Case-Based Axiomatic Design Assistant (CADA): Combining Axiomatic Design and Case-Based Reasoning to Create a Design Knowledge Graph for Pharmaceutical Engineering

Selvapriya M
Assistant Professor, Department of Pharmaceutical Technology,
Mahendra Engineering College, Namakkal
selvapriyam@mahendra.info

Abinaya S., Priya K.
Department of Pharmaceutical Technology
Mahendra Engineering College, Namakkal
abinaya432005@gmail.com
priyapriyak202@gmail.com

Abstract

The development of personalized drugs introduces new uncertainties and risks in production machinery design, which can be mitigated through structured work flows. As the commonly used V-Model approach has limitations in dealing with complex multi-domain problems, it is essential to address traceability and relationships between requirements and solutions in a regulated environment to ensure product quality. This study focuses on the conceptual design phase and develops a design methodology called the Case-based Axiomatic Design Assistant (CADA) to address this type of problem. It takes, as a starting point, Axiomatic Design (AD), due to its simplicity and graphical tools for quality evaluation, and Case-Based Reasoning (CBR), due to its capacity to integrate data structures and continuously improve. This combination is put into practice through a visual assistant that utilizes a knowledge graph to represent design elements comprehensively. This article describes the development, implementation, and testing process of CADA, which includes examples of the conceptual design for pharmaceutical manufacturing. The proposed CADA method facilitates systematic requirements analysis, structured reasoning, and solution evaluation, and overcomes the limitations of previous methodologies. It represents a novel approach with an intuitive workflow and advanced graphical capabilities, exemplified in the context of a conceptual design for pharmaceutical manufacturing. The inclusion of intrinsic data labeling capabilities and inference visualization enhances its relevance.

Keywords— pharma equipment; axiomatic design; case-based reasoning; knowledge graph; design for AI

I. Introduction

The early Product Design phase is considered one of the cornerstones of successful production equipment design. Over time, various design methodologies were created due to how designers gain the specific knowledge they need to understand user requirements and make decisions for the particular use case [1,2]. From a philosophical standpoint, knowledge and design are inherently related in the form of ontology, the science of things that exist, and epistemology, which is the methodology used to achieve and correctly understand knowledge [3]. Gruber [4] found an early definition for Ontology in the context of computer science as an "explicit specification of a conceptualization". This term is explained as "what exists is exactly that which can be represented". Later, Studer et al. [5] expanded this definition with a domain-specific component:"an ontology is a formal, explicit specification of a shared conceptualization". The term"conceptualization" hereby stands for "an abstract, simplified view of the world that we wish to represent for some purpose", as a general definition for knowledge representation for a specific use case [6]. Following the ideas of these statements, a structured design process starts with something existing (Ontology). It moves into a formalized information flow of reasoning or a cognitive process (Epistemology), resulting in a new situation that becomes Ontology [3].

2. Methods and Theories for CADA Design

The following summary of existing methods in the form of literature research is grounded in the literature published in the leading scientific databases, e.g., Web of Science (Core Collection) and Scopus.

Recognized Methods for Pharmaceutical Equipment DesignQuality by Design (QbD) is known as a systematic prospective analysis of product and process characteristics during the design phase [16]. The main goals of QbD are specifications and control parameters that enable processes to achieve predefined quality characteristics [17]. The ICH guideline Q8 (R2) on pharmaceutical development [18] instructs on using a quality-risk-based QbD approach to develop drug substances and manufacturing processes. Quality Target Product Profile (QTPP), as described in the Q8 (R2) guideline, forms the basis for design and development in the form of a set of measurable product properties most relevant to product quality. Critical Quality Attributes (CQA) can be derived based on this dataset. CQA is applied to the equipment and its internal mechanisms that are in use for the production to identify Critical Process Parameters (CPP). These physical, chemical, biological, or microbiological characteristics determine the product's ability to meet the QTPP. They must be in a dedicated range during the production process or in the product itself. QbD is important to remember during the method's development as it is a fundamental description of how pharma structures data-driven development of new equipment.

3. Results: Method Development, Implementation, and Testing of CADA Framework

Following the literature review, the research develops, implements, and tests a data driven, risk-based, and structured design method that meets the needs of conceptual design for pharmaceutical equipment. For this purpose, we combined existing and function proven design frameworks and data architecture to form a novel conceptual design method. The results of this study will then be described around the process of developing the CADA framework.

3.1. Method Development

The following Figure 1 shows the proposed method as a selection of different tools identified within the literature search. The combination and relevance of the individual building blocks are described in detail from the bottom to the top layer afterwards. Appl. Sci. 2025, 15, x FOR PEER REVIEW 8 of 24 The structure and usability of the method need to address the exceptional environment of the regulated pharmaceutical branch. Clear and easy-to-follow decision making and content visualization are critical success factors for this tool. The visual representation of the design and its internal information structure must be capable of labeling data and showing the output of a trained model in the same way.

Semantic Network (SN)

As knowledge, or in a more general form, "data", creates the backbone of every decision, it is important to us to have an accessible and interpretable information layer within our proposed method. Former design knowledge systems store information in fragments or tables, which may be hard for non-advanced designers to interpret without the context of the specific situation. Designers work best when they have a concrete design situation on which they can refer and base their decisions [8]. SNs implement entities and relations in an easy-to-follow way (Figure 2), which allows humans to read it.

4. Discussion

This research discussed a specific design method covering the needs of a domain belonging to the pharmaceutical engineering environment. Design methods in this section There is a growing need for more effective representation within the design community. Our proposed method addresses this by integrating well-established tools with modern data architecture. In particular, Axiomatic Design (AD), when combined with methodologies such as TRIZ, has shown positive impacts by enhancing domain understanding and supporting structured workflows [50]. However, merging tools like TRIZ and Problem-Solution Networks (PSN) still lacks clear, detailed guidelines for translating problems into compliant solutions [27]. In our approach, AD inherently offers a structured methodology, allowing designers to benefit from its domain-specific guidance throughout the design process.

While traditional research design methodologies often focus on textual knowledge representation—as seen in the original form of AD—Conceptual Design also employs visual elements such as sketches, CAD models, and images [48]. At the enterprise level, structuring product design knowledge can be further strengthened through the integration of TRIZ, Functional Tree Design, and relationship mapping [63]. These combinations are vital for organizing design data in ways that enable reuse and evaluation.

Our proposed method enhances this by incorporating a knowledge graph structure capable of handling both textual and graphical content. This is further supported by Case-Based Reasoning (CBR) attributes, which are essential to our data model. These attributes ensure that the information input and the algorithms used to derive problem–solution relationships remain structured and consistent.

A similar multidimensional perspective is found in the Design Knowledge Semantic Network (SKSN) by Yue et al. [64], underscoring the value of semantic network (SN)-based representations in technical design literature. Knowledge graphs also provide an effective means of structuring data for visualization purposes [44]. Visual guidance during database creation for CBR applications has already been implemented in platforms like iSee, although such tools tend to focus on different outcomes [65].

However, existing semantic network tools often lack a well-defined process or workflow and are not tailored to support our specific domain requirements in detail [48]. Our approach fills this gap by offering a regulated environment with a strong emphasis on transparency throughout the design and engineering process. For instance, ontology-based information models are already used in pharmaceutical engineering to support risk analysis [49], and similar structures are demonstrated in our use cases, showcasing the applicability and effectiveness of the proposed workflow.

There is a growing need for more effective representation within the design community. Our proposed method addresses this by integrating well-established tools with modern data architecture. In particular, Axiomatic Design (AD), when combined with methodologies such as TRIZ, has shown positive impacts by enhancing domain understanding and supporting structured workflows [50]. However, merging tools like TRIZ and Problem-Solution Networks (PSN) still lacks clear, detailed guidelines for translating problems into compliant solutions [27]. In our approach, AD inherently offers a structured methodology, allowing designers to benefit from its domain-specific guidance throughout the design process.

While traditional research design methodologies often focus on textual knowledge representation—as seen in the original form of AD—Conceptual Design also employs visual elements such as sketches, CAD models, and images [48]. At the enterprise level, structuring product design knowledge can be further strengthened through the integration of TRIZ, Functional Tree Design, and relationship mapping [63]. These combinations are vital for organizing design data in ways that enable reuse and evaluation.

Our proposed method enhances this by incorporating a knowledge graph structure capable of handling both textual and graphical content. This is further supported by Case-Based Reasoning (CBR) attributes, which are essential to our data model. These attributes ensure that the information input and the algorithms used to derive problem–solution relationships remain structured and consistent.

A similar multidimensional perspective is found in the Design Knowledge Semantic Network (SKSN) by Yue et al. , underscoring the value of semantic network (SN)-based representations in technical design literature. Knowledge graphs also provide an effective means of structuring data for visualization purposes. Visual guidance during database creation for CBR applications has already been implemented in platforms like iSee, although such tools tend to focus on different outcomes [34].

However, existing semantic network tools often lack a well-defined process or workflow and are not tailored to support our specific domain requirements in detail. Our approach fills this gap by offering a regulated environment with a strong emphasis on transparency throughout the design and engineering process. For instance, ontology-based information models are already used in pharmaceutical engineering to support risk analysis, and similar structures are demonstrated in our use cases, showcasing the applicability and effectiveness of the proposed workflow.

There is a growing need for more effective representation within the design community. Our proposed method addresses this by integrating well-established tools with modern data architecture. In particular, Axiomatic Design (AD), when combined with methodologies such as TRIZ, has shown positive impacts by enhancing domain understanding and supporting structured workflows. However, merging tools like TRIZ and Problem-Solution Networks (PSN) still lacks clear, detailed guidelines for translating problems into compliant solutions . In our approach, AD inherently offers a structured methodology, allowing designers to benefit from its domain-specific guidance throughout the design process.

While traditional research design methodologies often focus on textual knowledge representation—as seen in the original form of AD—Conceptual Design also employs visual elements such as sketches, CAD models, and images . At the enterprise level, structuring product design knowledge can be further strengthened through the integration of TRIZ, Functional Tree Design, and relationship mapping [35]. These combinations are vital for organizing design data in ways that enable reuse and evaluation.

Our proposed method enhances this by incorporating a knowledge graph structure capable of handling both textual and graphical content. This is further supported by Case-Based Reasoning (CBR) attributes, which are essential to our data model. These attributes ensure that the information input and the algorithms used to derive problem–solution relationships remain structured and consistent.

A similar multidimensional perspective is found in the Design Knowledge Semantic Network (SKSN) by Yue et al. , underscoring the value of semantic network (SN)-based representations in technical design literature. Knowledge graphs also provide an effective means of structuring data for visualization purposes [44]. Visual guidance during database creation for CBR applications has already been implemented in platforms like iSee, although such tools tend to focus on different outcomes [36].

However, existing semantic network tools often lack a well-defined process or workflow and are not tailored to support our specific domain requirements in detail . Our approach fills this gap by offering a regulated environment with a strong emphasis on transparency throughout the design and engineering process. For instance, ontology-based information models are already used in pharmaceutical engineering to support risk analysis, and similar structures are demonstrated in our use cases, showcasing the applicability and effectiveness of the proposed workflow.

Modular Design and Structured Workflows

Traditional approaches often fail to support the individual resolution of functional requirements in a modular manner—an essential capability for developing interchangeable components that can be independently implemented and tested. In response, CADA introduces a structured workflow that aids designers in identifying correlations and interrelationships among design elements. This approach helps in developing robust concepts and reduces the risk of unforeseen issues during implementation and testing.

The evolution of modern pharmaceutical equipment requires not only rapid market readiness but also uncompromising product quality. Compliance with regulatory standards, such as Good Manufacturing Practice (GMP) and Good Engineering Practice (GEP), demands detailed descriptions and thorough documentation of equipment and internal processes . One effective strategy to meet these demands is constructing new solutions using well-documented and validated modules—a modular engineering approach that is increasingly adopted across various engineering disciplines [37].

Our methodology supports this modular design philosophy by leveraging enterprise-wide design knowledge, facilitating compliance with pharmaceutical standards from the earliest stages of the design process. Moreover, the integration of Case-Based Reasoning (CBR) fosters continuous improvement—an essential component of robust quality management systems. While these capabilities are particularly vital in regulated industries like pharmaceuticals, they can also be adapted for use in other sectors. However, for unregulated fields, our model might involve additional complexity or efforts that may not be necessary.

Scalability and Practical Application of CADA

CADA is tailored for use in continuous learning environments, ideally within large organizations that involve multiple users. In smaller companies or startups, its effectiveness may be limited due to the smaller case memory, which reduces the efficiency of the recommendation features. Nonetheless, even in such settings, the quality feedback generated by the system remains beneficial.

5. Final Remarks

5.1 Main Conclusions

This research proposes a structured and visual method to support early-stage design activities in regulated environments. User-friendliness and guided decision-making are fundamental strengths of the approach. The proposed methodology is built upon three integrated pillars: Semantic Networks (SN), Case-Based Reasoning (CBR), and Axiomatic Design (AD). It was validated through three case studies addressing pharmaceutical automation challenges.

To evaluate the method's versatility, further studies should examine its applicability to a wider range of customer requirements and industrial contexts. Additionally, future research could explore incorporating TRIZ as an early-stage information model to strengthen and expand the design workflow [38].

Although our approach offers visual and qualitative feedback, it cannot be directly compared with traditional quantitative evaluation or decision-making tools. However, the CBR-based data structure provides a strong foundation for the application of AI techniques aimed at automating the design process according to user-defined requirements. Future work should focus on developing a training pipeline based on the assistant's data architecture to further support this evolution.

5.2 Limitations and Contributions

This research has led to the development of a visual design assistant built on the principles of Axiomatic Design, enhanced with CBR and Semantic Networks. The literature review was exploratory in nature, and although comprehensive, it may not encompass all relevant sources needed to fully validate the proposed theoretical framework.

Complex design problems often require multilayered analysis and iterative refinement, which can exceed the capabilities of rigid design methodologies. While Axiomatic Design provides a solid structural foundation, it does not inherently promote exploratory problem-solving, highlighting the importance of integrating flexible and learning-oriented methods like CADA Method.

REFERENCES

[1] G. M. Bonnema and F. J. A. M. Van Houten, "Use of models in conceptual design," *J. Eng. Des.*, vol. 17, pp. 549–562, 2006.

[2] Y. Umeda, M. Ishii, M. Yoshioka, Y. Shimomura, and T. Tomiyama, "Supporting conceptual design based on the function-behavior-state modeler," *Artif. Intell. Eng. Des. Anal. Manuf.*, vol. 10, pp. 275–288, 1996.

[3] Y. H. Yin, A. Y. C. Nee, S. K. Ong, J. Y. Zhu, P. H. Gu, and L. E. J. Chen, "Automating design with intelligent human-machine integration," *CIRP Ann. Manuf. Technol.*, vol. 64, pp. 655–677, 2015.

[4] T. R. Gruber, "A transition approach to portable ontology specifications," *Knowl. Acquis.*, vol. 5, pp. 199–220, 1993.

[5] R. Studer, V. R. Benjamins, and D. Fensel, "Knowledge engineering: Principles and methods," *Data Knowl. Eng.*, vol. 25, pp. 161–197, 1998.

[6] M. R. Genesereth and N. J. Nilsson, *Logical Foundations of Artificial Intelligence*, Burlington, MA, USA: Morgan Kaufmann, 1987.

[7] G. Pahl, W. Beitz, J. Feldhusen, and K.-J. Grote, *Engineering Design—A Systematic Approach*, London, UK: Springer, 2006.

[8] C. Yang, Z. Liu, H. B. Wang, and J. Q. Shen, "Reusing design knowledge based on design cases and knowledge map," *Int. J. Technol. Des. Educ.*, vol. 23, pp. 1063–1077, 2013.

[9] B. M. Li, S. Q. Xie, and X. Xu, "Recent development of knowledge-based systems, methods and tools for One-of-a-Kind Production," *Knowl.-Based Syst.*, vol. 24, pp. 1108–1119, 2011.

[10] M. C. Lin, C. C. Wang, M. S. Chen, and C. A. Chang, "Using AHP and TOPSIS approaches in customer-driven product design process," *Comput. Ind.*, vol. 59, pp. 17–31, 2008.

[11] E. Rauch, P. Dallasega, and D. T. Matt, "Axiomatic design based guidelines for the design of a lean product development process," in *Proc. 9th Int. Conf. Axiomatic Design (ICAD)*, Florence, Italy, 2015, pp. 112–118.

[12] ISPE, *GAMP® 5: A Risk-Based Approach to Compliant GxP Computerized Systems*, North Bethesda, MD, USA: Int. Soc. Pharm. Eng., 2008.

[13] F. Gottschalk, "GAMP 5/Introduction—Overview," *Pharm. Ind.*, vol. 72, pp. 1618–1626, 2010.

[14] P. Sarhadi, W. Naeem, K. Fraser, and D. Wilson, "On the application of Agile project management techniques, V-Model and recent software tools in postgraduate theses supervision," in *Proc. 13th IFAC Symp. Adv. Control Educ. (ACE)*, Hamburg, Germany, 2022, pp. 109–114.

[15] P. Cunningham and A. Bonzano, "Knowledge engineering issues in developing a case-based reasoning application," *Knowl.-Based Syst.*, vol. 12, pp. 371–379, 1999.

[16] E. Pallagi, R. Ambrus, P. Szabo-Revesz, and I. Csoka, "Adaptation of the quality by design concept in early pharmaceutical development of an intranasal nanosized formulation," *Int. J. Pharm.*, vol. 491, pp. 384–392, 2015.

[17] L. X. Yu, "Pharmaceutical quality by design: Product and process development, understanding, and control," *Pharm. Res.*, vol. 25, p. 2463, 2008.

[18] EMA, "ICH Guideline Q8 (R2) on Pharmaceutical Development." [Online]. Available: https://www.ema.europa.eu/en/documents/scientific-guideline/international-conference-harmonisation-technical-requirements-registration-pharmaceuticals-human-use_en-11.pdf

[19] FDA, "Guidance for Industry PAT—A Framework for Innovative Pharmaceutical Development, Manufacturing, and Quality Assurance." [Online]. Available: https://www.fda.gov/media/71012/download

[20] R. V. Barenji, Y. Akdag, B. Yet, and L. Oner, "Cyber-physical-based PAT (CPbPAT) framework for Pharma 4.0," *Int. J. Pharm.*, vol. 567, p. 18445, 2019..

[21] M. Ogot, "Conceptual design using axiomatic design in a TRIZ framework," *Procedia Eng.*, vol. 9, pp. 736–744, 2011.

[22] Z. Li and K. Ramani, "Ontology-based design information extraction and retrieval," *Artif. Intell. Eng. Des. Anal. Manuf.*, vol. 21, pp. 137–154, 2007.

[23] P. M. Khanolkar, A. Vrolijk, and A. Olechowski, "Mapping artificial intelligence-based methods to engineering design stages: A focused literature review," *Artif. Intell. Eng. Des. Anal. Manuf.*, vol. 37, p. e25, 2023.

[24] A. B. Arrieta *et al.*, "Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI," *Inf. Fusion*, vol. 58, pp. 82–115, 2020.

[25] A. A. Cabrera *et al.*, "What did my AI learn? How data scientists make sense of model behavior," *ACM Trans. Comput.-Hum. Interact.*, vol. 30, pp. 1–27, 2023.

[26] J. Han, P. R. N. Childs, and J. Luo, "Applications of artificial intelligence and cognitive science in design," *Artif. Intell. Eng. Des. Anal. Manuf.*, vol. 38, p. e6, 2024.

[27] R. Chauhan and E. Yafi, "Applicability of classifier to discovery knowledge for future prediction modelling," *J. Ambient Intell. Humaniz. Comput.*, vol. 14, pp. 10347–10362, 2022.

[28] E. Davis, "Knowledge representation," in *Int. Encycl. Soc. Behav. Sci.*, N. J. Smelser and P. B. Baltes, Eds., Oxford, UK: Pergamon, 2001, pp. 8132–8139.

[29] A. Aamodt and E. Plaza, "Case-based reasoning—Foundational issues, methodological variations, and system approaches," *AI Commun.*, vol. 7, pp. 39–59, 1994.

[30] R. L. de Mantaras and E. Plaza, "Case-based reasoning: An overview," *AI Commun.*, vol. 10, pp. 21–29, 1997.

[31] F. Meister, P. Khanal, and R. Daub, "Digital-supported problem solving for shopfloor steering using case-based reasoning and Bayesian networks," *Procedia CIRP*, vol. 119, pp. 140–145, 2023.

[32] C. A. Brown, "Teaching axiomatic design to engineers—Theory, applications, and software," *J. Manuf. Syst.*, vol. 24, pp. 186–195, 2005.

[33] M. M. Hakim and J. H. Garrett, "An object-centered approach for modelling engineering design products: Combining description logic and object-oriented modelling," *Artif. Intell. Eng. Des. Anal. Manuf.*, vol. 11, pp. 187–198, 1997.

[34] L. L. Zhang *et al.*, "Construction and application of enterprise knowledge base for product innovation design," *Appl. Sci.*, vol. 12, p. 6358, 2022.

[35] G. F. Yue, J. H. Liu, Q. Zhang, and Y. Z. Hou, "Building a design-rationale-centric knowledge network to realize the internalization of explicit knowledge," *Appl. Sci.*, vol. 13, p. 1539, 2023.

[36] M. Caro-Martínez *et al.*, "iSee: A case-based reasoning platform for the design of explanation experiences," *Knowl.-Based Syst.*, vol. 302, p. 112305, 2024.

[37] A. Schultheis, C. Zeyen, and R. Bergmann, "An overview and comparison of case-based reasoning frameworks," in *Proc. Case-Based Reasoning Res. Dev. (ICCBR)*, Aberdeen, UK, Jul. 2023, pp. 327–343.

[38] X. W. Xie, L. Chen, H. Z. Fang, and Y. X. Chen, "Research on process supervision and quality control system of modular pharmaceutical production line," in *Proc. 2nd IEEE Int. Conf. Comput. Sci. Inf. Technol.*, Beijing, China, Aug. 2009, pp. 69–73