as conflicts, reduced cohesion, and performance declines due to anonymity, which may outweigh the benefits of diversity and skill sets. Therefore, the ideal team size remains a matter of ongoing research (Jacobs et al., 2019).

Some studies suggest an optimal team size between 5–10 individuals, but factors like task complexity, individual skills, and project-specific requirements influence the appropriate team size (Akinola & Ayinla, 2014; Mao et al., 2016; Ostergaard & Summers, 2009; Sami et al., 2019). Larger teams often lead to social loafing, where individuals contribute less, and coordination becomes more complex as the number of communication channels increases. In contrast, smaller teams tend to foster more efficient collaboration and communication due to fewer members and closer interpersonal connections (Majalian et al., 1992). This results in faster decision-making and problem-solving but may limit the team's ability to address highly complex problems due to a lack of breadth in expertise (Akinola & Ayinla, 2014).

Understanding the relationship between team size and performance in complex tasks is not straightforward. While larger teams offer advantages such as more resources and diverse perspectives, the challenges related to group dynamics, communication, and coordination must be carefully evaluated when selecting the most suitable team size for a project.

2.2. Generating requirements

Effective generating of requirements is essential in the engineering design process, particularly in the conceptual design phase, which significantly influences the overall success of a project (Andreasen et al., 2015). Clear and well-defined requirements serve as the foundation for guiding the design process and are refined throughout the project’s lifecycle. They help establish a shared understanding among the design team and stakeholders about the project’s goals, limitations, and scope (Loucopoulos, 2005; Morkos et al., 2014). This shared understanding is critical for making informed decisions and avoiding misalignment between the team’s actions and the project's objectives (Loucopoulos, 2005).

Poorly defined requirements can lead to uncertainty, project delays, and design failures (Joshi et al., 2012; Loucopoulos, 2005; Mokammel et al., 2014). Generating effective requirements reduces the risk of these issues by ensuring that all stakeholders have a clear vision of the project’s scope and objectives. Different organizations provide standards for writing these requirements, with INCOSE, IEEE, and NASA offering specific guidelines on what constitutes a “good” requirement (Institute of Electrical and Electronics Engineers (IEEE), 2018; International Council on Systems Engineering (INCOSE), 2023; National Aeronautical and Space Administration, 2016). These standards emphasize clarity, consistency, and specificity in the requirement statements to prevent ambiguity.

Requirements should be framed using precise language, such as the use of the word “shall” to indicate a mandatory requirement. Vague expressions like “many” or “a few” should be avoided, and each requirement should focus on a single quality, characteristic, or function. Furthermore, requirements must be realistic, verifiable, and feasible to ensure that they can be effectively tested or validated during the project’s execution (Institute of Electrical and Electronics Engineers (IEEE), 2018; International Council on Systems Engineering (INCOSE), 2023; National Aeronautical and Space Administration, 2016).

Organizations such as INCOSE, IEEE, and NASA have developed similar standards for writing requirements. These include structuring the requirement with a condition, subject, modal term (e.g., “shall”), verb phrase, and target value, as shown in Table 1. Additionally, modal terms describe the obligation or manner in which the requirement must be fulfilled (Spivey et al., 2021a). Consistency across all requirements and throughout the requirements document is critical to ensure clarity and prevent contradictions. **In all the examples from NASA, INCOSE, and IEEE, key components such as the subject, modality, and verb phrase are consistently present.**

Table 1. Comparison of requirements syntax

			INCOSE Requirements		
Condition	**Subject**	**Modal**	**Verb Phrase**	**Modifier**	**Target Value**
	The <SOI>	shall	be compliant with government safety regulation <xyz, Section 1.2.3>		
	The <SOI>	shall	have an Availability of greater than xx%	over a period of greater than yyyy hours	> xx%, > yyyy hours
	The GPS	shall	display the User_Location	in accordance with <Display Standard XYZ>	
When <off-nominal condition>	the Operation_ Logger	shall	record the Warning_Message	within <performance measure>	
			IEEE Requirements		
Condition	**Subject**	**Modal**	**Verb Phrase**	**Modifier**	**Target Value**
When signal x is received	the system	shall	set the signal x received bit	within 2 seconds	2 seconds
At sea state 1	the Radar System	shall	detect targets at ranges out to 100 nautical miles		100 nautical miles
	The Invoice System	shall	display pending customer invoices	in ascending order of invoice due date	
95 % of	the transactions	shall	be processed in less than 1s		95 %, 1s
			NASA Requirements		
Condition	**Subject**	**Modal**	**Verb Phrase**	**Modifier**	**Target Value**
	The TVC	shall	gimbal the engine a maximum of 9 degrees ± 0.1 degree		9 degrees, ± 0.1 degree
	The TVC	shall	provide a force of 40,000 pounds ± 500 pounds		40,000 pounds, ± 500 pounds
	The system	shall	have a 1.4 factor of safety		1.4
	The spacecraft	shall	provide a direct Earth entry capability for 11500 m/s or greater		115000 m/s

3. Experiment design

The research focuses on experimentally examining how team size affects the performance of engineering design teams during requirements generation. Conducted in a classroom setting, this study provides participants with a familiar and natural environment. This section outlines the approach to analyze how variations in team size influence the quantity of requirements generated during the problem definition phase.

3.1. Participants

The study followed an approved experimental protocol from the local Institutional Review Board, with no identified risks for participants. A total of 1,208 pre-service engineers (undergraduate mechanical engineers) participated across five sections of an introductory Engineering and Computer Science course at a large public research university in the United States. The course, a mandatory first-semester requirement for all engineering and computer science students, involved participants majoring in computer science, bioengineering, electrical engineering, or mechanical engineering. Approximately 80% of the participants identified as male, and 5% were international students. The majority of participants were aged 17 to 20. Demographic data were not collected due to the scope of the experiment. The class sizes ranged from 170 to 300 students, all meeting in the same lecture hall on Tuesdays and Thursdays. Participants were instructed not to discuss the in-class activity with others. The experiment took place during regular class hours, and the lecture content was standardized across sections, with a guest lecture by the same researcher covering the importance of requirements in engineering design, requirements syntax, evaluation methods, common pitfalls, and stakeholder engagement. The lecture content is loosely based on (Ullman et al., 2025).

Pre-service engineering students were selected to ensure a uniform baseline of engineering knowledge. Previous studies have shown that pre-service engineers perform comparably to practitioners with at least three years of experience in generating requirements (Elena, 2019). Furthermore, research has indicated no significant difference in the quality or technical feasibility of solutions produced by first-year and senior engineering students (Genco et al., 2012).

After the lecture, participants were given detailed instructions for the requirements generation task. They were provided with a design problem statement and had 20 minutes to generate requirements. The participants were given 20 minutes due to the limitation of the class time and the time it took to organize teams and deliver the lecture content. Their documents were collected at the end of the session, with independent observers monitoring the teams to ensure that each team collaborated internally within their group while remaining independent from other teams. The participant materials consisted of two sections: one for creating a unique identifier and another with instructions for the requirements generation task, along with the design problem prompt. Participants were asked to assume the role of engineers working at a design firm and tasked with generating requirements for a specific problem Figure 1 illustrates the participant packet.

Please **individually** enter the:
two digits of your day of your birth, **first three letters** from the high school that you graduated from, and
last two digits of your student ID in one of the boxes below.
(This will be used as your unique identifier.)

Imagine you are employed by an engineering design firm; you have been tasks the generate requirements to solve the following problem:

In order to help people in wheel chairs to grab books from the highest level of the bookshelf (at 6 ft or above), a mechanism needs to be developed. The device must be safe to use, convenient, and operate smoothly without damaging the books. The assembly should be relatively simple so that it can be installed on most existing bookshelves.

Number	Requirement

Figure 1. Participant packet with prompt

3.2. Experiment variables

The study manipulates a single independent variable, team size, across three conditions: Teams of One, Teams of Three, and Teams of Six. Teams of One represent individuals working independently, while Teams of Three and Teams of Six represent smaller and larger groups, respectively. Although other variables such as communication styles, team culture, individual personalities, interpersonal dynamics, gender, and age could influence outcomes (Ostergaard & Summers, 2009), these factors are not the focus of this study. To minimize their impact, participants were randomly assigned to teams, reflecting the reality of diverse expertise in engineering teams.

Given the classroom setting, where participants are in close proximity, there is a risk that overhearing discussions from other teams could influence their requirements. To address this, two distinct design problem prompts are used: one for a bookshelf retrieval mechanism for wheelchair users and one for a bicycle safety lock. These prompts were adapted from a previous requirements generation study (Spivey et al., 2021a) and are outlined in Table 2. These two prompts have been evaluated for equivalency previously (Elena et al., 2020).

The data collected is in the form of requirements lists. The participant packet contains 21 rows for requirements to be written and participants were instructed to write on the back if they needed more room to write requirements. The quantity of requirements in the packet is the dependent variable of interest.

Bookshelf (BS) Prompt

"In order to help people in wheel chairs to grab books from the highest level of the bookshelf (at 6 ft or above), a mechanism needs to be developed. The device must be safe to use, convenient, and operate smoothly without damaging the books. The assembly should be relatively simple so that it can be installed on most existing bookshelves."

Safety Lock (SL) Prompt

"Design a safety lock for a bicycle that is to be permanently fastened to it (not to be removed when being used). The lock is to be a lasting accessory, yet can still be removed or adjusted if necessary. It should be small enough to be non-obtrusive to the bicyclist while riding and should be light weight and relatively inexpensive."

Figure 2. Design prompts from (Elena & Summers, 2019; Spivey et al., 2021b)

3.3. Requirement quantity

The quantity of requirements refers to the total number generated by the participant teams, serving as a metric for their ability to articulate a set of specifications. Quantity helps assess the teams' capacity for generating requirements and provides insights into the effects of team size in engineering design teams. A study was done tracking requirements evolution over eight design projects and its relation to project success in an engineering design course at a large public university. Results of the study suggest that a higher quantity of requirements improves the likelihood of project success (Summers et al., 2014). Another study looked at final reports from senior design classes collected over a ten-year period. The results of this study suggest that when the problem statement and requirements are lacking in detail, the final solution tends to reach, at most, a medium level of detail (Joshi, 2010). Conversely, achieving a highly detailed final solution is more probable when the initial problem statement and requirements are of either high or medium detail. Furthermore, a highly detailed final solution is more likely to correspond with a higher percentage of requirements being fulfilled (Joshi, 2010). Requirements are counted as single-thought statements based on established criteria (Spivey et al., 2021a).

For example, a requirement such as, "While in operation, the heat exchanger must cool the motor and remain under 60 decibels," is split into two distinct requirements because it contains two separate clauses. The revised requirements are:

1. "While in operation, the heat exchanger must cool the motor."
2. "While in operation, the heat exchanger must remain under 60 decibels."

Requirements are split when they include multiple verbs describing actions, multiple adjectives characterizing the design or object, various objects being acted upon, or when a verb includes a modifier specifying how the action should be performed (Spivey et al., 2021a). Additionally, requirements are divided if they feature multiple modifiers to the object, conditional expressions linking two functions or characteristics, or distinct thoughts combined in one statement.

However, requirements are not split if (Spivey et al., 2021a):

- a separate clause clarifies the purpose,
- a single conditional applies to the object,
- two mutually exclusive options are presented, or
- two objects must coexist to fulfil the requirement

The complete coding scheme is available at (Spivey, 2019). A complete list of criteria for splitting requirements is provided in Table 3.

Table 2. Criteria for splitting requirements

Requirements will be split into multiple requirements if:	
1	There are more than one verb describing an action of the explicit or implicit subject, separated by a conjunction such as and, but, or, /, etc.;
2	There are more than one adjective describing the design (i.e. the device must be reliably easy to use);
3	There are more than one object that the verb of the subject acts upon
4	There is a modifier to the verb of the subject (i.e. the device must grab the books safely);
5	There are multiple modifiers to the object being acted on (i.e. the device must pick up books that are light and heavy)
6	There are more than one adjective describing the object
7	There is a conditional expression describing two functions or characteristics (i.e. the device must be strong while remaining lightweight)
8	There are two complete thoughts in one requirements box, either separated by parentheses or in multiple distinct sentences
	Requirements should not be split up if:
9	A separate clause is used to describe the purpose of a requirement (*The device must be strong so it doesn't break*)
10	A single conditional applies to the object rather than the subject (*The device must pick up a book that is lightweight*)
11	Two options are suggested that CANNOT coexist (*The mechanism should have a trigger or button to operate*)
12	Two objects exist that MUST exist with the other to complete the requirement (*device must support the person AND the wheelchair*)

4. Results & discussions

The data analysis in this study followed a two-step process of ensuring homogeneity across course sections of the same team size and comparing requirement quantity across different team sizes (1, 3, and 6). To test for homogeneity across course sections of the same team size, six ANOVAs ($\alpha = 0.05$) were performed across the four sections of the course, for each team size. The analysis revealed that for the Bookshelf prompt, Teams of One had a pair of sections with different variances (p-value$<$0.044). Similarly, for the Safety lock prompt, Teams of One had a pair of sections with different variances (sections 005 and 006, p-value$<$0.04). Similar trends were observed in Teams of Three, with two instances of variance differences. Teams of Six showed no significant differences across sections. Despite these minor variances, a closer examination of the ranges suggested that the differences were not substantial. The study concluded that there were no meaningful differences in the number of requirements generated by each team size across course sections.

The study tested three hypotheses:

- There is no difference or Teams of Three generate fewer or the same number of requirements as Teams of Six;
- There is no difference in the number of requirements generated between the groups being compared; and
- Teams of One will generate more requirements than Teams of Three or Six.

The first section of the first-year general engineering course was used as a pilot to verify time allocation and thus excluded. This resulted in 944 participants from the initial 1,208 participants, and a total of 4,310 requirements. Table 4 provides an overview of requirements generation across different team sizes and prompts, showing the number of teams, initial and final counts, average requirements per team, and split requirements. While there is an imbalance in the number of teams, these are large compared to many other past collaborative studies of engineering design that typically include five to ten teams total (Chartres et al., 2023; Kleinsmann et al., 2012b; Ostergaard et al., 2005; Wetmore III et al., 2010). The average number of requirements generated for the BS prompt is more for all team sizes than the average number of requirements generated for the SL prompt

Table 3. Number of split requirements

BS Prompt	Team of 1	Team of 3	Team of 6
Number of Teams	66	41	45
Preliminary Count	842	568	592
Final Count	1023	602	647
Average Requirements per Team (Final Count)	15.5	14.68	14.38
Number of Times Split (% of preliminary requirements)	145 (17.22%)	34 (5.99%)	46 (7.77%)
SL Prompt	Team of 1	Team of 3	Team of 6
Number of Teams	50	45	47
Preliminary Count	646	573	623
Final Count	748	610	680
Average Requirements per Team (Final Count)	14.96	13.77	13.6
Number of Times Split (% of preliminary requirements)	98 (15.17%)	34 (5.93%)	52 (8.35%)

(by less than one requirement). The ratios of the split requirements are also similar. Thus, the prompts themselves appear to be similar.

Statistical analysis using ANOVA ($\alpha = 0.05$), both with and without outliers, confirmed no significant differences in the average number of requirements generated between Teams of One, Teams of Three, and Teams of Six (See Figure 2). However, a trend was observed: the average number of requirements generated decreased as team size increased. The average number of requirements generated went from 15.5 to 14.68 to 14.38 for Teams of One, Three, and Six, for the Bookshelf prompt, respectively. While for the Safety Lock prompt, the number of requirements went from 14.96 to 13.77 to 13.6 for Teams of One, Three, and Six, respectively. Teams of One had the highest average number of split requirements, on average 2.5 times more than the Teams of Three and Six, respectively. This implies that individual participants may have formulated more comprehensive or multi-functional requirements, while larger teams tended to decompose complex concepts into separate, more specific requirement statements.

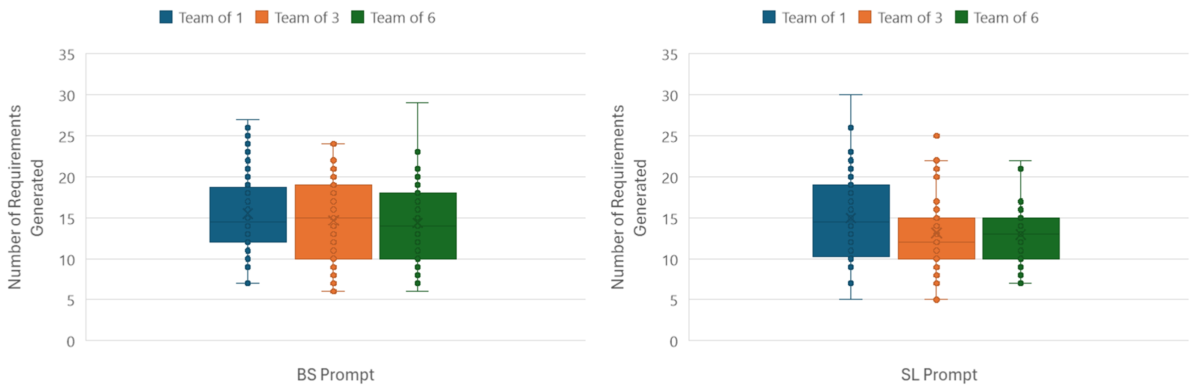

Figure 3. Requirements generated across teams

5. Conclusion

The study's findings suggest that team size does not significantly affect the quantity of requirements generated. However, the trend of decreasing average requirements as team size increases warrants further investigation. Based on these results, it may be more beneficial to initially generate requirements individually and then merge them as a team. Further, if the "cost" of the collaboration is factored into the considerations, the efficiency of requirements generation is definitely higher for small teams.

One key limitation of this study is the method of counting requirements. The study counted a requirement if a verb was present, which may not fully capture the quality or depth of the requirements. For example, "low-cost" and "The design must cost under $1000 to manufacture" were both counted as single requirements, despite the latter providing more detailed information. In the future, researchers should evaluate the completeness of requirements, assessing whether they leave room for ambiguity or interpretation.

Future research should focus on comparing the variety of requirements across team sizes, examining the diversity and coverage of requirement categories. If a Team of One generates 21 requirements, but they are all related to the overall dimensionality of the product while a Team of Three generates seven requirements, but each covering a different aspect, such as maintenance, assembly, packaging, cost, operations, function, and durability, the Team of Three might have developed a better understanding of the problem. A simple count is not sufficient to measure the value of the results of the design activity. As with the quantity, quality, novelty, and variety metrics developed to compare idea generation techniques (Shah et al., 2000, 2003), a similar set of metrics is needed to compare the team performance. Developing more nuanced methods for quantifying requirements that account for the depth and quality of information provided will be crucial. This study focused on a first analysis of the requirements generated, future research will study variety and completeness of the requirements.

These additional analyses will provide a more comprehensive understanding of the relationship between team size and the effectiveness of requirements generation in engineering design processes.

References

Akinola, O. S., & Ayinla, B. I. (2014). An Empirical Study of the Optimum Team Size Requirement in a Collaborative Computer Programming/Learning Environment. *Journal of Software Engineering and Applications*, 07(12), 1008–1018. https://doi.org/10.4236/jsea.2014.712088

Andreasen, M. M., Hansen, C. T., & Cash, P. (2015). Conceptual Design. *Springer International Publishing*. https://doi.org/10.1007/978-3-319-19839-2

Bernerth, J. B., Beus, J. M., Helmuth, C. A., & Boyd, T. L. (2023). The more the merrier or too many cooks spoil the pot? A meta-analytic examination of team size and team effectiveness. *Journal of Organizational Behavior*, 44(8), 1230–1262. https://doi.org/10.1002/job.2708

Chartres, I., Gidel, T., & Moulin, C. (2023). The Importance of Individual Work in Collaborative Design Meeting: Impact on Design Tools and Methodologies. *Proceedings of the Design Society*, 3, 3405–3414. https://doi.org/10.1017/PDS.2023.341

Deng, Y., Marion, T., & Olechowski, A. (2022). Does Synchronous Collaboration Improve Collaborative Computer-Aided Design Output: Results From a Large-Scale Competition. *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 86267, V006T06A026.

Dym, C. L. L., & Little, P. (2004). Engineering Design: A Project-Based Introduction. John Wiley and Sons.

Elena, M. V. (2019). Understanding Requirement Generation: Studies on Interventions and Comparison between Novices and Practitioners [Clemson University]. https://open.clemson.edu/all_theses/3076/

Elena, M. V., Patel, A., & Summers, J. D. (2020). Designing design prompts: a systematic approach to support engineering design research. *Journal of Design Research*, 18(5–6), 327–355.

Elena, M. V., & Summers, J. D. (2019). Requirement Generation: Lecture Intervention Impact on Variety and Novelty. *ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, V003T04A011.

Genco, N., Hölttä-Otto, K., & Seepersad, C. C. (2012). An Experimental Investigation of the Innovation Capabilities of Undergraduate Engineering Students. *Journal of Engineering Education*, 101(1), 60–81. https://doi.org/10.1002/j.2168-9830.2012.tb00041.x

Grogan, P. T., & de Weck, O. L. (2016). Collaboration and complexity: an experiment on the effect of multi-actor coupled design. *Research in Engineering Design*, 27(3), 221–235. https://doi.org/10.1007/s00163-016-0214-7

Institute of Electrical and Electronics Engineers (IEEE). (2018). *Systems and software engineering-Life cycle processes-Requirements engineering*. https://doi.org/10.1109/IEEESTD.2018.8559686

International Council on Systems Engineering (INCOSE). (2023). *Guide to Writing Requirement*s.

Jacobs, S., Pfarr, M., Fazelpour, M., Koroma, A., & Mesfin, T. (2019). *EFFECT OF TEAM SIZE ON PROBLEM-SOLVING AND SOLUTION QUALITY: AN EMPIRICAL STUDY*. http://asmedigitalcollection.asme.org/IDETC-CIE/proceedings-pdf/IDETC-CIE2019/59278/V007T06A036/6453936/v007t06a036-detc2019-97719.pdf

Joshi, S. (2010). *MAPPING PROBLEM AND REQUIREMENTS TO SOLUTION: DOCUMENT ANALYSIS OF SENIOR DESIGN PROJECTS*. Clemson University.

Joshi, S., Summers, J. D., & Mocko, G. M. (2012). Requirements in Engineering Design: What are we teaching? *Proceedings of the TMCE* 2012, 1–8.

Kleinsmann, M., Deken, F., Dong, A., & Lauche, K. (2012a). Development of design collaboration skills. *Journal of Engineering Design*, 23(7), 485–506. https://doi.org/10.1080/09544828.2011.619499

Kleinsmann, M., Deken, F., Dong, A., & Lauche, K. (2012b). Development of design collaboration skills. *Journal of Engineering Design*, 23(7), 485–506. https://doi.org/10.1080/09544828.2011.619499

Loucopoulos, P. (2005). Requirements engineering. *In Design process improvement* (pp. 116–139). Springer London. https://doi.org/10.1007/978-1-84628-061-0_5

Majalian, K. A., Kleinman, D. L., & Serfaty, D. (1992). The effects of TEam Size on team coordination. *IEEE International Conference on Systems, Man and Cybernetics*, 1992-January, 880–886. https://doi.org/10.1109/ICSMC.1992.271682

Mao, A., Mason, W., Suri, S., & Watts, D. J. (2016). An experimental study of team size and performance on a complex task. *PLoS ONE*, 11(4). https://doi.org/10.1371/journal.pone.0153048

Milne, A., & Leifer, L. (1999). The Ecology of innovation in engineering design. *International Conference on Engineering Design*.

Mokammel, F., Coatanea, E., Christophe, F., Ba Khouya, M., & Medyna, G. (2014). Towards an Approach for Evaluating the Quality of Requirements. *Proceedings of the ASME Design Engineering Technical Conference*, 2 B. https://doi.org/10.1115/DETC2013-13708

Morkos, B., Mathieson, J., & Summers, J. D. (2014). Comparative analysis of requirements change prediction models: manual, linguistic, and neural network. *Research in Engineering Design*, 25(2), 139–156.

National Aeronautical and Space Administration. (2016). *NASA Systems Engineering Handbook*. https://www.nasa.gov/reference/systems-engineering-handbook/

O'Shields, S. T., & Summers, J. D. (2018). Collaborative design between industry practitioners: an interview-based study. *The International Journal of Engineering Education*, 34(2), 824–832.

Ostergaard, K. J., & Summers, J. D. (2009). Development of a systematic classification and taxonomy of collaborative design activities. *Journal of Engineering Design*, 20(1), 57–81. https://doi.org/10.1080/09544820701499654

Ostergaard, K. J., Wetmore III, W. R., Divekar, A., Vitali, H., & Summers, J. D. (2005). An experimental methodology for investigating communication in collaborative design review meetings. *Co-Design*, 1(3), 169–185.

Otto, K., & Wood, K. L. (2001). Product Design: Techniques in Reverse Engineering and New Product Development (1st ed.). Prentice Hall.

Pahl, G., Beitz, W., Blessing, L., Feldhusen, J., Grote, K.-H. H., & Wallace, K. (2013). Engineering Design: A Systematic Approach (Second, Ed.; 3rd ed., Vol. 11). Springer-Verlag London Limited.

Sami, A., Kakolaki, R. K., & Taghados, A. (2019). Impact of Team Size, Project Scale and Level of Education on Software Build Event Status in Enriched Event Streams. 2019 *27th Iranian Conference on Electrical Engineering (ICEE)*, 2045–2049. https://doi.org/10.1109/IranianCEE.2019.8786442

Shah, J. J., Kulkarni, S. V, & Vargas-Hernandez, N. (2000). Evaluation of idea generation methods for conceptual design: effectiveness metrics and design of experiments. *J. Mech. Des.*, 122(4), 377–384.

Shah, J. J., Smith, S. M., & Vargas-Hernández, N. (2003). Metrics for Measuring Ideation Effectiveness. *Design Studies*, 24, 111–134.

Spivey, N. (2019). *An Exploratory Study of the Influence of Design Process Ordering on the Requirement Generation of Novice Designers*.

Spivey, N., Ortiz, J., Patel, A., Davenport, B., & Summers, J. D. (2021a). Analysis of the Impact of Requirement-Sketch Sequencing on Requirement Generation in Conceptual Design. *Journal of Mechanical Design*, 143(12). https://doi.org/10.1115/1.4051079

Spivey, N., Ortiz, J., Patel, A., Davenport, B., & Summers, J. D. (2021b). Analysis of the Impact of Requirement-Sketch Sequencing on Requirement Generation in Conceptual Design. *Journal of Mechanical Design*, 143(12), 1–13. https://doi.org/10.1115/1.4051079

Staats, B. R., Milkman, K. L., & Fox, C. R. (2012). The team scaling fallacy: Underestimating the declining efficiency of larger teams. *Organizational Behavior and Human Decision Processes*, 118(2), 132–142. https://doi.org/10.1016/j.obhdp.2012.03.002

Summers, J. D., Joshi, S., & Morkos, B. (2014, August 17). Requirements Evolution: Relating Functional and Non-Functional Requirement Change on Student Project Success. Volume 3: *16th International Conference on Advanced Vehicle Technologies; 11th International Conference on Design Education; 7th Frontiers in Biomedical Devices*. https://doi.org/10.1115/DETC2014-35023

Surowiecki, J. (2005). *The wisdom of crowds*. Anchor.

Ullman, D. G., Summers, J. D., & Fielding, J. (2024). *Product Design Best Practices (1st ed.)*. BVT Publishing.

Ullman, D. G., Summers, J., & Fielding, J. (2025). *Product Design Best Practices (First Edition)*. BVT Publishing.

Weiss, M., & Hoegl, M. (2016). Effects of relative team size on teams with innovative tasks: An understaffing theory perspective. *Organizational Psychology Review*, 6(4), 324–351. https://doi.org/10.1177/2041386615620837

Wetmore III, W. R., Summers, J. D., & Greenstein, J. S. (2010). Experimental study of influence of group familiarity and information sharing on design review effectiveness. *Journal of Engineering Design*, 21(1), 111–126.