Building Axiomatic Design for Pre-College STEM Students

An Interactive Qualifying Project Report

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Abstract

This paper aims to integrate Axiomatic Design (AD) principles into K-12 education while focusing on the potential benefits it has on pre-college STEM students. The reasoning for this study stems from the growing importance of design education in the K-12 education system and the need to equip students with essential problem-solving skills and increase their creativity and innovation. A review of existing literature on the teaching of design theory and methods in K-12 education reveals the gaps in the integration of Axiomatic Design principles and limited research on its effectiveness for pre-college STEM students. This study proposed an approach to Axiomatic Design applying interactive and hands-on teaching strategies made for K-12 students to enhance their understanding and application of design principles. By utilizing a literature review methodology, the study explores existing research on AD education in K-12 and assesses the effectiveness of multiple instructional approaches used to teach AD to pre-college STEM students. The findings highlight the potential value of integrating Axiomatic Design principles into K-12 education, with positive impacts on student learning outcomes and teacher practices. Moreover, the discussion examines the implications of the findings, emphasizing the importance of AD education in promoting students' problem-solving abilities and preparing them for future STEM endeavors. In conclusion, this paper emphasizes the importance of integrating AD principles into K -12 education and offers recommendations for enhancing design education in a pre-college STEM setting to then equip students better for the challenges of the modern world.

1. Introduction
    1.1. Objective

This paper's objective is to learn 1) if and how scientific design theory and methods are taught in K-12, 2) examine if Suh's Axiomatic Design (AD) could be valuable for pre-college STEM students, and 3) suggest some approaches to teaching AD to these students.

2. Rationale

    2.1. Importance of the project

This project is important because there is a need to equip students with fundamental critical thinking and problem-solving skills. “In Axiomatic Design: Advances and Application, Suh [2001] states that in the past, many engineers have designed their products iteratively, empirically, and intuitively, based on years of experience, cleverness or creativity, and involving much trial and error”. These skills are essential for their future careers and success in the growing 21st century. As highlighted in “Critical Thinking in STEM learning,” Tripon [2001] states that “CT (critical thinking) development means to support students for developing CT which are required for a successful professional life, and also refers to the way of teaching at a high level of efficiency". Thus, incorporating AD into pre-college STEM education not only addresses the issues of traditional design approaches it also prepares students for challenges in the real world where the ability to think critically and solve problems is important.

3. State of the art

    3.1 Review literature on how design theory and methods are taught in K-12

Teaching design theory and methods in K-12 education reflects a growing awareness of the importance of integrating engineering design principles into everyday math and science curricula. “While stand-alone technology/engineering courses do exit at the middle school level, curricula are being developed and teachers are being trained so that engineering design can be taught along with everyday math and science” (Ganesh & Schnikka,2014). The emergence of design thinking integrated learning is an approach to teaching design theory and methods in non-professional design fields, “Consequently, rooted in design thinking, DTIL refers to a new paradigm in non-professional design fields that aims to develop students' innovative problem-solving ability through design practice” (Li & Zhan,2022).
3.2 How are the effectiveness and value of the instruction analyzed, if at all

The examination of the effectiveness of the effectiveness and value of Axiomatic Design instruction for pre-college STEM students is an evolving area of research with some faults in identifying existing literature. Although, there is an increasing emphasis on STEM integration in curriculums, English (2016) stated that “there appears inadequate research that yields substantive evidence of desired learning outcomes". This identifies the need for rigorous research that can provide as much support for the efficacy of Axiomatic Design instruction in achieving the educational purpose. Krajcik & Delen (2017) emphasized that “A contextualized problem or question, which we refer to as a driving question, is critical to students being able to see the relevance of their learning". Furthermore, it was stated that “An axiomatic approach to design allows engineering design to be taught as a science. As in other sciences, basic underlying principles like broad applications can be taught” Brown (2005).

4. Approach

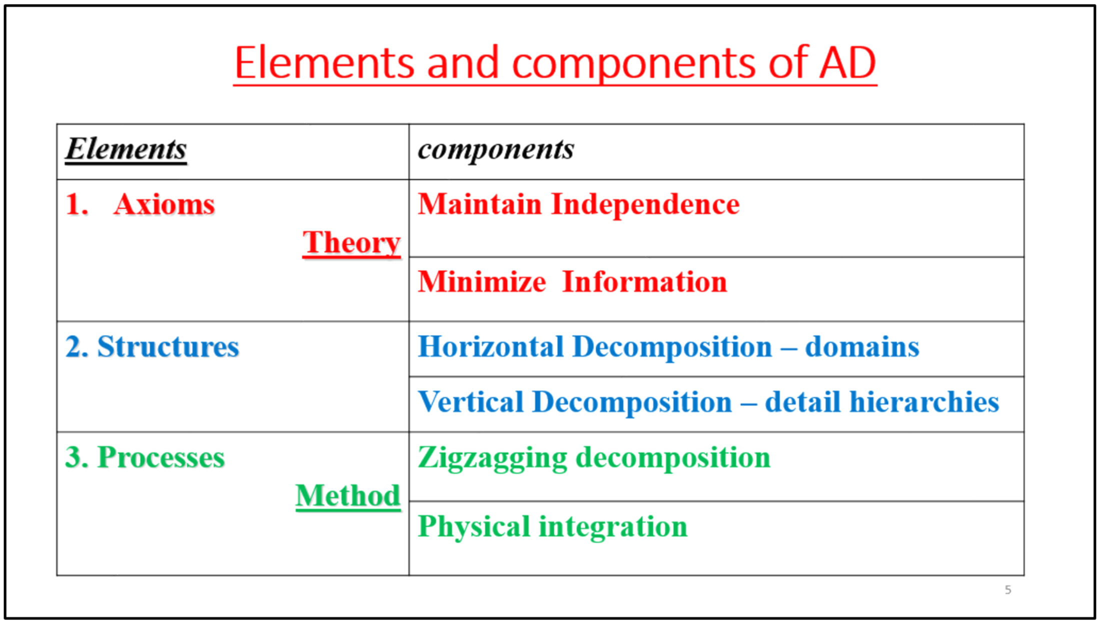
Suh’s Axiomatic Design (AD) offers a systemic and structural approach to engineering design that can be highly valuable for pre-college STEM students. Besides the traditional methods of teaching design, which consists of a trial-and-error approach, AD gives students a clear framework that is grounded in fundamental principles. This approach shows the importance of achieving functional independence and minimizing complexity in design solutions, principles that are essential in engineering practice. In contrast to other methods of teaching design, which focus on specific techniques, AD teaches students to think critically about the fundamental principles of design while applying them systematically to solve problems. Moreover, AD encourages students to understand the purpose behind decision-making and evaluating a design, not only does this create a deeper understanding of engineering concepts but it promotes more creativity and innovation so that students can explore unique design alternatives.

5. Methods

5.1. Literature review of how Suh’s Axiomatic Design (AD) could be valuable for pre-college STEM students, basic literature on AD – start with Suh's book Principles of Design 1990 Oxford Press)

Suh’s work in “The Principles of Design” published in 1990 by Oxford University Press is the basis of understanding Axiomatic Design (AD). In this book, Suh does a great job of introducing the fundamental principles and methodologies of AD, by laying out the groundwork for its application in various engineering and design contexts. The principles outlined in the book provide a structural framework that addresses design challenges by emphasizing the importance of understanding customer needs, minimizing design complexity, and maintaining system integrity as shown in Figure 1. Furthermore, another literature review builds upon Suh’s work to explore the applications and implications of Axiomatic Design across various domains. In “Axiomatic Design: Advances and Applications” Suh expands on the same principles introduced in the “Principles of Design”, which offers more in-depth insights into Axiomatic Design through real-world examples that demonstrate the efficacy of Axiomatic Design in improving design quality.

Figure 1 is an example that illustrates a structural framework of what Axiomatic Design consists of based on the principles and objectives.



Elements and components of AD

Elements	components
1. Axioms Theory	Maintain Independence
	Minimize Information
2. Structures	Horizontal Decomposition – domains
	Vertical Decomposition – detail hierarchies
3. Processes Method	Zigzagging decomposition
	Physical integration

5

Figure 1 – PowerPoint slide on the Element and components of AD (Brown 2024)

Figure 2 refers to the different levels of abstraction within a system's design. The design domains help structure the design process and properly help students understand the relationships between the different components of a system.

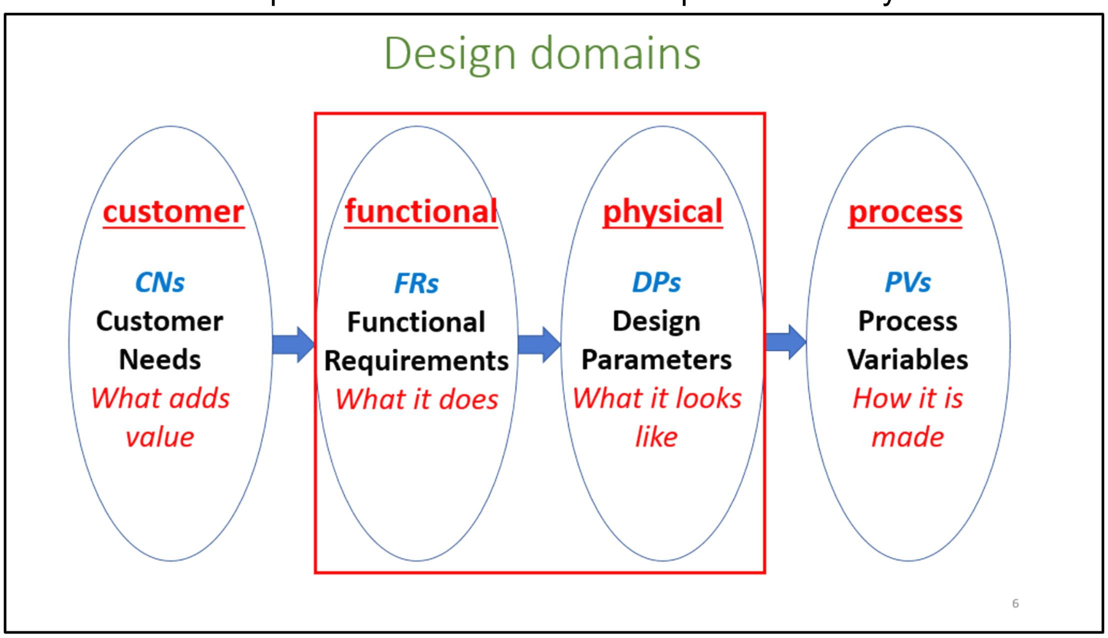


Figure 2 – PowerPoint Slide on the design domains of AD (Brown 2024)

5.2 Literature review of effective ways of teaching k-12 students to see how AD might be taught.

In exploring the literature reviews on effective ways of teaching K-12 students to see how AD might be taught, it's important to examine a variety of instructional approaches. For instance, Project-based learning has a highly effective approach where students collaborate on projects to address different real-world challenges. Incorporating Axiomatic Design using project-based learning allows educators to guide students through the design process and engage them in iterating their designs based on feedback that may be given. Project-based learning approach promotes communication and creativity among students. Additionally, researchers consistently highlight the effectiveness of hands-on approaches in engaging K-12 students. This method requires active participation in problem-solving activities as well as experimentation and exploration to gain a sense of understanding of the concepts which provides students the opportunity to apply theoretical knowledge which enhances their learning skills. Furthermore, various literature reviews showing how educators effectively use Axiomatic Design to connect these principles to STEM learners, demonstrate how students can not only tackle engineering challenges, but they can also master the true essence of Axiomatic Design concepts.

6. Results

6.1. Review of teaching AD success

Based on the numerous amounts of literature reviews, it can be analyzed that the success of teaching Axiomatic Design (AD) to pre-college STEM students is evident through "a systematic approach to design that emphasizes functional independence and simplicity" (Suh,2001). This structured framework empowers students to analyze complex problems methodically and develop innovative solutions that comply with fundamental engineering principles shown in Figure 3 a description on what this literature consists of. The implementation of Axiomatic Design principles in the classroom setting has increased a significant interest amongst students that, "About 50% of the students are extremely interested in the project and end up devoting too much time to it" (Park,2014). Thus, this important level of student engagement indicates the effectiveness of Axiomatic Design instruction in capturing the student's interest and encouraging enthusiasm for learning. Overall, this demonstrates the positive impact of teaching AD on students' approach to design and their level of engagement in STEM education.

In Table 1., a chart was created to give a breakdown on what makes the two literature reviews similar and difference when addressing Axiomatic Design to better enhance the understanding that both articles display.

Table 1. Comparison of Suh 2001 and Park 2014 *AD.*

Aspect	**Suh (2001)**	**Park (2014)**
Focus of the Article	Discusses advances and applications of axiomatic design	Focuses on teaching conceptual design using axiomatic design
Author(s)	Nam P. Suh	Gyung-Jin Park
Publication Year	2001	2014
Journal/Source	-	Journal of Mechanical Science and Technology
Audience	Researchers, practitioners, engineers	Engineering students and practitioners
Main Topics Covered	-Principles and applications of axiomatic design -Case studies and examples -Advances in the field	-Teaching methods and strategies-Application to conceptual design-educational outcomes
Methodology/Approach	Literature review, case studies	Descriptive analysis of teaching methods and outcomes
Key Findings/Contributions	-Advances in axiomatic design theory - Practical applications in engineering -Importance of independence and information axioms	-Effectiveness of axiomatic design in teaching conceptual design - Enhanced problem -Solving skills -Application to real-world projects
Scope and Depth of Discussion	In-depth exploration of theory and applications	Focus on pedagogical aspects with practical examples
Implications for Practice	Provides insights for practitioners and engineers in applying axiomatic design	Offers guidance and strategies for educators teaching conceptual design using axiomatic principles
Overall Tone	Academic and research-focused	Educational and instructional

6.2. Scientific, rule-based, approach to design decisions based on 2 axioms, i.e., rules.

Axiomatic Design (AD) principles being included in teaching pre-college STEM students have formed meaningful results that are rooted in scientific, rule-based approaches to design decisions. As stated by Suh (1990), “The first axiom of AD states that information is not created nor destroyed in a design process". This foundational principle emphasizes the importance of maintaining consistency that ensures that students' approach to design problems consists of all relevant information and avoids redundancies. Furthermore, “the second axiom of AD aims to ensure independence between functional requirements and design parameters to enhance the design's robustness and flexibility” (Suh,1990). Through these axioms, students are equipped with the skills to adapt to design decisions and systemic frameworks for problem-solving. A real-world example of this is shown in Figure 4.

Figure 4 is a PowerPoint that was created to illustrate the axiom rules with a water faucet that provides a clear and visually appealing way to convey complex design principles and its application to a real-world example.

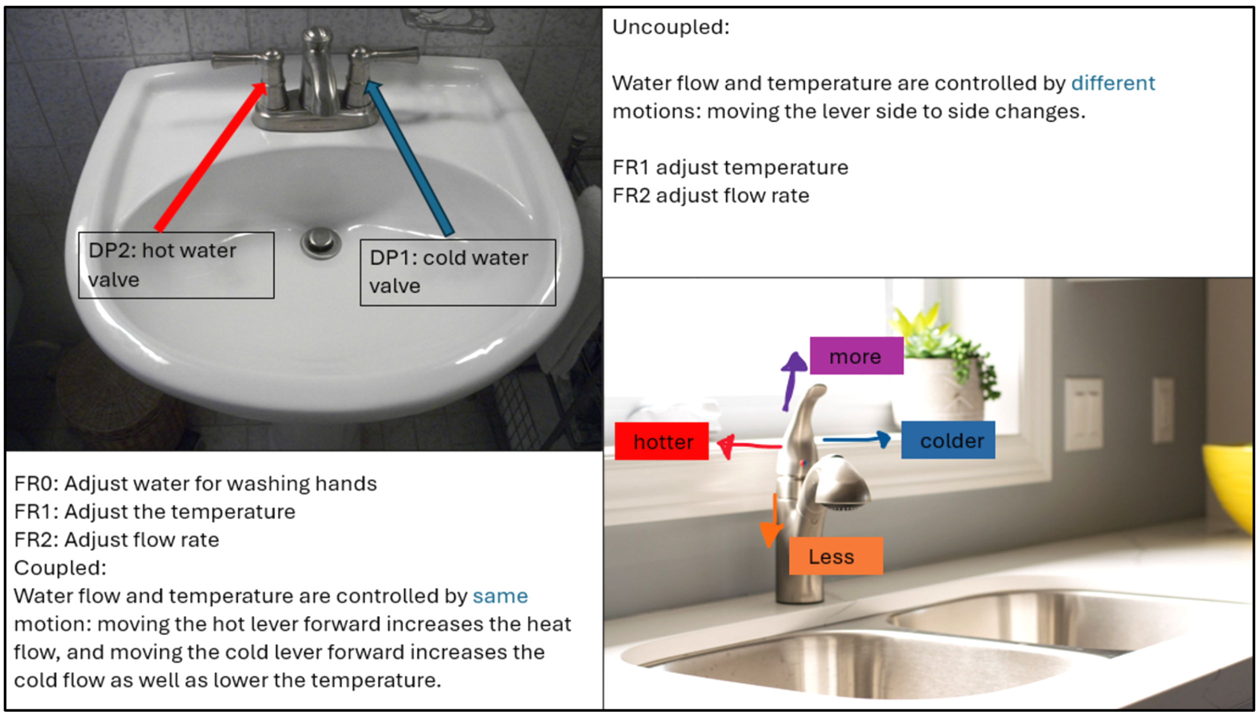


Figure 4 – PowerPoint Slide that illustrates the axiom rules with a water faucet.

6.3. Hierarchical, parallel functional-physical decomposition - provides the framework for handling any intricacy of the design problem.

As emphasized by Suh (1990) stated “Hierarchical, parallel functional-physical decomposition allows us to organize complex systems into manageable hierarchical levels". This approach allows students to break down complex design problems into more manageable components. Moreover, “Parallel functional-physical decomposition allows designers to work on function and physical aspects of the system in parallel, reducing design time and enhancing design quality” (Suh,2001). This parallel approach limits the design time and enhances better design quality by allowing designers to experience unique design alternatives in parallel and evaluate the effectiveness of the approach in meeting the functional requirements. Furthermore, Karnopp et al.,2012 states that "To model a system, it is usually necessary to first break it up into smaller parts that can be modeled and perhaps studied experimentally and then to assemble the system model from the parts". Thus, this modeling approach aligns with the hierarchical, parallel functional-physical decomposition because it provides students with a systematic framework for modeling complex systems that creates a deeper understanding of their behaviors and interactions.

Figure 5 is an example that plays a crucial role in Axiomatic Design by providing a systematic approach to organizing and understanding complex systems. By breaking down the system in such a way designers can better analyze and manage the design process in a more robust and efficient way.

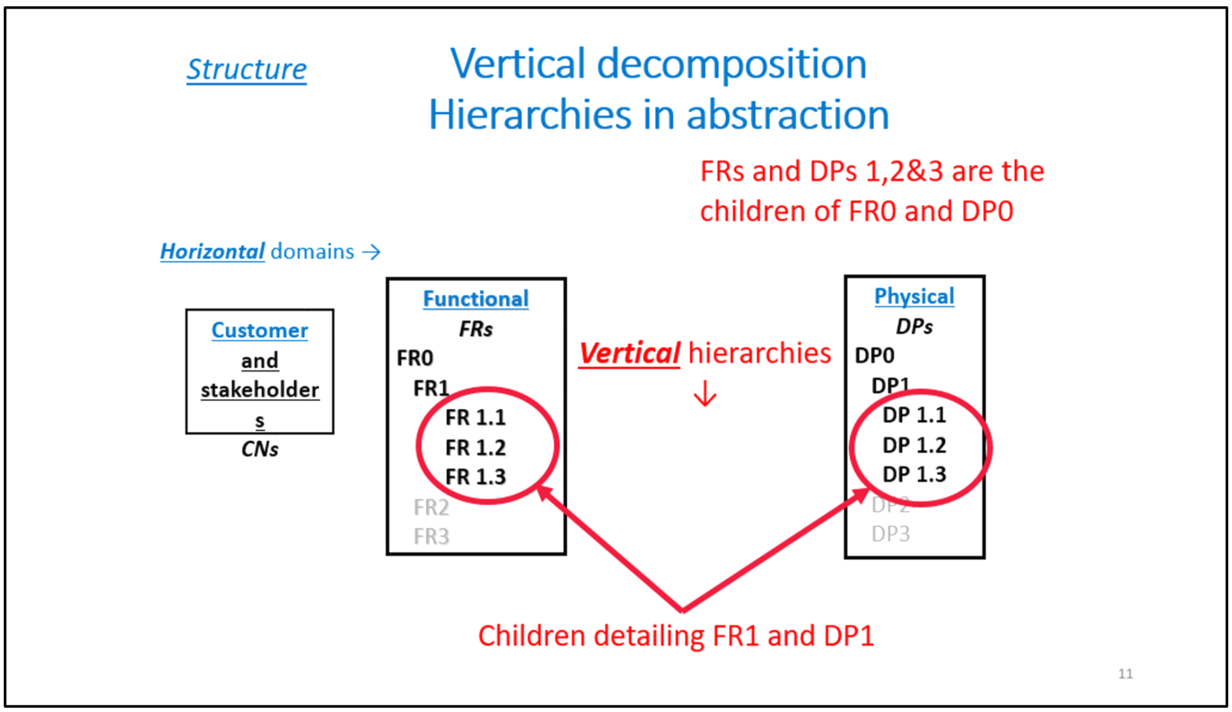


Figure 5 – PowerPoint Slide on the vertical decomposition hierarchies in abstraction breakdown (Brown 2024)

6.4. Suggest some ways AD might be taught to k-12 students.

Several approaches for teaching Axiomatic Design (AD) to K-12 students can be suggested by emphasizing practical applications and collaborative problem-solving which is shown in Figure 6. According to Nordlund et al.,2016, p.218, "establishing the right set of FRs is critical to the success of the design because these will govern the rest of the process". These FRs are the foundation for the entire design process that leads to the following decisions and iterations. Therefore, teachers can introduce Axiomatic

Design by engaging students in activities that focus on identifying and prioritizing FRs relevant to real-world problems. Having these hands-on activities allows students to develop a clear understanding of how important FRs are in guiding design decisions and empowering critical thinking skills important for effective problem-solving. English & King,2015 stated, “We consider idea generation to encompass brainstorming and planning where students share and formulate ideas, discuss strategies, and develop a collaborative plan". By promoting a supportive and collaborative learning environment, educators can encourage students to explore different ideas, generate innovative solutions, and develop effective strategies.

In Table 2., a chart that was created to provide clear and organized comparison of the two articles making it easy for others to understand the process that both authors took to grasp a better idea on their approach to Axiomatic Design.

Table 2– A chart illustrating the similarities and differences in both articles about AD.

Aspect	**Nordlund et al. (2016)**	**English & King (2015)**
Focus of the Article	Making abstract concrete through axiomatic design	STEM learning through engineering design
Authors	Nordlund, M., Kim, S., Tate, D., Lee, T., Oh, H.	English, L.D., & King, D.T.
Publication Year	2016	2015
Journal/Source	Procedia CIRP	SpringerOpen
Audience	Researchers, practitioners, engineers	Educators, researchers, STEM education community
Main Topics Covered	-Application of axiomatic design in making abstract concepts tangible - Case studies and examples	- Fourth-grade students’ investigations in aerospace -STEM learning through engineering design -Educational outcomes
Methodology/Approach	Descriptive analysis, case studies	Qualitative research, observational study
Key Findings/Contributions	-Concrete applications of axiomatic design principles -Enhanced problem-solving skills -Importance of mapping functions to design parameters	-Fourth-grade students’ engagement in engineering design -Learning outcomes and student perceptions of STEM education
Scope and Depth of Discussion	Focus on practical applications and examples	In-depth exploration of student learning experiences and outcomes
Implications for Practice	Provides insights for practitioners and educators	Offer guidance for educators on implementing engineering design

	in applying axiomatic design principles	activities in STEM education
Overall Tone	Practical and application oriented	Educational and research-focused

7. Discussion

7.1. In what way is scientific design theory and method being taught in K-12?

Traditionally, design concepts in the K-12 curriculum were taught through a basic intuitive problem-solving or trial-and-error method that lacks a clear framework focused on scientific principles. However, educational practices are increasingly implementing scientific design theory and methods into K-12 curricula through various academic strategies as shown in Figure 7. One approach to teaching scientific design theory and methods in K-12 is project-based learning. Educators are implementing engineering design principles into STEM curricula to challenge students to identify real-world problems, analyze the requirements, and then develop a solution. By engaging students in practice design projects educators are deepening students' skills. Additionally, interdisciplinary approaches to teaching design in K-12 education are becoming increasingly important. Through emphasis, students can see a genuine connection between the integration of design processes in different subject areas. Overall, by integrating scientific design theory and method into K-12 education, there is a visible shift shown toward a more structural and systemic approach to teaching design.

Figure 7 is an example that serves as a visual aid to help educators, students and stakeholders understand the differences between an algorithmic and an axiomatic approach while providing a framework that informs decisions about instructional strategies and curriculum development in STEM education.

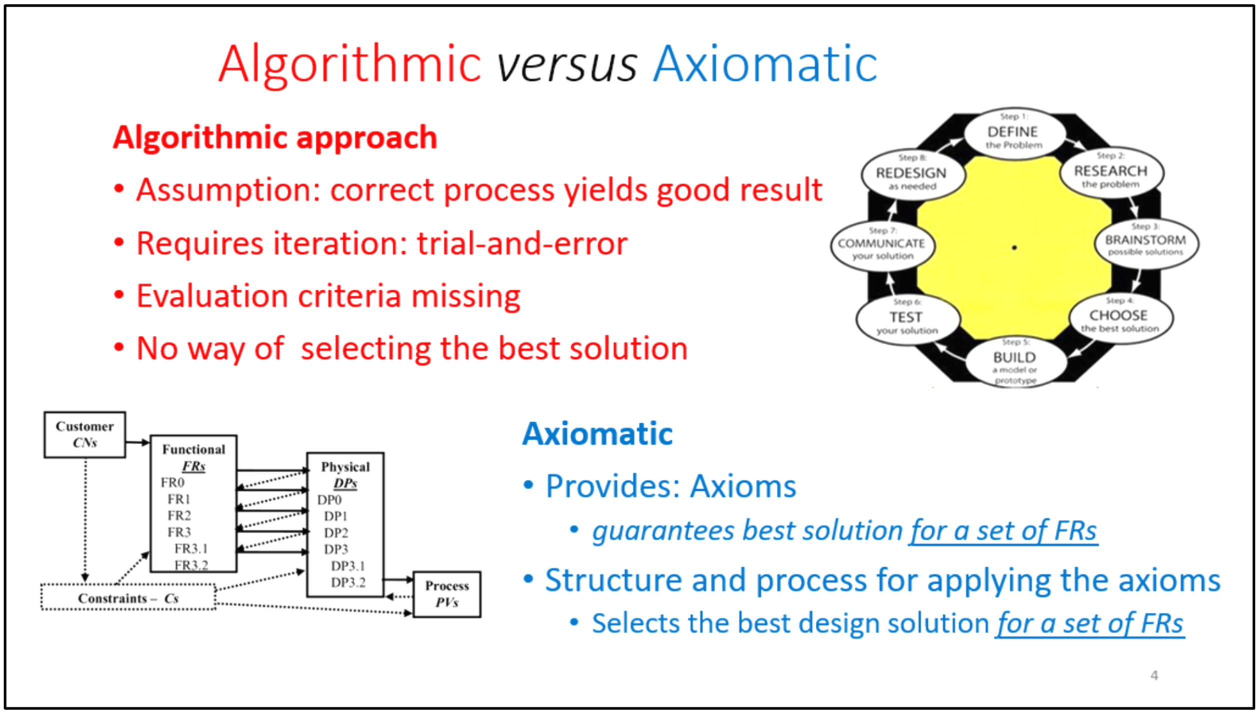


Figure 7 – PowerPoint Slide on the obvious difference of Algorithmic and Axiomatic approach (Brown 2024)

7.2. Is AD valuable to pre-college STEM students?

The value of Axiomatic Design (AD) to pre-college STEM students becomes more noticeable through the systematic and structured approach to engineering design. Axiomatic Design provides a framework that emphasizes fundamental principles such as maintaining independence and minimizing information so that students can have a clear method for approaching design challenges in which those challenges are shown in Figure 8. Axiomatic Design encourages students to analyze complex problems, identify the functional requirements, and develop innovative solutions that follow fundamental engineering principles. Moreover, Axiomatic Design prepares pre-college STEM students for the 21st-century workforce's demands, providing them with practical skills applicable across various disciplines. As students are being taught to think systematically about design problems and apply the principles to their solutions, Axiomatic Design creates a problem-solving mindset that expands beyond engineering science, mathematics, and technology. Overall, the value of AD being taught to pre-college STEM students lies in the ability to provide a structured framework so that they have the skills and mindset to tackle any challenges that they face.

Figure 8 is an example that gives a list of challenges that students and/or educators may come across when it comes down to the design process.

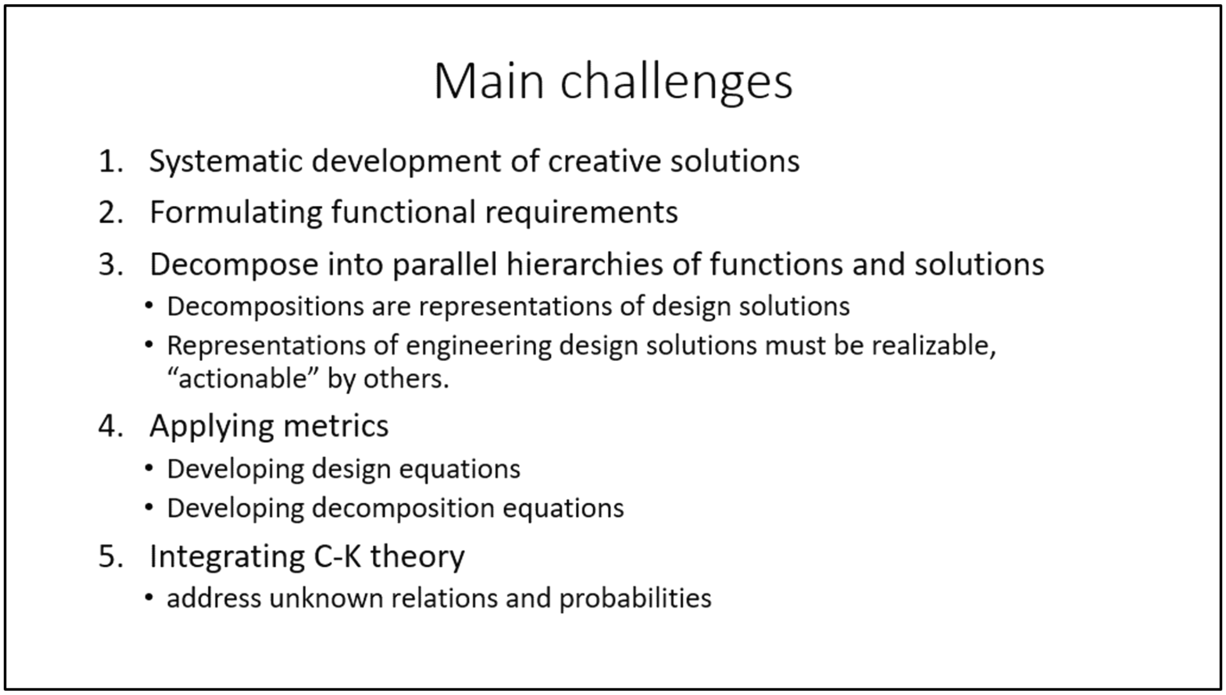


Figure 8 – PowerPoint Slides on the potential flaws within the AD process (Brown 2024)

7.3. What impacts does teaching AD have on students and teachers?

Teaching AD empowers students to know the importance of having problem-solving skills and a deeper understanding of engineering principles. By providing students with a structural framework for approaching design challenges, AD encourages critical thinking, analytical skills, and creativity. Students who learn AD principles are better advanced to tackle real-world challenges, and they also get inspired to pursue careers in engineering and related fields, addressing the growing demands for STEM professionals in the workforce. Moreover, teaching AD has a significant impact on teachers because of their instructional approaches and promoting professional development. Educators who incorporate the AD principle into theory teaching practices tend to develop a deep understanding of engineering design concepts and methodologies. Overall, the impacts of teaching AD on both teachers and students foster critical thinking, creativity, collaboration, and innovation.

8. Conclusion

In conclusion, the integration of scientific design propositions and styles in K-12 education represents a pivotal step towards equipping scholars with important problem-solving skills and encouraging their creativity and innovation. While scientific design proposition is being honored as precious in K12, there is a need for further comprehensive approaches to it being enforced. Likewise, educators should continue to explore innovative teaching strategies and educational styles that effectively incorporate scientific design into the K-12 class, ensuring all scholars have access to high-quality design education.

Numerous literature reviews emphasize that Axiomatic Design (AD) is valuable to pre-college STEM students because it holds significant potential as an educational tool. Axiomatic Design offers unique benefits in teaching design theory and problem-solving skills, provides students with a structural framework for approaching design problems, and emphasizes the importance of independence and information axioms. By including Axiomatic Design Principles in the K-12 curriculum, educators can better prepare students for higher education and future careers in STEM through critical thinking and creativity, where complex design challenges are common.

Based on my findings there are positive outcomes from both students and teachers. Students benefit from improved problem-solving abilities and increased engagement in STEM subjects, while teachers find interesting ways to incorporate Axiomatic Design into their curriculum and enhance their instructional practices. However, more research needs to be done to fully understand the long-term impacts of teaching Axiomatic Design, and to develop more desirable implementation strategies that can maximize its benefits for all participants.

9. Reference

9.1. Brown, C. A. (2005). Teaching axiomatic design to engineers—Theory, applications, and software. Journal of Manufacturing Systems, 24(3), 186-195. https://doi.org/10.1016/s0278-6125(06)80007-5

9.2. Brown C.A. (2024) The Design Theory Workshop and Tutorial, Special Interest Group of the Design Society, Ecole des Mins, Paris 2024

9.3. English, L. D. (2016, March 1). STEM education K-12: Perspectives on integration. SpringerLink. https://link.springer.com/article/10.1186/s40594-016-0036-1#citeas

9.4. English, L. D., & King, D. T. (2015, August 19). STEM learning through engineering design: Fourth-grade students' investigations in aerospace. SpringerOpen.https://stemeducationjournal.springeropen.com/articles/10.1186/s40594-015-0027-7

9.5. Foley, J. T., & Harðardóttir's, S. (2016, December). Creative Axiomatic Design.https://www.researchgate.net/publication/306030830_Creative_Axiomatic_Design

9.6. Ganesh, T. G., & Schnittka, C. G. (2014). Engineering education in the middle grades. Engineering in Pre-College Settings, 89-116. https://doi.org/10.2307/j.ctt6wq7bh.9

9.7. Karnopp, D. C., Margolis, D. L., & Rosenberg, R. C. (2012). System dynamics: Modeling, simulation, and control of mechatronic systems. John Wiley & Sons.

9.8. Krajcik, J., & Delen, I. (2017, April). Engaging learners in STEM education. https://www.researchgate.net/publication/317258685_Engaging_learners_in_STEM_education_Engaging_learners_in_STEM_education

9.9. Li, T., & Zhan, Z. (2022, August). A Systematic Review on Design Thinking Integrated Learning in K-12 Education. Applied Sciences 12(16):8077. https://www.researchgate.net/publication/362701861_A_Systematic_Review_on_Design_Thinking_Integrated_Learning_in_K-12_Education

9.10. Nordlund, M., Kim, S., Tate, D., Lee, T., & Oh, H. (. (2016). Axiomatic design: Making abstract concrete. Procedia CIRP, 50, 216-221. https://doi.org/10.1016/j.procir.2016.04.146

9.11. Park, G. (2014). Teaching conceptual design using axiomatic design to engineering students and practitioners. Journal of Mechanical Science and Technology, 28(3), 989-998. https://doi.org/10.1007/s12206-013-1170-z

9.12. Park, G. J. (2011, May). https://www.axiomaticdesign.com/wp-content/uploads/icad-2011-paper29-park.pdf

9.13. Parker, K. R., Chen, I. C., Chiang, C. H., & Liao, C. H. (2022, August 15). Exploring the relationship between computational thinking and learning satisfaction for non-STEM college students. SpringerOpen. https://educationaltechnologyjournal.springeropen.com/articles/10.1186/s41239-022-00347-5

9.14. Smith, C. L., Maclin, D., Houghton, C., & Hennessey, M. G. (2000). Sixth-grade students' Epistemologies of science: The impact of school science

experiences on epistemological development. Cognition and Instruction, 18(3), 349-422. https://doi.org/10.1207/s1532690xci1803_3
9.15. Suh, N. P. (2001). Axiomatic design: Advances and applications.
9.16. Suh, N. P. (2022, July 6). Axiomatic design - Advances and applications - Functional specs, Inc. Functional Specs, Inc. https://www.axiomaticdesign.com/technology/axiomatic-design-advances-and-applications/
9.17. Suh, N. P., & Ralph & Eloise F Cross Professor and Head of the Department of Mechanical Engineering Nam Pyo Suh. (1990). The principles of design. Oxford University Press on Demand.
9.18. Tripon, C. (2020, April). CRITICAL THINKING IN STEM LEARNING. https://www.researchgate.net/publication/368812394_CRITICAL_THINKING_IN_STEM_LEARNING