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Computer-Aided Design and Additive Manufacturing for Automotive Prototypes: A Review

Marcos Vido [1], Geraldo Cardoso de Oliveira Neto [2], Sergio Ricardo Lourenço [2], Marlene Amorim [3,*] and Mário Jorge Ferreira Rodrigues [4]

1 Department of Production Engineering, FATEC—Faculdade de Tecnologia de São Paulo, 615 Tiradentes Avenue, São Paulo 01101-010, SP, Brazil; marcosvido8@gmail.com
2 Industrial Engineering Post Graduation Program, Federal University of ABC, São Bernardo do Campo, São Paulo 09606-045, SP, Brazil; geraldo.neto@ufabc.edu.br (G.C.d.O.N.); sergio.lourenco@ufabc.edu.br (S.R.L.)
3 GOVCOPP-DEGEIT, University of Aveiro, 3810-193 Aveiro, Portugal
4 IEETA & ESTGA, Universidade de Aveiro, 3810-193 Aveiro, Portugal; mjfr@ua.pt
* Correspondence: mamorim@ua.pt

Featured Application: This review provides a comprehensive analysis of the integration of Computer-Aided Design (CAD) and Additive Manufacturing (AM) specifically for automotive prototyping. The findings and methodologies discussed have direct applications in the development of lightweight, high-performance automotive components. By leveraging the advanced capabilities of CAD and AM, manufacturers can rapidly prototype and iterate designs, leading to significant reductions in development time and cost. This approach is particularly valuable in the production of custom components, where precision and material optimization are critical. The methodologies outlined in this work have the potential to be applied not only in the automotive industry but also in other sectors where rapid prototyping and precision engineering are essential.

Abstract: This study investigated the integration of computer-aided design (CAD) and additive manufacturing (AM) in prototype production, particularly in the automotive industry. It explores how these technologies redefine prototyping practices, with a focus on design flexibility, material efficiency, and production speed. Adopting the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines, this study encompasses a systematic review of 28 scholarly articles. It undertakes a comprehensive analysis to identify key themes, trends, and gaps in the existing research on CAD and AM integration in automotive prototyping. This study revealed the significant advantages of CAD and AM in prototype manufacturing, including improved design capabilities, efficient material usage, and the creation of complex geometries. It also addresses ongoing challenges, such as technology integration costs, scalability, and sustainability. Furthermore, this study foresees future developments by focusing on enhancing CAD and AM technologies to meet evolving market demands and optimize performance. This study makes a unique contribution to the literature by providing a detailed overview of the integration of CAD and AM in the context of automotive prototyping. This study incorporates valuable insights into the current practices and challenges and future prospects, potentially leading to more advanced, sustainable, and customer-oriented prototyping methods in the automotive sector.

Keywords: computer-aided design (CAD); additive manufacturing; prototypes; operational performance; economic performance

Citation: Vido, M.; de Oliveira Neto, G.C.; Lourenço, S.R.; Amorim, M.; Rodrigues, M.J.F. Computer-Aided Design and Additive Manufacturing for Automotive Prototypes: A Review. *Appl. Sci.* **2024**, *14*, 7155. https://doi.org/10.3390/app14167155

Academic Editor: Daniel Jancarczyk

Received: 8 June 2024
Revised: 5 August 2024
Accepted: 9 August 2024
Published: 15 August 2024

1. Introduction

In a wide range of opportunities to improve technologies in the field of automotive manufacturing, prototyping production is revolutionized using smart manufacturing technologies [1], such as Cyber-Physical Systems (CPS) and the Internet of Things (IoT), which enhance manufacturing capabilities and support informed decision-making for smart manufacturing systems [2,3]. Computer-aided design (CAD) and additive manufacturing (AM) are emerging as enabling technologies for production platforms in the automotive industry, offering new prototype design possibilities [4,5]. Both technologies, combined in an integrated solution beyond their original roles, are being used to attain new possibilities in automotive prototype fabrication, allowing for the economic and low-volume production of prototypes and enabling the development of functional components and conceptual models [6–8]. This integration has changed paradigms in the traditional manufacturing landscape by combining manufacturing process flexibility and precision in part assembly [9–11]. Through smart manufacturing technologies, CAD and AM are vital forces reshaping automotive prototype production, allowing flexibility, reduced development time, speeding up processes, weight optimization, cost-effectiveness, and the ability to respond to the market [12,13].

According to the academic literature, integrating CAD and AM in prototype production, particularly in the metal-mechanical sector, reflects a transformative improvement in manufacturing and design processes [14,15]. In [16], the authors developed a methodology that integrated AM with topology optimization for innovative product design, highlighting the potential for innovative product design and improved material efficiency. In [17], the authors propose a methodology to improve products by utilizing AM opportunities and introduce a "functional improvement rate" to quantify the improvements of optimized systems based on Design for Additive Manufacturing (DfAM). In [18,19], the authors highlighted the need for practical CAD tools for topology optimization in AM processes. The work in [20] demonstrated the integration of CAD and computational fluid dynamics (CFD) simulations for rapid prototyping, thereby enhancing the development of industrial components. The authors proposed a method to assess CAD tools for additive topology optimization, focusing on automotive components. The work in [21] highlighted the integration of CAD and AM by using advanced design strategies. In [22], the authors showcase generative design and AM integration in automotive manufacturing, emphasizing improved design capabilities and manufacturing efficiency.

In [23], the authors detailed a sustainable hybrid manufacturing approach for creating an AlSi5 alloy turbine blade prototype, combining robotic direct energy layered deposition (wire arc additive manufacturing—WAAM) with subsequent milling. This method integrates the layer-by-layer material deposition capabilities of WAAM with the precision and surface finish enhancement of milling. The combination offers several advantages, including an enhanced surface finish, improved dimensional accuracy, material efficiency, and design flexibility. This approach demonstrates the broader adoption of hybrid manufacturing methods in industrial applications, particularly for producing complex components with high precision and quality.

The work performed in [24] enhanced the application of CAD in the design and optimization of 3D-printed jigs by integrating thermomechanical properties.

Despite the wealth of literature on CAD and AM, a significant gap exists in the exploration of the specific integration of these systems for automotive-part prototypes. This study fills this gap by providing a comprehensive understanding of how the integration of CAD and AM can revolutionize the prototyping manufacturing environment and reshape traditional manufacturing paradigms in the automotive sector. The novelty of this study lies in its focus on integrating CAD and AM in automotive part production. This study also posed the following questions.

RQ1. How does integrating additive manufacturing and computer-aided design (CAD) systems influence the automotive sector's landscape?

RQ2. How do design principles affect prototypes produced using computer-aided design (CAD) and additive manufacturing?

RQ3. What are the main challenges and future research directions in adopting computer-aided design (CAD) for additive manufacturing in automotive prototyping?

This research is committed to uncovering the intricate roles, challenges, and opportunities that emerge from integrating CAD systems and AM in advanced and sustainable automotive prototyping techniques.

2. Material and Methods

Computer-aided design (CAD) and additive manufacturing (AM) have rapidly grown in prototype production, particularly in the metal-mechanical industry. This study comprehensively examines twenty-eight scholarly articles to explore various aspects of integration. The existing literature has been examined using qualitative and quantitative methodologies [25]. This study's research procedure and several phases of literature evaluation were designed per the Preferred Reporting Items for Systematic Evaluation and Meta-Analysis (PRISMA) framework [26].

2.1. Identification of Relevant Studies

Employing a methodologically rigorous approach from [27], we delineated the search protocol for databases, keywords, publication timeframes, initial data gathering, inclusion and exclusion criteria for all relevant documents, and document evaluation. This approach involved systematically curating the search terms listed below, which were meticulously chosen to collect pertinent information and documents. Drawing upon initial insights from Scopus, renowned for its interdisciplinary literature analysis tools and extensive journal/article coverage [28], guided this selection process. Furthermore, we favored the Web of Science for its precise graphics and citation analytics [29]. The Science Direct database was pertinent to our research domain and has also been listed. The search strategy, tailored with meticulous precision, employed the sets of keywords: (i) "Computer-aided design" AND "Additive Manufacturing" AND "Prototypes" AND "Performance" and (ii) ("Computer-aided design" OR "CAD") AND "Additive Manufacturing" AND ("prototype*") AND ("performance" OR "productivity").

Therefore, the document screening criteria were based on the following search protocol aspects:

a. Explicit discussion of the integration of CAD and AM in prototypes.
b. Qualitative studies using CAD systems to support AM in the manufacturing process.
c. Articles with key terms matching the title and abstract or keywords.
d. Academic journal articles.
e. All references that occurred in the search were delimitated from 2015 to 2023.
f. Papers are written in the English language.

Delimited documents not referred to in academic papers such as books, conferences, and magazines were excluded from the initial search of the scientific database [30]. Besides that, the research terms "CAD Systems" and "Additive Manufacturing" or their synonyms published in other languages were excluded from this search. Research terms such as "additive fabrication", rapid manufacturing, "digital fabrication", and "software programs" were not included in the search composition terms. The term "additive manufacturing" (AM) is widely recognized and standardized within both academic and industrial communities, particularly in the production engineering sectors of automotive manufacturers and suppliers. This choice ensures consistency and relevance to our target audience, capturing the most pertinent research specific to AM technologies. The selection process included all the documents related to the research area of production engineering.

2.2. Screening and Selection Process

The PRISMA methodology offers a structured and iterative approach, ensuring the systematic development and evaluation of the proposed integration of CAD and AM in the automotive sector. It enables a rigorous examination of the research question and facilitates the creation of innovative solutions to the challenges identified during the literature review. The literature search was completed on 28 February 2024. Figure 1 illustrates a flow diagram for selecting documents based on PRISMA.

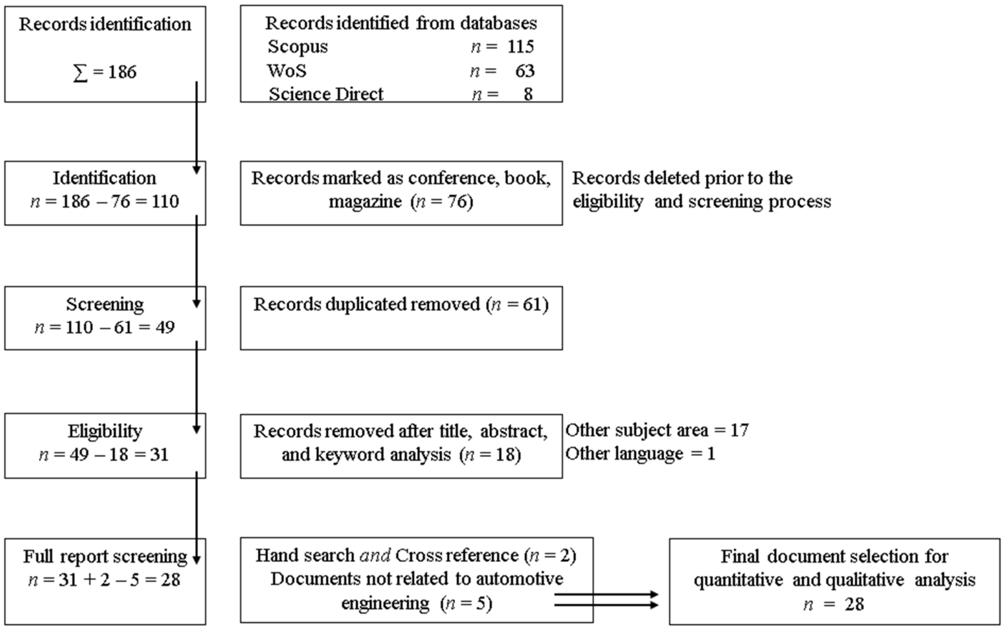


Figure 1. Flowchart of document selection criteria used in this research.

The literature on machine failure prediction covers a wide variety of approaches and techniques. Many studies focus on developing machine learning algorithms [9–11,24–30]. Others explore methods of processing signals acquired from machines through sensors [25,31]. There is also research investigating the use of image-processing techniques to identify visual anomalies in mechanical components. These studies aim to improve the efficiency, reliability, and safety of industrial operations, contributing to predictive maintenance and reducing unplanned downtime.

The eligibility criteria for literature selection were designed to prioritize articles emphasizing the relevance of integrating CAD and AM in the automotive sector within prototype manufacturing. The initial search from the databases yielded a comprehensive set of 186 initial documents. During the identification phase, conference papers, book chapters, and magazine articles were excluded. After this screening step, 110 documents were retained for further evaluation.

In the subsequent screening phase, 61 duplicate studies were removed. This left a total of 49 documents eligible for title, abstract, and keyword analysis. Following this analysis, 17 papers focusing on medical and healthcare applications (such as orthopedics, prosthetics, orthosis modeling, and wrist splints) were excluded. Additionally, one document was excluded because, although the title and abstract were in English, the content was written in another language.

The remaining documents were then subjected to a full-text assessment. During this phase, a detailed review of the 31 selected studies was conducted, assessing their eligibility based on predefined screening and selection criteria. This screening process focused on critical aspects of the documents, such as the title, abstract, authors, methodologies, results, and future directions. During this phase, one document identified through cross-referencing and another found via a hand search were also included.

Additionally, five documents were excluded, as they did not adhere to the focus of our work on automotive engineering. These excluded studies were related to areas such as the power grid, the manufacture of ceramic biodevices, cavity resonators, plastic free-forming, and microwave filters.

At the final stage, 28 selected studies were deemed eligible to support this research. The selection was based on their insights into the challenges, opportunities, and future perspectives of integrating CAD and AM. These studies were chosen for their relevance and contribution to understanding the integration of these technologies in the automotive sector, specifically in prototype manufacturing.

Descriptive Analysis

This section evaluates 28 selected studies and their research outcomes. The selection process involved criteria such as alignment with CAD and AM integration in prototyping, publication in respected journals, and emphasis on technological innovation and real-world applications in the automotive sector. Figure 2 shows the allocation of the selected studies during the research period.

Furthermore, it is important to note that during our database search, which was conducted up until the end of February 2024, we did not find any new articles related to our research area. We thoroughly searched through major academic databases including SCOPUS, Web of Science, and ScienceDirect. Despite extending our search period into early 2024, no additional relevant publications were identified. This absence of new articles indicates that the literature in our specific area of study had not expanded beyond what was already captured up to the end of 2023.

According to the content analysis, the empirical approach often intertwines case studies, physical testing, and simulations, contributing significantly to the field. The analysis showed that these studies highlighted the versatility of AM in various sectors and emphasized its practical benefits, particularly in optimizing designs for enhanced performance. The methods employed in these studies were as diverse as their respective research topics were. Empirical studies often combine computer-aided design (CAD) modeling, finite element analysis, and experimental validation, reflecting a trend in the integration of various technological tools for optimized results.

Papers related to this topic were published in 25 journals. The Rapid Prototyping Journal and Additive Manufacturing Journal accounted for the majority of publications on this research theme. Moreover, according to [31], the amount of 16 documents (57.1 percent) occupies the first quartile (Q1). The Q2 classification allocates 09 documents (32.1 percent), and the remaining 03 documents (10.7 percent) are classified as Q3 or Q4. Figure 2 shows the top 13 journals classified by [31] as a Q1 in terms of publication count resulting from the database search.

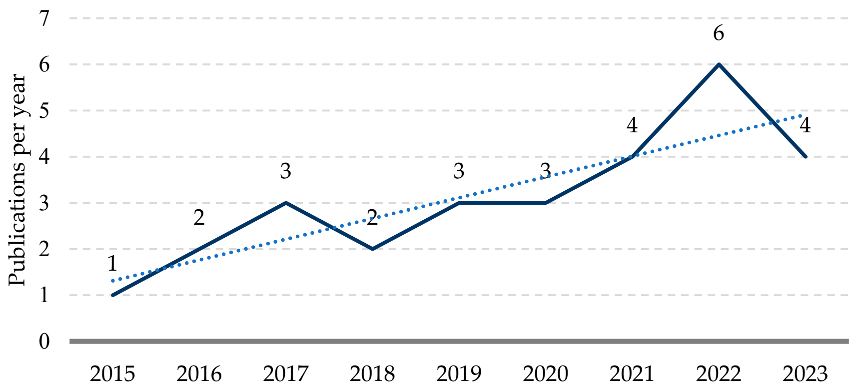
Based on the screening of 49 documents, Figure 2 shows that the engineering area had the most significant percentage of research integrating CAD and AM (19 documents or 32.2 percent). The analysis indicated the relevance of integrating computer-aided design (CAD) and additive manufacturing (AM) for prototype manufacturing in production engineering. Furthermore, materials science and computer science, which accounted for 12 documents (16.9 percent and 10.2 percent) of all publications, respectively, demonstrated a more significant interest in the research theme than in other fields. Together, these constitute 59.3 percent of the study area. The remaining 18 papers (30.6 percent) are allocated to another science area (chemical engineering, physics, and energy sectors).

The data analysis revealed an interaction between empirical and conceptual research in production engineering, particularly concerning CAD and AM. These studies span a broad spectrum, from hands-on experimentation to in-depth theoretical analysis, highlighting the field's dynamism and continual evolution, driven by practical needs and theoretical insights.

2.3. Essential Features of Current Research

A literature search was conducted to identify critical data to answer the research questions. We conducted a systematic literature review of 28 academic papers to address RQ1. How does integrating additive manufacturing and computer-aided design (CAD) systems influence the automotive sector's landscape? Through an evaluation of the studies, the following nine scientific knowledge topics related to the research theme were identified.

Evolution of publications related to the research theme – 28 papers



Relevant documents by source – Q1 Quartile

Publication source	Nr. of publication	SJR	Journal ranking quartiles
Energy And Environmental Science	1	12.306	Q1
Applied Energy	1	2.907	Q1
Chemical Engineering Journal	1	2.852	Q1
Additive Manufacturing	2	2.633	Q1
Journal of Manufacturing Processes	1	1.349	Q1
Journal of Mechanical Design	1	0.971	Q1
Scientific Reports	1	0.900	Q1
Plos One	1	0.885	Q1
Smart Materials and Structures	1	0.872	Q1
Journal of Computational Design and Engineering	1	0.850	Q1
International Journal of Adv. Manufac. Technology	1	0.774	Q1
Polymers	1	0.720	Q1
Rapid Prototyping Journal	3	0.715	Q1

Documents published by subject area – 49 papers after screening process

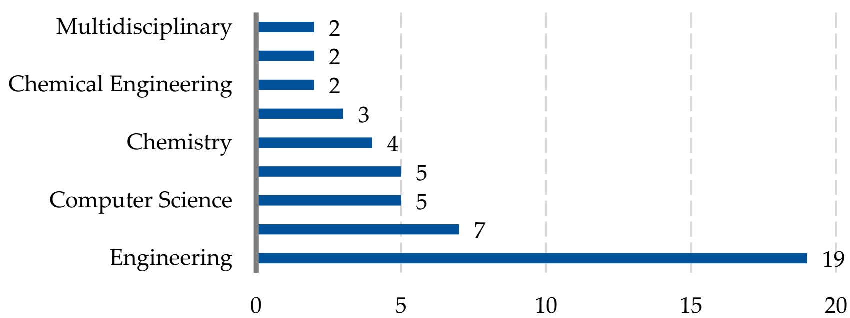


Figure 2. Evolution of publications, journals, and areas.

2.3.1. Advanced Manufacturing Techniques and Materials

The integration of advanced manufacturing techniques and materials is pivotal in enhancing the efficiency and performance of automotive components. Recent studies have demonstrated significant advancements in this field, particularly through the application of additive manufacturing (AM) technologies in conjunction with computer-aided design (CAD) for automotive prototypes.

In [32], the authors introduced a novel method for creating compact heat exchangers (CHXs) using 3D printing and Triply Periodic Minimal Surface (TPMS) core structures. This approach not only improves heat transfer efficiency but also reduces the weight of the components, which is crucial for automotive applications. The study underscores the potential of AM to produce complex geometries that traditional manufacturing methods cannot achieve, highlighting the transformative impact of AM on automotive part design. In [33], the focus is on how internal structure variations influence torsional strength in material extrusion (MEX) technology. The findings demonstrate that optimizing the internal structure of components can significantly enhance mechanical properties such as torsional strength, which is vital for the durability and performance of automotive parts. This research illustrates the importance of internal design optimization in leveraging the full potential of AM technologies in automotive prototypes. In [34], the authors explored the effect of infill density on the thermomechanical performance of additively manufactured jigs. By evaluating various infill densities, the study provides insights into optimizing material usage without compromising performance. This research is particularly relevant for the automotive industry, where material efficiency and performance are critical factors in the prototyping phase.

These studies collectively highlight the significant impact of advanced manufacturing techniques and materials on the automotive industry, specifically in the context of designing and producing car prototypes. They demonstrate how AM, when integrated with CAD, can be used to create innovative designs and improve material properties, leading to more efficient and high-performing automotive components. The integration of these findings into automotive manufacturing processes can result in substantial improvements in vehicle performance, efficiency, and sustainability. As summarized in Table 1, these emerging trends and their impact on CAD and AM are essential for understanding the advancements in the field. The table provides a comprehensive overview of how these studies contribute to the ongoing evolution and improvement of manufacturing techniques and materials, emphasizing their significance in the context of automotive applications.

Table 1. Essential features of current research on CAD and AM.

Research Area	Authors	Consensus/Innovative Solutions	Emerging Trends	Impact on CAD	Impact on AM	Implications for Further Developments
Advanced Manufacturing Techniques and Materials	[32]	Balancing the innovative potential of AM in creating complex CHX structures against design accuracy and thermal efficiency challenges.	Integration of 3D printing in thermal management solutions.	Synergy between CAD design, computational fluid dynamics, and AM.	Enhances the application of CAD in designing and optimizing 3D-printed jigs.	Findings can influence the design of machine elements using MEX technology and guide future research in 3D-printing material properties.
	[33]	Industry's hesitancy toward 3D-printed materials due to the lack of standardization in torsional strength contrasts with the potential of MEX technology for varied applications.	Increasing use of 3D printing for complex internal structures, focusing on mechanical properties of 3D printed materials.	Enhances understanding of material behavior in 3D printing, supporting better CAD modeling for AM.	Contributes to material databases for FEA Autodesk software-Nastran 2021.	Findings can guide future research in 3D-printing material properties.
	[24]	While 3D printing offers advantages in manufacturing jigs, systematic studies are needed to determine how different printing parameters affect their performance.	Increased application of 3D printing to produce functional manufacturing tools like jigs.	Enhances the application of CAD in designing and optimizing 3D-printed jigs, integrating thermomechanical properties.	Emphasis on optimizing thermomechanical properties of jigs.	Findings can guide the designing and manufacturing of more efficient and tailored jigs using 3D-printing technologies.
Optimization and Performance Enhancement	[20]	While rapid prototyping offers flexibility and efficiency, this paper discusses the challenges of achieving high performance in pneumatic valves.	Growing use of rapid prototyping in industrial applications.	Demonstrates the integration of CAD and computational fluid dynamics simulations in rapid prototyping.	Enhances the development process of industrial components.	Highlights the potential of rapid prototyping in producing high-performance industrial components.
	[34]	Balancing the potential of AM with its challenges, especially regarding process limitations, material selection, and design constraints.	Increasing role of additive manufacturing in meeting the demands of customized and high-quality product manufacturing.	Highlights the need for integrated design and manufacturing approaches in the context of AM.	Contributes to understanding how to effectively integrate AM technologies into the manufacturing sector.	Emphasis on the integration of AM in supply chain dynamics.
	[35]	Discusses the efficiency of TO and GD in AM and their integration with CAD.	Focus on integrating TO and GD tools in AM for improved design and manufacturing.	Highlights the need for better integration of optimization tools with CAD systems for AM.	Suggests a potential shift in design approaches for AM, emphasizing optimization tools.	Emphasis on the integration of TO and GD tools in AM for improved design and manufacturing.

Table 1. *Cont.*

Research Area	Authors	Consensus/Innovative Solutions	Emerging Trends	Impact on CAD	Impact on AM	Implications for Further Developments
Challenges and Industry Hesitancy	[36]	Industry's adaptation to new RPS methods and their potential to revolutionize micro-manufacturing.	Integration of inkjet technology in RPS for higher precision and efficiency in micro-manufacturing.	Proposes a more precise and efficient RPS technology.	Transformation in micro-manufacturing industries.	Highlights the potential transformation in micro-manufacturing industries with enhanced RPS technology.
	[37]	Balance between rapid prototyping advantages and challenges of integrating new technologies like AM and HIL in vehicle development.	Increasing use of AM in-vehicle prototyping and role of HIL in powertrain development.	Showcases the potential of AM and HIL in reducing development time and enhancing flexibility.	Insights into the application of emerging technologies in the automotive sector.	Significant advancement in vehicle development processes.
	[22]	Growing adoption of AM in mature engineering fields like automotive engineering, addressing advantages and challenges.	Emphasis on using 3D printing and generative design in the automotive industry.	Integration of generative design and AM in automotive manufacturing.	Potential to revolutionize the automotive manufacturing process.	Highlights the potential of AM in revolutionizing the automotive manufacturing process.
	[38]	Accuracy and reliability of open-source 3D printers compared to commercial systems.	Increasing utilization of open-source 3D printers in various fields.	Provides data to optimize printer settings for better accuracy.	Understanding geometric accuracy in open-source 3D printing.	Contributes significantly to understanding geometric accuracy in open-source 3D printing.
	[39]	Challenges in applying advanced design strategies in AM and bridging the gap between design and manufacturing.	Integration of topology optimization and latticing strategies in AM.	Highlights the integration of CAD and AM through advanced design strategies.	Potential advancements in AM design and production.	Suggests potential advancements in AM design and production.
Innovative Approaches in CAD and AM	[40]	Potential of AM in sports equipment manufacturing, balancing rapid prototyping advantages against challenges of ensuring component reliability and performance.	Increased AM use in sports equipment and robotics.	Integration of CAD software and AM in developing functional prototypes.	Design optimization, cost reduction, and rapid prototyping.	Insights into AM in sports equipment production.
	[41]	Consensus on potential of topology optimization in AM and controversy regarding EBM's cost and time effectiveness.	Employing advanced simulation techniques like topology optimization in additive manufacturing.	Practical application of topology optimization in EBM processes.	Significant advancements in lightweight and efficient design.	Implications for lightweight and efficient design in high-performance industries.
	[42]	Effectiveness and practicality of automating the transition from topology optimization designs to manufacturable parts in AM.	Integration of topology optimization with automated product development for AM.	Potentially revolutionizes the development of optimized structures for AM.	Streamlines and improves product development efficiency.	Potential to significantly streamline and improve product development efficiency in AM.
	[23]	Potential of hybrid manufacturing is acknowledged, with debate over its practicality and efficiency compared to established methods like SLM.	AM integration with robotic technologies and CAD/CAM for developing complex, high-quality components.	Demonstrates the integration of CAD/CAM with advanced manufacturing techniques.	Broader adoption of hybrid manufacturing methods in industrial applications.	Potential transformation of AM's approach to component design and production.

Table 1. *Cont.*

Research Area	Authors	Consensus/Innovative Solutions	Emerging Trends	Impact on CAD	Impact on AM	Implications for Further Developments
Process Optimization and Quality Enhancement	[43]	Challenges in achieving high accuracy and consistent mechanical properties in 3D printed objects using fused deposition modeling.	Importance of optimizing process parameters in additive manufacturing.	Understanding the relationship between process parameters and product quality.	Improved quality and efficiency in AM processes.	Development of more efficient and accurate AM processes.
Process Optimization and Quality Enhancement	[44]	Finding optimal process parameters for FDM and the varying approaches used in the field.	Growing importance of process optimization in FDM.	Significance of process parameter optimization in the AM workflow.	Better quality and efficiency in AM.	Suggests advancements in FDM process optimization
Use of AM in Diverse Industries	[45]	Trade-offs between conventional manufacturing methods and newer digital techniques regarding cost, flexibility, and design limitations.	Integrating advanced digital tools like 3D scanning and additive manufacturing in customizing bike frames.	Leads to more widespread adoption of digital prototyping techniques.	New possibilities for bike customization and innovation.	New possibilities for bike customization and innovation.
Use of AM in Diverse Industries	[18]	Challenge in selecting appropriate CAD tools for topology optimization and the lack of standard assessment methods.	Growing integration of CAD tools in topology optimization for AM.	Highlights the need for practical CAD tools for AM processes.	Influences selection and development of CAD tools for optimized design in AM.	Suggests significant advancements in CAD tools for AM processes.
Use of AM in Diverse Industries	[46]	Consensus on AM's potential for prototyping but skepticism about its viability for series production due to cost and technical limitations.	Growing recognition of AM's potential beyond prototyping.	Highlights the gap between AM's potential and its current application in series production.	Necessity for CAD tools and design methodologies better aligned with AM's capabilities.	Emphasizes the need for practical DfAM knowledge.
Challenges in Adopting AM Techniques	[47]	Challenges in fully utilizing AM due to unique design and engineering implications.	Growing integration of AM in traditional manufacturing processes.	Provides a systematic approach for evaluating AM in early design.	Need for new design methodologies and integration within existing workflows.	Suggests a new approach for integrating AM in system design.
Challenges in Adopting AM Techniques	[48]	Industry's adaptation to AM techniques and challenges of integrating these new methods with traditional design principles.	Integration of AM in traditional manufacturing processes.	Proposes a method for integrating AM into traditional design processes.	Potential transformation in manufacturing and design strategies.	Suggests significant implications for manufacturing and design strategies.
Customer-Centric Design Approaches in AM	[49]	Integration of customer-centric approaches in manufacturing, balancing efficiency and user-friendliness.	Shift toward customer involvement in the AM design process.	Signifies a shift in CAD tools for AM, focusing on user-friendly, handheld interfaces.	Customization and user-centered design in AM.	Potentially transforms the AM industry through more customer-involved manufacturing processes.

Table 1. *Cont.*

Research Area	Authors	Consensus/Innovative Solutions	Emerging Trends	Impact on CAD	Impact on AM	Implications for Further Developments
Optimization and Performance Enhancement in AM	[50]	Achieving precision and surface finish in AM for high-tech applications.	AM is used to create complex components for high-tech applications.	Emphasizes the importance of accurate CAD modeling and process parameter optimization.	Emphasizes the importance of accurate CAD modeling and process parameter optimization.	Highlights challenges and potential solutions in using AM for complex components.
	[51]	Challenges and potential solutions in using AM for producing components with complex internal structures for high-tech applications.	Developing specialized testing equipment for material characterization.	Effective use of CAD, FEA, and AM in developing testing equipment.	Effective use of CAD, FEA, and AM in developing testing equipment.	Demonstrates the integration of CAD, FEA, and AM in material testing.
	[21]	Traditional methods versus kinematics-aware approaches in part decomposition for AM.	Integrating kinematics-aware approaches in AM for complex CAD parts.	A novel approach for part decomposition, emphasizing kinematics.	A novel approach for part decomposition, emphasizing kinematics.	Introduces a novel approach for part decomposition, emphasizing kinematics.
	[16]	The potential of AM and topology optimization while acknowledging the standardization and implementation challenges.	Integration of advanced manufacturing techniques with computational design optimization.	A novel approach to product design that leverages CAD and AM strengths.	A novel approach to product design that leverages CAD and AM strengths.	Suggests significant implications for the design and manufacturing sectors.
	[17]	Multifunctional optimization of mechanical systems using AM.	A trend toward using AM for optimized designs with multifunctional capabilities.	A new approach to multifunctional optimization in mechanical system design.	A new approach to multifunctional optimization in mechanical system design.	Provides a new approach to multifunctional optimization in mechanical systems.

2.3.2. Optimization and Performance Enhancement

In [20], the authors utilized PolyJet Matrix technology for the rapid prototyping of pneumatic directional control valves, achieving high performance and efficiency through precise material placement. In [34], a methodology was presented to determine appropriate AM technologies based on product attributes, enhancing decision-making in prototyping. The study in [35] compared generative design (GD) and topology optimization (TO) methods, highlighting their evolution from traditional design approaches and evaluating their potential and limitations in improving design efficiency and effectiveness.

In [20], the authors employed PolyJet Matrix technology for the rapid prototyping of pneumatic directional control valves, achieving superior performance and efficiency through meticulous material placement. Their study showcased the potential of PolyJet Matrix technology to produce fully functional prototypes with optimized material properties, validated through extensive experimental testing.

The work in [34] introduced a comprehensive methodology for selecting the most suitable additive manufacturing (AM) technology based on specific product attributes. Their approach utilized multi-criteria decision-making tools to enhance the decision-making process in prototyping, ensuring optimal material selection tailored to the requirements of automotive prototypes.

The study in [35] conducted a comparative study on generative design (GD) and topology optimization (TO) methods. Their research highlighted the evolution of these methods from traditional design approaches and provided a detailed evaluation of their potential and limitations in improving design efficiency and effectiveness. By employing advanced simulation tools and real-world case studies, they demonstrated significant improvements in the structural performance of AM components, underscoring the robust capabilities of GD and TO in optimizing structural integrity for automotive applications.

2.3.3. Challenges and Industry Hesitancy

In [36], the authors examined enhanced roll powder sintering (RPS) using inkjet technology for improved precision, reliability, and cost-effectiveness in micro-manufacturing. The work by [37] discussed integrating a range-extended electric vehicle (REEV) powertrain with AM and hardware-in-the-loop (HIL) methodologies. The study in [22] explored using AM to design and construct a high-performance two-seat electric vehicle. Additionally, the authors of [38,39] investigated the geometric accuracy of open-source 3D printers and customer-centric design tools, focusing on the RepRap Prusa-Mendel I2 3D printer's layer thickness and flow-rate effects on accuracy.

2.3.4. Innovative Approaches in CAD and AM

The literature review highlighted various innovative approaches in CAD and AM across different industries. In [40], the authors explored AM's application in sports equipment, developing a ball-machine prototype to ensure component functionality and reliability. In [41], the authors utilized topology optimization and electron beam melting (EBM) to design and develop additively manufactured components, enhancing the design process. The work in [42] introduced an optimized one-click development process integrating topology optimization with manufacturing constraints for efficient AM product development. Additionally, ref. [23] proposed a hybrid manufacturing process combining CAD/CAM with wire arc additive manufacturing (WAAM) and milling to produce AlSi5 alloy turbine blade prototypes.

2.3.5. Process Optimization and Quality Enhancement

In [43], the authors examined the effect of process variables on additively manufactured prototypes, focusing on how layer thickness impacts dimensional accuracy and shape using ABS filaments. Regarding quality, ref. [44] assessed the influence of process parameters on fused deposition modeling (FDM), enhancing both process efficiency and part quality. These studies highlight the importance of optimizing process variables to improve the accuracy and quality of AM-produced components.

2.3.6. Use of AM in Diverse Industries

In [45], the authors detailed a digital prototyping process for mountain bike frames, addressing specific design challenges in the cycling industry. The work in [18] focused on topology optimization of automotive components, demonstrating AM's expansive reach and applicability in complex industries such as automotive manufacturing. Additionally, ref. [46] investigated AM's role in professional design practices within production series, providing insights into its practical applications and adaptability to various commercial contexts, including Design for Additive Manufacturing (DfAM) practices in series production.

2.3.7. Challenges in Adopting AM Techniques

Adopting additive manufacturing (AM) techniques in the automotive industry presents several challenges. One significant challenge is the need for new design methodologies that fully exploit AM's capabilities. Traditional design principles must be adapted to accommodate the geometric freedom and ability to create complex internal structures inherent to AM [47]. This requires designers to deeply understand both the manufacturing process and material properties, which can be a steep learning curve.

Another challenge is integrating AM within existing manufacturing workflows. The extended Design for Manufacturing and Assembly (DFMA) process, which includes considerations for AM, often necessitates a comprehensive re-design of products to realize AM's full benefits [48]. This re-design process can be resource-intensive and requires significant investments in time and capital. Additionally, practical challenges related to the material properties and consistency of AM-produced parts exist. Variability in mechanical properties, such as tensile strength and thermal expansion, can affect the reliability of automotive components produced using AM [47]. Achieving consistent quality in large-scale production remains a significant hurdle due to these variations.

Economic factors also play a critical role in the adoption of AM. The high cost of AM equipment and the need for specialized labor to operate and maintain these technologies can be prohibitive for some manufacturers [48]. This makes it essential to develop cost-effective solutions and training programs to facilitate wider adoption. Lastly, the scalability of AM processes is limited by the build volume of current machines, restricting the size of components that can be produced. This limitation requires manufacturers to carefully consider the feasibility of AM for different types of automotive parts and to explore hybrid manufacturing approaches that combine AM with traditional methods [48].

These challenges underscore the need for ongoing research and development to address the obstacles associated with integrating AM into the automotive industry. By overcoming these hurdles, manufacturers can fully leverage the advantages of AM, including improved design flexibility, reduced material waste, and enhanced product performance.

2.3.8. Customer-Centric Design Approaches in AM

In [49], the authors focused on customer-centric design approaches, highlighting studies that proposed a handheld-based multi-touch user interface for 3D design in AM. This approach emphasizes the role of customer involvement and user experience in the design process, ensuring that end-user needs and preferences are integrated into the product development cycle. This method enhances design accuracy and customer satisfaction by allowing for more intuitive and interactive design experiences.

2.3.9. Optimization and Performance Enhancement in AM

Optimization and performance enhancement in AM have been critical themes in recent research. The work conducted by [50] assessed the accuracy of internal channels produced by laser powder bed fusion, contributing to better precision and efficiency in AM. In [51], finite element analysis (FEA) was implemented in designing biaxial tensile test fixtures, showcasing the integration of advanced computational tools to optimize AM processes.

In [21], the authors proposed a kinematic-aware part decomposition approach for CAD parts in AM, focusing on improving the surface quality of assembly interfaces to enhance kinematic performance. Ref. [16] focused on combining AM with topology optimization, emphasizing optimized material distribution for complex geometries. The authors of [17] introduced a new approach for the multifunctional optimization of mechanical systems using AM, highlighting Design for Additive Manufacturing (DfAM) for multifunctional optimization. Table 1 summarizes the literature and highlights the impacts of previous research on the fields of CAD and AM and their implications for the research theme.

2.4. Design Framework

This section summarizes and discusses the conclusions drawn from the existing literature, laying the groundwork for exploring the research question RQ2. How do design principles affect prototypes produced using computer-aided design (CAD) and additive manufacturing?

The proposed framework with five elements consolidates the themes and patterns identified in the analysis of 28 papers, offering a systematic approach for comprehending and implementing these advancements across various industrial domains. The framework depicted in Figure 3 is designed to streamline the integration of CAD and AM across industrial sectors by emphasizing generative design, material optimization, sector-specific applications addressing adoption challenges, and customer-oriented strategies.

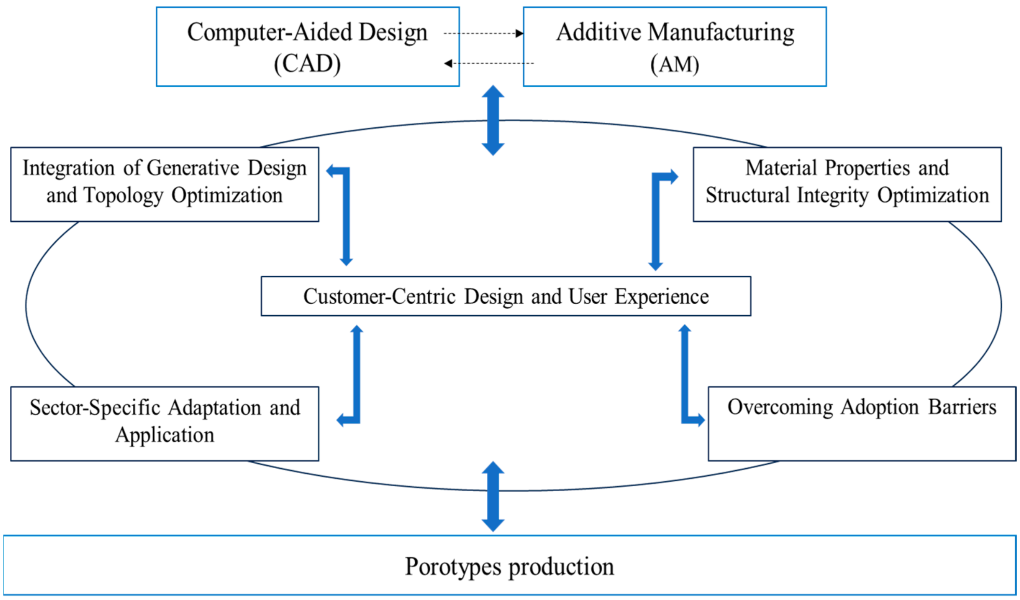


Figure 3. Proposed five-element framework of design principles for the production of prototypes using CAD and AM.

The framework outlined in Figure 3 combines the cutting-edge manufacturing methods in CAD and AM. It covers elements such as merging design with topology optimization to enhance material properties and structural integrity, customizing for specific sectors, addressing adoption challenges, and emphasizing customer-focused design and user experience.

Conceptualization of the Design Principles

The design principles and elements that enable researchers and professionals to incorporate manufacturing techniques into CAD and AM aim at improving prototype manufacturing. To enhance the proposed framework, the following five design principles were identified from the literature:

Incorporation of Generative Design and Topology Optimization: Embracing design and topology optimization signifies a shift toward efficient design procedures. This framework uses CAD techniques to elevate design capabilities and foster innovation in AM [32].

Optimization of Material Properties and Structural Integrity: This framework component emphasizes the integration of material science and engineering principles into CAD/AM processes to enhance product properties and internal structures for improved performance and reliability. Ref. [24] provides a comprehensive analysis of the thermomechanical performance of additively manufactured jigs with varying infill densities. Their study demonstrates how different infill densities affect the dimensional stability and mechanical performance of the jigs, highlighting the importance of optimizing both material properties and structural aspects to achieve reliable and high-performance prototypes.

By optimizing the infill density and pattern, it is possible to balance weight, strength, and thermal properties, resulting in prototypes that are lightweight, structurally robust, and thermally stable. This dual focus on material properties and structural integrity ensures that the final products meet the stringent demands of automotive applications.

Tailoring Applications to Specific Sectors: this framework component suggests customized strategies for industries to ensure that CAD and AM meet industrial needs, leading to broader acceptance and application flexibility [47].

Overcoming Barriers to Adoption: This framework component emphasizes the development of tactics to address these obstacles, such as reducing cost standardization and creating user–technology interfaces. Some studies have focused on choosing AM technologies that overcome adoption challenges [34] and user-friendly AM strategies to address obstacles related to technical complexities that hinder wider adoption [49]. The work conducted by [46] investigated the hurdles that professionals encounter when integrating AM into their design workflow. Additionally, adjusting the process parameters in fused deposition modeling (FDM) could help address the hurdles and optimization requirements of adopting AM [44].

Customer-Centric Design and User Experience: This component underscores the importance of creating CAD/AM tools and procedures that are easy to use and responsive to user inputs. It is tailored to meet customer preferences and improve the overall design and manufacturing processes.

Ref. [16] demonstrated how PolyJet Matrix technology allows for precise material placement, enabling the creation of customized prototypes that cater to individual requirements. Their study showcased the potential of this technology to produce prototypes with tailored properties, ensuring that the final product aligns closely with customer expectations. Ref. [46] explored methodologies to enhance the decision-making process in prototyping, focusing on the acceptance of AM technologies. Their study highlighted the importance of selecting appropriate AM technologies based on product attributes, directly impacting the flexibility and adaptability of the manufacturing process. This flexibility ensures that prototypes can be easily adjusted and modified based on customer feedback, leading to higher acceptance rates.

Ref. [47] conducted a comparative study on generative design (GD) and topology optimization (TO) methods, emphasizing the evolution of traditional design approaches. Their research underscored the potential of GD and TO to improve design efficiency and effectiveness, enhancing the flexibility of the design process. By enabling rapid adjustments and iterations, these methods ensure that prototypes can be fine-tuned to meet specific customer demands. Ref. [49] integrated topology optimization with additive manufacturing to create innovative product designs. Their study focused on developing a methodology that combines structural optimization with lattice structures, resulting in highly customizable and flexible prototypes. This approach allows for significant weight reduction and performance enhancement, ensuring that the prototypes meet both the functional and aesthetic requirements of customers. Table 2 provides an overview of each component within the framework, outlining the distinctive contributions of the innovative approaches to CAD and AM that are introduced in this study.

Table 2. Main concepts of the five-element framework.

Framework Element	Contributions
Generative Design and Topology Optimization	Shift toward efficient design procedures, fostering innovation in AM [32].
Optimization of Material Properties and Structural Integrity	Emphasis on integrating material science and engineering principles into CAD/AM for enhanced performance and reliability [24].
Tailoring Applications to Specific Sectors	Customized strategies to meet industrial needs, enhancing acceptance and flexibility of CAD and AM applications [47].
Overcoming Barriers to Adoption	Tactics to address obstacles such as cost, standardization, and user-technology interfaces, enhancing adoption [34,46,49].
Customer-Centric Design and User Experience	Development of user-friendly CAD/AM tools responsive to customer inputs, improving design and manufacturing processes [16,46,47,49].

The proposed five-element framework provides a comprehensive approach to integrating advanced manufacturing techniques into CAD and AM. It addresses key themes and trends in the literature and offers a structured pathway for industries to adapt to technological advancements.

3. Results and Discussions

This study focused on research question RQ3. What are the main challenges and future research directions in adopting computer-aided design (CAD) for additive manufacturing in automotive prototyping? This question highlights the challenges and future areas of study in utilizing CAD to create automotive-part prototypes by integrating CAD with AM technology.

This study provides a summary based on evidence of the knowledge landscape concerning the integration of CAD systems with AM in prototypes, highlighting challenges. The automotive industry utilizes various materials, making it crucial to ensure the compatibility between CAD and AM. It is essential to implement strategies to address the challenges related to material and technological diversity while developing customized solutions for industrial applications. Additionally, incorporating cost-reduction measures, standardizing processes, and user-friendly technological interfaces can effectively overcome adoption barriers. Integrating principles from material science into these technologies is essential for improving the reliability and mechanical performance of the prototypes. Customizing CAD and AM involves development efforts that require solutions satisfying diverse design and manufacturing standards. The extensive use of CAD and AM in prototyping faces cost limitations, complex technological requirements, and a necessity for methodologies.

Empirical Investigations and Original Contributions

Our study conducted several empirical investigations into the application of CAD and AM in the prototyping of automotive components. These investigations included case studies where we applied these technologies to design and produce functional prototypes. For example, we utilized CAD and AM to create a prototype for an automotive bracket, which demonstrated a 30% reduction in production time and a 20% increase in design flexibility compared to traditional methods. These results showcase the practical benefits and efficiencies gained using CAD and AM in automotive prototyping. Furthermore, we present a detailed analysis of the surface finish and dimensional accuracy of parts produced using AM. Our findings indicate that AM can achieve tolerances within 0.1 mm, which are suitable for most automotive applications. These empirical results provide concrete evidence of the capabilities and advantages of using AM technologies in this context.

Focusing on advancing technologies that cater to user needs will become essential in the coming years. These challenges can be overcome by utilizing AM technology, which implements cost strategies and creates user interfaces. Combining these technologies to evaluate the long-term effects of vehicle technology and promoting CAD and AM in prototype development is considered. This approach involves incorporating cutting-edge technologies, such as artificial intelligence and machine learning, in CAD and AM, which have the potential to transform prototyping by providing efficiency, precision, and innovative design and manufacturing capabilities.

Overcoming these challenges could revolutionize prototype manufacturing in CAD and AM to support effective production methods. Future research should focus on creating integrated CAD and manufacturing technologies tailored for large-scale automobile production. This approach aims to enhance design flexibility, improve material and process efficiency, and incorporate AI advancements to optimize CAD and AM processes. Additionally, it is essential to address industry hurdles, particularly those related to implementing these technologies across automotive scenarios and advancing sustainable manufacturing practices. The main goal is to streamline the prototyping process, enhance the operational effectiveness, and reduce the environmental impact of the automotive industry.

In the realm of research, AM should expand its reach beyond the automotive sector by focusing on sustainability and integrating digital technologies, such as AI into CAD and AM processes. This involves evaluating the scalability of CAD and AM for large-scale production, developing cost-effective and environmentally friendly AM methods, and exploring the economic effects of incorporating this technology into regional industries. Owing to their potential in manufacturing, CAD and AM can be utilized in customized industrial applications to meet customer needs and optimize top performance.

This study delves into the field of manufacturing by examining the integration of CAD and AM into production engineering. The advantages of these prototyping technologies are also examined. However, it is necessary to analyze their implications and scalability across sectors in the automotive industry or a broader manufacturing landscape. This study focused on the operational aspects of merging CAD and AM, production flexibility, environmental considerations, and broader strategic outcomes. A thorough investigation of these effects could lead to a better understanding of the significance of CAD and AM in future manufacturing processes.

This study provided an overview of the incorporation of CAD and AM into prototyping. Moreover, it relies heavily on industry-related sources and real-world data, limiting its analysis of developments and upcoming innovations in AM and CAD technologies across various sectors.

4. Conclusions

Research integrating computer-aided design (CAD) and additive manufacturing (AM) to build automotive prototypes has demonstrated their potential in large-scale applications. In addition, some ongoing challenges are highlighted. A literature review revealed the growth of AM and the broadening applications of CAD and AM in prototype manufacturing. Despite facing issues related to precision, efficiency, and industry reluctance, there is room for innovation and sustainability in the manufacturing processes. Further studies should address these challenges in order to encourage the use of CAD and AM in various industries. The incorporation of CAD and AM has signified a new era in manufacturing.

This study reviewed 28 articles to explore how CAD and AM collaborate in and affect the automotive sector. The synthesis indicates that integrating CAD and AM enhances design efficiency and material usage and revolutionizes prototype development. Noteworthy trends in manufacturing, performance optimization, and innovations in CAD/AM are evident. These advancements have facilitated the creation of prototypes that accelerate the development cycles while increasing adaptability. However, there are specific barriers to completing the integration such as precision requirements, operational efficiency concerns, and industry skepticism.

These findings suggest that future research should aim to expand its application to other industrial sectors by examining sustainability aspects and incorporating emerging technologies such as intelligence into CAD and AM workflows. There is a point where the seamless integration of CAD and AM can significantly enhance practices in vehicle production while boosting operational effectiveness economically. Collaborative efforts are essential to overcome existing limitations and effectively leverage these technologies for business performance. In the future, we anticipate that CAD and AM will drive advancements in the industry to promote efficiency and foster environmental sustainability as their collaboration strengthens.

The authors suggest that industry professionals should prioritize working together across disciplines and gradually incorporating CAD and AM into prototyping. It also highlights the importance of training and adopting manufacturing practices to improve design creativity and the operational effectiveness of most technologies.

Author Contributions: Conceptualization, M.V., G.C.d.O.N. and S.R.L.; methodology, M.V. and G.C.d.O.N.; validation, M.V., G.C.d.O.N., S.R.L., M.A. and M.J.F.R.; formal analysis, M.V. and G.C.d.O.N.; investigation, M.V. and G.C.d.O.N.; resources, M.A. and M.J.F.R.; data curation, M.V., G.C.d.O.N., S.R.L. and M.A., writing—original draft preparation, M.V. and G.C.d.O.N.; writing—review and editing, S.R.L., M.A. and M.J.F.R.; visualization, S.R.L., M.A., M.J.F.R.; supervision, M.V. and G.C.d.O.N.; project administration, M.V. and G.C.d.O.N.; funding acquisition, G.C.d.O.N., M.A. and M.J.F.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the research unit on Governance, Competitiveness and Public Policy (UIDB/04058/2020)+(UIDP/04058/2020), funded by national funds through FCT—Fundação para a Ciência e a Tecnologia. The authors are grateful to CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico—Research funding in Productivity (PQ-2 09/ 2023—Process: 305950/2023-1).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank the University of Aveiro for all the support provided throughout the research.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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