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Applications and Challenges of Engineering Design in Automotive Sector: A Review

By

Aarush Patwari

The Ahmedabad International School, Ahmedabad

Abstract

Purpose: This review paper aims to provide a comprehensive overview of engineering design applications, with a particular focus on the automotive sector, and to analyze the challenges associated with implementing them.

Design/methodology/approach: The paper conducts an extensive literature review, synthesizing findings from numerous studies across various engineering design applications.

Findings: The review reveals that engineering design has significantly evolved, integrating advanced technologies like AI and optimization techniques. In the automotive sector, applications range from knowledge-based engineering for rapid design to model-based systems engineering for complex system integration. Key challenges identified include managing increasing system complexity, integrating new technologies, balancing sustainability with performance, and effective knowledge management in multidisciplinary teams.

Practical implications: The findings underscore the need for continued investment in design technologies, greater interdisciplinary collaboration, integration of sustainability principles into core design practices, and enhanced focus on human-centred design approaches in the automotive industry. The paper also highlights the importance of developing more robust virtual collaboration tools and practices.

Originality/value: By identifying key trends, challenges, and research gaps, this paper offers valuable insights for both academics and practitioners in the field of engineering design.

Keywords: Engineering design, Automotive engineering, Knowledge-based engineering, Model-based systems engineering, Sustainable design

Introduction

Engineering design is a systematic, intelligent process of solving open-ended problems to fulfil human needs and wants (Dym et al., 2005). Its importance has grown significantly worldwide, becoming a crucial driver of innovation and competitiveness across various industries (Pahl et al., 2007).

Numerous studies have emphasized the advantages of engineering design in diverse sectors. For instance, in aerospace, it has led to significant improvements in aircraft efficiency and safety (Curran et al., 2015). In the medical field, engineering design has revolutionized patient care through innovative medical devices (Clarkson & Eckert, 2005). The manufacturing sector has seen enhanced productivity and reduced costs through the application of design for manufacturing principles (Boothroyd & Dewhurst, 1987).

The automotive industry, in particular, has experienced a growing need for advanced engineering design approaches driven by increasing vehicle complexity, stringent regulatory requirements, and the push for more sustainable transportation solutions (D'Ambrosio & Soremekun, 2017). Engineering design in this sector is crucial for addressing challenges such as vehicle electrification, autonomous driving, and lightweight construction (Denil et al., 2017).

While there is substantial research on the applications of engineering design in various sectors, including the automotive sector, there is a lack of comprehensive reviews that synthesize existing literature and provide a holistic overview of the field (Horváth, 2004). This review paper aims to address this gap by providing a comprehensive analysis of engineering design applications, with a particular focus on the automotive sector. It will explore the various applications, benefits, and challenges of engineering design, synthesizing findings from numerous studies to offer insights into current practices and future directions in this critical field.

Meaning and Evolution of Engineering Design

Engineering design involves the systematic application of scientific and mathematical principles to create products, structures, and systems that meet specified needs (Dimarogonas, 1993; Cross, 1989). The field has expanded from its initial focus on mechanical systems to encompass a wide range of factors such as environmental sustainability, user experience, and social impact (Horváth, 2004).

Historical Evolution

Initially, engineering design was primarily concerned with functional aspects and optimization, relying on simple trial-and-error methods with minimal documentation and systematic approaches. Over time, it has changed to sophisticated, computer-aided techniques that enhance precision and efficiency (Dimarogonas, 1997; Cross, 1989). There has been a formalization of design methodologies, leading to the establishment of design science, which aims to categorize and systematically arrange design knowledge (Horváth, 2004).

This multifaceted field now incorporates various domains such as design theory, design methodology, design epistemology, design history, taxonomy, technology, praxeology, modelling, metrology, axiology, and philosophy (Hubka & Eder, 1996; Horváth, 2004).

Integration of Qualitative and Quantitative Methods

Modern engineering design combines both qualitative and quantitative methods to enhance problem-solving capabilities. The integration of artificial intelligence (AI) and optimization techniques is a prominent example, enabling better representation and solution of design problems (Cagan et al., 1997).

Functional Modelling and Standardization

The need for a formal functional representation in engineering design has been highlighted in efforts to standardize design processes and to ensure that they are repeatable and meaningful across various applications. For example, functional modelling is a key tool used in quality assurance programs such as Ford's Design for Six Sigma, which aims to meet customer needs consistently (Hirtz et al., 2002).

Decision-Making and Social Choice

Engineering design has become increasingly interdisciplinary and technology-driven. It relies on advanced computational tools, simulation techniques, and data-driven approaches to solve complex design problems (Wynn & Clarkson, 2018).ne of the most significant developments in recent years is the adoption of model-based systems engineering (MBSE). This approach enables the creation of comprehensive digital models that represent all aspects of a system, which lead to better integration and optimization of various subsystems (D'Ambrosio & Soremekun, 2017).

Sustainability and lifecycle considerations have also become an important area of engineering design. Designers are now expected to consider the environmental impact of their products from cradle to grave, incorporating principles of circular economy and design for disassembly (Reddy, Reddy and Kumar, 2023).

The rise of Industry 4.0 and smart manufacturing has further transformed engineering design practices. Internet of Things (IoT) technologies, digital twins, and advanced analytics are being integrated into the design process, to enable real-time monitoring and optimization of product performance (Tao et al., 2018).

Moreover, the current state of engineering design emphasizes user-centred approaches and human factors engineering. These changes have led to increased collaboration between designers, engineers, and end-users, resulting in products that are not only technically sound but also more intuitive and user-friendly (Boy, 2017).

Additionally, the field has seen a growing emphasis on open innovation and collaborative design. Online platforms and virtual design environments are facilitating global collaboration, allowing diverse teams to work together on complex design projects regardless of geographical boundaries (Ferguson et al., 2022).

Applications of Engineering Design

Engineering design finds applications across a wide spectrum of industries and fields, demonstrating its critical role in driving innovation and solving complex problems.

Automotive Sector

The automotive industry has been at the forefront of adopting and adapting engineering design principles to improve vehicle performance, safety, and sustainability. One of the key applications in this sector is the use of knowledge-based engineering (KBE) techniques for the rapid design and analysis of automotive structures. The integration of KBE with Computer-Aided Design (CAD) tools leads to streamlined design processes, significantly reducing the time and cost involved in developing new automotive components (Pinfold & Chapman, 2001).

MBSE is widely used in the automotive sector to facilitate better integration and optimization of various subsystems (D'Ambrosio & Soremekun, 2017). It is particularly valuable in designing complex systems such as electric powertrains and autonomous driving technologies.

The development of energy-absorbing structures for side impact protection in rally cars exemplifies how engineering design enhances safety in high-speed collisions (Njuguna, 2011). Additionally, the use of advanced materials and composite structures in automotive design helps reduce vehicle weight and improve fuel efficiency, addressing both performance requirements and environmental concerns (Ratnayake, 2014).

AI and machine learning enable the analysis of large datasets to identify optimal design solutions that meet performance, safety, and cost criteria. For example, AI-driven optimization techniques are used to design lightweight yet robust vehicle structures, enhancing fuel efficiency and reducing emissions (Denil et al., 2017).

Aerospace Industry

In the aerospace industry, engineering design plays a crucial role in developing advanced aircraft components and systems and creating efficient and safe aircraft structures (Chapman & Pinfold, 2001). KBE techniques are extensively used for systematic capture, transfer, and reuse of engineering knowledge (Verhagen, 2013).

Concurrent engineering and integrated design approaches ensure that various subsystems work seamlessly together while meeting stringent performance and safety standards (Curran et al., 2015). The use of multidisciplinary design optimization (MDO) frameworks allows aerospace engineers to simultaneously address various design challenges, such as aerodynamics, structural integrity, and material selection, resulting in more efficient and innovative aircraft designs.

Biomedical Engineering

In the biomedical field, the application of design principles requires a unique blend of engineering knowledge, biological understanding, and consideration of human factors.

One significant application is in the design of prosthetic limbs. Engineers use advanced modelling techniques and materials science to create prosthetics that are functional, comfortable and aesthetically pleasing. The integration of sensors and actuators in prosthetic design has led to the development of smart prosthetics that can more closely mimic natural limb movements (Cloutier et al., 2015).

Engineering design is also used in the design of medical imaging equipment to create more efficient and accurate diagnostic tools, such as MRI machines and CT scanners that can improve image quality while reducing radiation exposure and increasing patient comfort (Clarkson & Eckert, 2005).

Manufacturing and Production Engineering

In the manufacturing sector, Design for Manufacturing and Assembly (DFMA) principles are widely applied to enhance product efficiency and reduce costs by considering manufacturing constraints during the design phase. This helps improve product quality and also accelerates time-to-market (Boothroyd & Dewhurst, 1987).

IoT technologies, digital twins, and advanced analytics are integrated into the design process, enabling real-time monitoring and optimization of product performance (Tao et al., 2018). This helps create more flexible and responsive manufacturing systems that can quickly adapt to changing market demands.

Civil Engineering and Architecture

In civil engineering and architecture, engineering design is fundamental to creating safe, functional, and aesthetically pleasing structures.

Building Information Modeling (BIM) is a key application of engineering design which allows for the creation of detailed 3D models that incorporate not just the physical aspects of a building, but also information about materials, costs, and project timelines. This helps in identifying potential issues early in the development process and facilitates better collaboration between different stakeholders (Cloutier et al., 2015).

Sustainable design has become increasingly important in civil engineering and architecture. Engineers apply design principles to create energy-efficient buildings, incorporate renewable energy systems, and minimize the environmental impact of construction. This includes the use of green building materials, passive design strategies for natural heating and cooling, and water conservation techniques (Sherwin & Bhamra, 2000).

Environmental Engineering

Engineering design plays a crucial role in addressing environmental challenges and developing sustainable solutions in areas such as water treatment, air pollution control, and waste management.or example, in designing wastewater treatment plants, engineers use modelling and simulation techniques to optimize the treatment process, ensuring that it meets regulatory standards while minimizing energy consumption and operational costs. Similarly, in the design of air pollution control systems, engineers apply fluid dynamics principles and chemical engineering concepts to create efficient scrubbers and filters (Ruschitzka et al., 2010).

Engineers apply design principles in the design of renewable energy systems to improve the efficiency of solar panels, wind turbines, and other renewable energy technologies. This involves optimizing the physical design of these systems, as well as developing smart grids and energy storage solutions to manage the intermittent nature of renewable energy sources (Pinfold & Chapman, 2001).

Computer Science and Software Engineering

User Interface (UI) and User Experience (UX) design is a critical application of engineering design principles in software development. Engineers and designers work together to create interfaces that are not only visually appealing but also intuitive and efficient to use (Verhagen, 2013; Boy, 2017).

In the field of AI and ML, engineering design principles are applied to create algorithms and models that can effectively learn from data and make accurate predictions or decisions. This involves designing the architecture of neural networks, choosing appropriate learning algorithms, and optimizing model performance (Cagan et al., 1997).

Applications of Engineering Design in Automotive Sector

The automotive industry stands at the forefront of engineering design innovation, leveraging cutting-edge technologies and methodologies to address complex challenges in vehicle performance, safety, sustainability, and user experience. This section describes the various applications of design engineering in the automotive sector.

Knowledge-Based Engineering (KBE) in Automotive Design

KBE has emerged as a cornerstone in modern automotive design, revolutionizing the way vehicles are conceptualized and developed. KBE techniques support the rapid design and analysis of automotive structures, significantly reducing the time and cost involved in developing new components (Pinfold & Chapman, 2001).

One of the most significant applications of KBE is in the design of vehicle body structures. Chapman and Pinfold (2001) demonstrated the effectiveness of KBE in the rapid design and analysis of automotive structures. Their research showed that KBE techniques, when integrated with Computer-Aided Design (CAD) tools, allow for streamlined design processes, enabling engineers to quickly generate and evaluate multiple design iterations.

The adoption of KBE in automotive design offers several key benefits including reduced design time, improved design quality, enhanced innovation and cost reduction.

Model-Based Systems Engineering (MBSE) in Automotive Design

MBSE provides a holistic approach to vehicle design, facilitating better integration and optimization of various subsystems (D'Ambrosio & Soremekun, 2017).

MBSE is particularly valuable in designing and integrating complex systems such as electric powertrains and autonomous driving technologies. D'Ambrosio and Soremekun (2017) highlighted the challenges and opportunities of applying MBSE in automotive system design, emphasizing its role in managing the increasing complexity of vehicle electronics and software systems. The advantages of adopting MBSE include improved system integration; enhanced traceability between requirements, design decisions, and system components; efficient validation and verification of system designs, reducing costly late-stage changes and improved communication between different engineering disciplines, improving cross-functional collaboration.

Artificial Intelligence and Optimization in Automotive Design

The integration of AI and optimization techniques enable the analysis of large datasets to identify optimal design solutions that meet performance, safety, and cost criteria.

AI-driven optimization techniques are increasingly used to design lightweight yet robust vehicle structures. Denil et al. (2017) explored the potential of agile model-based systems engineering, which incorporates AI techniques to enhance the design process. This approach allows for rapid iteration and optimization of vehicle designs, balancing multiple competing criteria such as weight reduction, structural integrity, and manufacturability.The use of AI and optimization in automotive design can lead to enhanced performance, improved efficiency by quickly evaluating thousands of design alternatives, cost reduction by optimizing material use and manufacturing processes, and sustainability through designing more fuel-efficient vehicles.

Safety-Focused Engineering Design

Safety is a paramount concern in automotive design, with engineering principles being applied to create vehicles that better protect vehicle occupants and other road users.

The development of energy-absorbing structures for side impact protection in rally cars shows how engineering design enhances safety in high-speed collisions. Njuguna (2011) demonstrated the application of advanced materials and design techniques in creating more effective crash protection systems. These principles are increasingly being applied to consumer vehicles, improving overall road safety.

The emphasis on safety in automotive design engineering yields several benefits:

1. Improved Occupant Protection: Advanced design techniques lead to vehicles that better protect occupants in the event of a collision.
2. Enhanced Vehicle Dynamics: Safety-focused design often improves overall vehicle handling and stability.
3. Regulatory Compliance: Innovative safety designs help manufacturers meet and exceed evolving safety regulations.
4. Consumer Confidence: Vehicles with advanced safety features often enjoy higher consumer trust and market appeal.

Sustainable and Green Vehicle Design

As environmental concerns become increasingly pressing, automotive design engineering has shifted focus towards creating more sustainable and eco-friendly vehicles.

The design of electric vehicles (EVs) is a significant application of sustainable design principles in the automotive sector. This includes the development of efficient electric powertrains, battery systems, and charging infrastructure. Cloutier et al. (2015) discussed the transition to model-based systems engineering, which is particularly relevant in the complex design process of EVs.he use of advanced materials and composite structures in automotive design helps reduce vehicle weight and improve fuel efficiency. Ratnayake (2014) explored the use of KBE techniques in material selection and criticality classification, which is crucial for developing lightweight yet safe vehicle structures.

The focus on sustainable design in the automotive sector offers numerous benefits such as reduced environmental impact as vehicles with lower emissions and reduced carbon footprint are designed. improved energy efficiency through the use of lightweight materials and optimized designs, cost savings for consumers through reduced fuel consumption or energy use and regulatory compliance for the increasingly stringent environmental regulations.

Human-Centred Design in Automotive Engineering

The application of human-centred design principles in automotive engineering has led to substantial improvements in user experience and vehicle ergonomics.

Human-centred design is particularly seen in the development of in-vehicle user interfaces and infotainment systems (Boy, 2017).

Incorporating human-centred design principles in automotive engineering offers several advantages:

1. Enhanced User Experience: Vehicles designed with user needs in mind offer more intuitive and enjoyable driving experiences.
2. Improved Safety: Well-designed interfaces reduce driver distraction, potentially improving road safety.
3. Increased Brand Loyalty: Positive user experiences can lead to increased customer satisfaction and brand loyalty.
4. Competitive Advantage: Vehicles with superior ergonomics and user interfaces can stand out in a crowded market.

Challenges of using Engineering Designhile engineering design has revolutionized various industries including the automotive sector, its implementation comes with a set of significant challenges. These challenges span technological, organizational, and human factors, often requiring innovative solutions and ongoing research to overcome.

Complexity Management

One of the primary challenges in modern engineering design is managing the increasing complexity of systems, especially in the automotive industry.

As vehicles become more sophisticated, incorporating advanced electronics, software systems, and mechatronic components, the complexity of the design process grows exponentially. This complexity makes it difficult to predict system behaviour, manage interactions between subsystems, and ensure overall system reliability (D'Ambrosio & Soremekun, 2017).

To address this challenge, researchers have explored various approaches:

- MBSE: D'Ambrosio and Soremekun (2017) proposed MBSE as a potential solution to manage complexity in automotive system design. MBSE provides a structured approach to handle complex systems, improving traceability and system integration.
- Hierarchical Design Approaches: Cloutier et al. (2015) discussed the transition from systems thinking to model-based systems engineering, suggesting hierarchical modelling techniques to break down complex systems into manageable components.

Despite these advancements, fully managing the complexity of modern vehicle systems remains an ongoing challenge, requiring continuous research and innovation.

Integration of New Technologies

The rapid pace of technological advancement poses a significant challenge in engineering design for the automotive sector.

Integrating new technologies such as AI, autonomous driving systems, and advanced materials into existing design processes can be extremely challenging. It requires not only technical expertise but also a fundamental shift in design paradigms (Denil et al., 2017).

Researchers have proposed several approaches to address this challenge:Agile Model-Based Systems Engineering: Denil et al. (2017) explored the potential of agile methodologies in model-based systems engineering to facilitate the rapid integration of new technologies into the design process.

- KBE: Verhagen (2013) suggests that KBE can play a crucial role in managing and integrating new technological knowledge throughout the product lifecycle.

The challenge of seamlessly integrating rapidly evolving technologies into engineering design processes remains noteworthy.

Sustainability and Environmental Considerations

Incorporating sustainability and environmental considerations into engineering design in the automotive industry presents unique challenges.

Designing vehicles that are both high-performing and environmentally friendly often involves conflicting objectives. Engineers must balance factors such as fuel efficiency, emissions reduction, and use of sustainable materials with performance, cost, and consumer preferences (Ratnayake, 2014).

Several research directions aim to address this challenge:

- Life Cycle Assessment (LCA) Integration: Incorporating LCA into the early stages of the design process can help engineers make more informed decisions about the environmental impact of their designs (Sherwin & Bhamra, 2000).
- Advanced Materials Research: Ratnayake (2014) discusses the use of knowledge-based engineering techniques for material selection, which can aid in choosing more sustainable materials without compromising performance.

Despite these efforts, balancing sustainability with other design objectives is a major challenge in automotive engineering design.

Human-Centred Design Implementation

Implementing human-centred design principles in engineering, particularly in automotive design, presents unique challenges.

Balancing technical requirements with user needs and preferences can be complex. Additionally, predicting and quantifying user experience in the early stages of design is challenging, often leading to costly late-stage changes (Boy, 2017).

Researchers have proposed several approaches to address this challenge:

- Experience-Based Design: Boy (2017) advocates for an experience-based approach to the human-centred design of complex systems, focusing on understanding and modelling user experiences throughout the design process.
- Virtual Reality (VR) in User Testing: The use of VR technologies in early-stage user testing has shown promise in predicting user experiences and identifying potential issues before physical prototyping (Clarkson & Eckert, 2005).

While these methods have potential, fully integrating human-centred design principles into the technical constraints of automotive engineering remains challenging.

Knowledge Management and Transfer

Effective knowledge management and transfer within and between projects is a significant challenge in engineering design.

As engineering projects become more complex and teams become more geographically distributed, capturing, storing, and effectively transferring knowledge becomes increasingly difficult. This challenge is particularly acute in the automotive industry, where projects often span several years and involve large, multidisciplinary teams (Verhagen, 2013).

Several research directions aim to address this challenge:

- Ontology-Based Knowledge Management: Verhagen (2013) proposes an ontology-based approach for knowledge lifecycle management, particularly within aircraft lifecycle phases, which could be adapted for automotive applications.
- KBE Systems: Pinfold and Chapman (2001) demonstrate the application of KBE techniques in automotive body structure design, showing how these systems can capture and reuse engineering knowledge effectively.

As the field of engineering design continues to evolve, addressing these challenges will be crucial for realizing the full potential of design methodologies in creating safer, more efficient, and more sustainable vehicles.

Conclusion

This review paper has provided a comprehensive overview of engineering design applications, with a particular focus on the automotive sector, and the challenges associated with implementing these design principles.

Engineering design has demonstrated its versatility and importance across various industries such as in the aerospace sector (Chapman & Pinfold, 2001), manufacturing industry (Boothroyd & Dewhurst, 1987), civil engineering (Cloutier et al., 2015), environmental engineering (Ruschitzka et al., 2010) and computer science (Verhagen, 2013).

The automotive industry has been at the forefront of adopting and adapting engineering design principles. KBE has revolutionized the rapid design and analysis of automotive structures, significantly reducing development time and costs (Pinfold & Chapman, 2001). MBSE has been helpful in the integration and optimization of complex vehicle systems (D'Ambrosio & Soremekun, 2017). The integration of AI and optimization techniques has enabled the design of lightweight yet robust vehicle structures, improving both performance and efficiency (Denil et al., 2017). Safety-focused design has led to the development of energy-absorbing structures, greatly improving crash protection (Njuguna, 2011). Sustainable vehicle design has driven the creation of electric vehicles and the use of lightweight materials (Ratnayake, 2014). Human-centred design approaches have considerably improved vehicle ergonomics and user interfaces, enhancing the overall user experience (Boy, 2017).

Despite its benefits, the implementation of engineering design faces several challenges. Managing the complexity of modern vehicle systems, with their numerous interconnected components, poses significant difficulties in predicting system behaviour and managing subsystem interactions (D'Ambrosio & Soremekun, 2017). The rapid pace of technological advancement presents challenges in integrating new technologies into existing design processes (Denil et al., 2017). Balancing sustainability considerations with performance and cost requirements adds another layer of complexity to the design process (Ratnayake, 2014). Implementing truly human-centred design remains difficult, particularly in quantifying user experience and balancing it with technical requirements (Boy, 2017). Lastly, effective knowledge management within large, multidisciplinary projects continues to be a significant challenge (Verhagen, 2013).

This review highlights the evolving nature of engineering design theory, emphasizing the need for more integrated theoretical frameworks that can address the various challenges of engineering design, particularly in automotive manufacturing. The findings suggest a shift towards more holistic design theories that incorporate sustainability, human factors, and complex systems management.

From a practical standpoint, this review emphasizes the need for continued investment in design technologies and methodologies to manage increasing product complexity. The findings highlight the importance of greater interdisciplinary collaboration and knowledge sharing in design processes. There is a clear need for better integration of sustainability principles into core design practices, as well as enhanced focus on human-centred design approaches in technical fields, ensuring that end-user needs and experiences are central to the design process.

While comprehensive, this review has several limitations. Its primary focus on the automotive sector may limit the generalizability of some findings to other fields. Given the fast-paced nature of technological advancements, some of the latest developments may not be fully represented in the reviewed literature. The review may not fully capture global variations in engineering design practices and challenges, as it primarily relies on English-language publications. Additionally, the review is primarily qualitative, lacking statistical analysis of trends in engineering design research and practice.

Based on the findings and limitations of this review, several areas for future research emerge. There is a need for cross-industry comparative studies to provide insights into best practices and transferable methodologies. Research into the integration of emerging technologies like AI and augmented reality into engineering design processes is crucial. Exploring human-AI collaboration in design and improving knowledge management in multidisciplinary design teams are also important areas for future research.

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