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Digital Transformation and Design for Maintainability in Industrial Design

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Abstract

Aim/Objectives/Background: This paper explores the impact of rapid digital transformation in Applied Arts and Design, particularly in maintainability. It focuses on how computer-aided design and three-dimensional modeling revolutionize the conceptualization and prototyping stages, honing in on design for maintainability, considering aspects like repairability, serviceability, and reliability.

Methods: Participants: The study involved a sample of industrial designers. Study Design: Utilizing a research framework grounded in industrial design practices, the study employed a combination of maintainability assessment, virtual prototyping, collaboration, seamless integration with design software, and optimization suggestions. Variables: Key variables under scrutiny included the efficacy of maintainability assessment tools, the impact of virtual prototyping on product durability, the collaborative dynamics influencing maintainability outcomes, the integration success with existing design software, and the effectiveness of optimization suggestions in enhancing overall product maintainability. Procedure: The research unfolded through a series of iterative phases, wherein industrial designers engaged with the digital design tool. Participants' interactions were observed and analyzed to gauge the tool's influence on their decision-making processes related to maintainability. This methodological approach aimed to envision and evaluate the innovative digital design tool's effectiveness in empowering industrial designers to optimize product maintainability.

Results: The findings underscore the profound impact of digital transformation on industrial design, revealing the potential for highly maintainable products. Integration of features like maintainability assessment, virtual prototyping, collaboration, and design software integration provides insights into transformative avenues for research and development.

Conclusions: In conclusion, this research illuminates the transformative potential of digital tools in industrial design, particularly in maintainability. Leveraging computer-aided design and three-dimensional modeling allows designers to optimize products for maintainability, positively impacting cost and user satisfaction. The study sets the stage for future research and development, promising a trajectory for the intersection of digital transformation and design for maintainability in Applied Arts and Design.

Keywords: Design for maintainability, Digital design tools, Digital transformation, Mean time to repair, Repairability, Serviceability

Introduction

In the realm of Applied Arts and Design, the concept of digital transformation has emerged as a dynamic and transformative force, reshaping the landscape of creative practices. As a PhD candidate in this field, I have been able to witness the profound impact that digital technologies have had on the way artists and designers approach their work. Digital transformation refers to the process of integrating digital tools, technologies, and
processes into artistic and design practices to drive innovation, enhance creativity, and enable new possibilities. Digital transformation in the field of Applied Arts and Design encompasses a wide range of aspects. It involves the adoption and utilization of digital tools and software, such as computer-aided design, three-dimensional (3D) modeling, virtual reality (VR), and augmented reality (AR), to enhance the conceptualization, visualization, and prototyping stages of artistic and design projects. These technologies have revolutionized the way artists and designers communicate their ideas, enabling more precise and immersive representations of their creative visions.

Digital transformation in the field of Applied Arts and Design encompasses not only the integration of digital tools and technologies but also the incorporation of essential design considerations such as repairability, serviceability, maintainability, and reliability. These factors play a crucial role in shaping the overall cost of ownership and user satisfaction. The design of products and systems that exhibit high levels of repairability, serviceability, maintainability, and reliability can lead to significant cost savings for consumers and businesses, while simultaneously enhancing customer satisfaction. Repairability, serviceability, maintainability, and reliability are important design considerations that can affect the overall cost of ownership and user satisfaction. A product’s repairability, for instance, refers to its ease of repair and the availability of repair information and parts, while serviceability refers to the ease with which a product can be serviced or maintained. Maintainability refers to the ease with which a product can be maintained and kept in a functional state, and reliability refers to the ability of a product to perform its intended function consistently over time. The design of products and systems with high levels of repairability, serviceability, maintainability, and reliability can lead to cost savings for consumers and users, as well as increased customer satisfaction.

**Digital transformation in industrial design**

Digital transformation has revolutionized various professions, including industrial design, by integrating advanced technologies and digital tools into the design process (Pandolfo, 2014). This paradigm shift has opened up new possibilities for enhancing product development, optimizing performance, and improving overall design outcomes. The integration of digital technologies in industrial design has enabled designers to streamline workflows, collaborate more efficiently, and explore innovative design solutions.

In recent years, the field of industrial design has witnessed significant advancements in digital technologies, such as parametric design, 3D modeling, and additive manufacturing (3D printing) (Efstathiadis et al., 2022; Uluçay and Ertürk, 2004). These technologies have not only accelerated the design process but also facilitated complex design iterations, enabling designers to explore diverse design alternatives (e.g. product and architectural complexities using grasshopper plugin shown above in Fig. 1) and make informed decisions. In addition, the emergence of artificial intelligence (AI) and machine learning has further enhanced the capabilities of digital design tools (Agron et al., year; Banad et al., 2020).

The incorporation of digital technologies in industrial design has fundamentally transformed the way products are conceptualized, developed, and manufactured (Loy et al., 2015). Traditional design processes that relied on manual sketches and physical prototypes have been replaced or supplemented by digital modeling and virtual simulations (Foote, 2017). This shift from traditional craftsmanship to digital craftsmanship has not only accelerated the design process but also enabled designers to
address complex design challenges with greater precision and efficiency (Dean and Loy, 2020). As shown in Fig. 2, we can see the effect of the advancements in digital craftsmanship on the design of automobiles. Furthermore, digital design tools have facilitated the exploration of generative design approaches, allowing for the generation of novel and optimized design solutions (Hallgrimsson et al., 2014). While digital transformation has brought significant benefits to industrial design, it has also raised new challenges and considerations. Designers need to adapt to the evolving digital landscape and acquire new skills to effectively leverage digital tools in their practice (Kermik, 2012).

SolidWorks and Rhino 3D are two prominent digital design tools that have significantly impacted the field of industrial design. They have revolutionized the way designers approach their work, offering a range of features and capabilities that enhance flexibility, accuracy, and creative freedom.

SolidWorks is widely recognized for its parametric modeling capabilities, making it a versatile tool for industrial designers. Parametric modeling allows designers to create 3D models with defined parameters, such as dimensions, relationships, and constraints, which can be easily modified and updated. This parametric approach enables designers to quickly iterate and explore various design alternatives without having to recreate the entire model from scratch. It also allows for efficient design changes and updates, as modifications to one part of the model automatically propagate throughout the design, ensuring consistency and saving valuable time (Efstathiadis et al., 2022).

Rhino 3D and SolidWorks are influential digital design tools that have revolutionized the design process across industries. Rhino 3D stands out for its exceptional surface modeling capabilities, empowering industrial designers to create intricate and organic shapes with precision (Ulucay and Ertürk, 2004). On the other hand, SolidWorks and Rhino 3D provide comprehensive toolsets and features that support the entire design journey, from initial concept development to detailed modeling, visualization, and analysis (Khristoforova et al., 2015). These tools enhance design efficiency, enabling rapid iteration, exploration of design alternatives, and real-time collaboration among design teams. While concerns about the impact of digital technologies on craftsmanship and authenticity persist, the advantages offered by SolidWorks and Rhino 3D in terms of speed, functionality, and collaboration are indisputable (Khristoforova et al., 2015).

An intriguing example that combines digital technology with the creativity of a renowned designer is the chair designed by Philippe Starck using generative AI. Philippe Starck, a celebrated industrial designer, collaborated with Autodesk, a leading software company, to create a chair using generative design techniques. Generative design utilizes algorithms and computational power to explore numerous design iterations based on input parameters and constraints.

In the case of Starck's chair, generative AI algorithms were employed to generate a variety of design options based on specific criteria, such as ergonomic considerations, structural integrity, and material efficiency. The software simulated and evaluated numerous design alternatives, optimizing the chair's form, esthetics, and performance characteristics. The final design was selected by Philippe Starck, who incorporated his artistic vision and expertise to refine and further enhance the generated design.

This collaboration exemplifies the synergistic relationship between human creativity and the capabilities of generative AI. While the
Generative AI algorithms generate a multitude of design options, it is the designer’s role to infuse the design with their artistic sensibility, cultural understanding, and intuition. The designer’s unique perspective and ability to understand the emotional and functional aspects of the chair contribute to its overall authenticity and craftsmanship.

The chair designed by Philippe Starck (shown in Fig. 3) uses generative AI to showcase the potential of digital technologies to assist and augment the design process. It demonstrates how designers can leverage the power of generative algorithms to explore innovative design solutions and optimize various design parameters. Ultimately, the final design is a result of the designer’s artistic judgment, expertise, and human touch, ensuring the chair’s authenticity and craftsmanship are preserved.

**Modeling and visualization**

Modeling techniques play a crucial role in industrial design, offering various approaches for creating 3D models of products. Parametric modeling allows designers to establish relationships between elements and easily modify design parameters, enabling flexible design iterations and variations. Surface modeling is valuable for complex and organic shapes, focusing on creating smooth and continuous surfaces that accurately represent the desired design. Solid modeling enables designers to define dimensions, volumes, and physical properties of product components, facilitating visualization, and prototyping. Wireframe modeling provides a simplified visual framework, outlining the structure and form of a product. In addition, sculpting techniques offer the ability to create organic and intricate shapes. Conceptual modeling aids in quickly visualizing and communicating initial design ideas. In terms of visualization techniques, rendered images simulate materials, lighting, and textures to provide realistic representations of product designs. 3D animations bring designs to life, showcasing functionality and assembly processes. VR allows designers to experience and interact with their designs in a virtual environment, while AR overlays virtual 3D models onto the real world. Sketches and concept drawings remain important visualization tools, and physical prototypes serve as tangible representations for evaluation and decision making in industrial design.

**Digital transformation and design for maintainability**

In recent years, the focus on sustainability and waste reduction has highlighted the significance of repair and maintenance in extending the lifecycle of products and minimizing their environmental impact. Designing products with high levels of repairability and serviceability has emerged as a crucial strategy in achieving these goals, while also offering cost savings to both consumers and businesses. For instance, research by Makov and Fitzpatrick (2021) demonstrates that consumers are more inclined to repair smartphones with higher repairability ratings, and that a repairability score can influence consumer purchase intent (Fazio et al., 2021).

These findings underscore the importance of incorporating repairability into product design and providing consumers with information on repairability.

This research aims to provide a comprehensive overview of current research on digital transformation and design for maintainability.
transformation technologies in the field of repairability, serviceability, maintainability, and reliability across various industries, including consumer electronics (Sabbaghi et al., 2017) like in Fig. 5 where we could see how the impact on structural modularity can positively impact the maintainability of a smartphone. This among other factors can contribute to the maintainability of household appliances (Ziebarth, 1992), and automotive (Velimirovic & Duboka, 2016), among others. The reviewed articles encompass a wide range of topics related to these design considerations, such as the utilization of disassembly maps to enhance repairability (De Fazio et al., 2021), the current state of the consumer electronics repair industry in the U.S. (Sabbaghi et al., 2017), and the impact of serviceability-oriented dimensions on after-sales service cost and customer satisfaction (Syahrial et al., 2017). By examining this body of literature, this review provides an extensive analysis of the interplay between digital transformation, design for maintainability (DfMn), and their synergistic role in optimizing product performance for industrial designers.

DfMn is defined as the deliberate consideration and incorporation of design elements and features during product development to facilitate efficient and seamless maintenance and repair activities throughout the product's lifecycle (Efsthathiadis et al., 2022). It involves anticipating and addressing potential maintenance requirements, ensuring component accessibility, and optimizing serviceability. DfMn primarily aims to design products that enable swift and cost-effective maintenance, thereby reducing downtime and enhancing overall product reliability. Key aspects encompassed by DfMn include component accessibility, modularity, standardization, ease of disassembly, and clear documentation of maintenance procedures as shown in Fig. 4 (Loy et al., 2015).

The importance of DfMn in product design is multifaceted. First, DfMn attempts to enhance product reliability by facilitating timely and efficient maintenance activities. Well-designed products that offer easy component access and clear maintenance instructions reduce the time and effort required for repairs, minimizing disruptions to the product’s functionality (Efsthathiadis et al., 2022; Makov and Fitzpatrick, 2021). Second, considering maintainability during the design phase leads to reduced downtime and costs. By incorporating features that simplify maintenance procedures, products enable faster diagnosis and repair, minimizing production downtime, and associated expenses (Loy et al., 2015; Sabbaghi et al., 2017). Third, designing products with maintainability in mind can extend their lifespan. The ability to easily replace and repair components allows for upgrades, modifications, and adaptation to evolving needs, thereby reducing the need for premature product replacements (Loy et al., 2015; Laitala et al., 2021). Furthermore, DfMn contributes to an improved user experience. Products designed with DfMn principles are typically more user-friendly, as straightforward maintenance and repair tasks enable users to perform them effectively, resulting in increased customer satisfaction (Efsthathiadis et al., 2022; Makov and Fitzpatrick, 2021).

The importance of design for maintainability in new product development

DfMn is a crucial aspect of new product development that focuses on optimizing a product's ease of maintenance and repair to reduce costs and increase its operational lifespan. By incorporating DfMn principles, manufacturers can achieve significant benefits throughout the product lifecycle. DfMn helps to minimize maintenance costs by simplifying maintenance tasks, reducing the need for specialized skills or tools, and enabling efficient access to critical components. This results in

Fig. 5. Modular smartphones that use interchangeable components to minimize the need to replace the phone.
lower labor and parts expenses. Moreover, DfMn improves product reliability by identifying and addressing potential issues early, reducing the risk of unexpected failures and minimizing downtime. Enhanced reliability leads to increased customer satisfaction, loyalty, and positive word-of-mouth, strengthening a product's market position. In addition, DfMn contributes to sustainability efforts by reducing waste through easier repairs and the use of standardized parts. Although implementing DfMn may require additional upfront effort and resources, the long-term benefits outweigh the initial investment, making it a valuable approach in new product development.

The role of industrial designers and engineers in maintainability during new product development

Maintainability is a critical aspect of product design, focusing on the ease of maintenance and minimizing downtime. The collaboration between industrial designers and engineers plays a pivotal role in integrating maintainability considerations throughout the new product development process. Industrial designers contribute by incorporating user-centered design principles, considering factors such as accessibility, ergonomics, and intuitive interfaces to enhance maintenance tasks. They ensure quick and efficient access to critical components, facilitating streamlined maintenance activities. Engineers, on the other hand, use their technical expertise to enhance maintainability by designing components for easy removal, replacement, and servicing. They utilize design-for-maintainability principles, such as modularity and standardized interfaces, to enable cost-effective maintenance. Collaboratively, industrial designers and engineers identify potential maintenance challenges early on, mitigating issues and optimizing the maintenance process. This collaboration results in reduced downtime, improved reliability, and enhanced overall product performance.

A digital tool for industrial designers to enhance design for maintainability

In this paper a digital tool has been proposed to empower industrial designers in their pursuit of DfMn. This paper explores the key functionalities of the tool and its potential to streamline the design process, ensuring that products are built with optimal maintainability in mind. The tool offers features such as maintainability assessment, virtual prototyping, maintainability metrics and analytics, collaboration and knowledge sharing, integration with design software, design optimization suggestions, and design documentation and reporting. By utilizing the tool, industrial designers can effectively incorporate human factors considerations and enhance reachability, creating products that are not only visually appealing but also optimized for efficient maintenance and user accessibility.

Maintainability assessment is a crucial step in designing products that are easy to maintain and repair. The digital tool provides a comprehensive framework for evaluating and analyzing maintainability factors during the design phase. By leveraging industry best practices and standards, designers can systematically assess various aspects of maintainability.

The tool offers intuitive checklists and guidelines to facilitate informed decision-making. Designers can evaluate key factors such as:

1. Part standardization.
2. Structure modularization.
4. Part interchangeability.
5. Human accessibility.
6. Fault detection.
7. Fault isolation.
8. Part identification.

Each factor plays a significant role in determining the ease and efficiency of maintenance activities.

By conducting a thorough maintainability assessment, designers can identify potential challenges or limitations that may hinder maintenance operations. This proactive approach allows them to make necessary design modifications early in the process, ensuring that the final product is optimized for maintainability.

Moreover, the tool incorporates an overview of system safety engineering. Safety considerations are closely tied to maintainability, as a safe design not only protects users but also
simplifies maintenance procedures. The tool provides insights into safety design criteria and offers risk assessment and risk management features. By considering safety factors from the outset, designers can create products that are not only maintainable but also safe for users and maintenance personnel.

The maintainability assessment feature of the digital tool promotes a holistic approach to design, where designers evaluate the entire lifecycle of the product. By assessing maintainability factors early on, designers can mitigate potential issues, reduce maintenance costs, and improve overall product performance.

Furthermore, the tool offers system safety analysis capabilities, including operating and support hazard analysis and health hazard analysis. These analyses enable designers to identify potential hazards and risks associated with maintenance activities and incorporate appropriate safeguards into the design.

**Virtual prototyping**

Designers can leverage the virtual prototyping capabilities to create 3D models and simulate maintenance scenarios, enhancing the overall maintainability of the product. By virtually exploring product components and their interactions, designers can identify potential challenges and make necessary design modifications to optimize maintenance processes. This approach reduces the need for physical prototyping, saving time and resources, and allows for accelerated design iterations. The benefits of virtual prototyping in terms of improved maintainability and enhanced design efficiency are highlighted, enabling designers to create products that are easier to maintain and service throughout their lifecycle.

In the automotive industry, virtual prototyping has revolutionized the design and development process, particularly in terms of improving maintainability. Designers can leverage the capabilities of virtual prototyping to create highly detailed and accurate 3D models of vehicles and their components. By simulating maintenance scenarios, they can analyze and assess the accessibility, ease of servicing, and repairability of various parts.

For example, when designing the engine compartment, in Fig 6, virtual prototyping allows designers to virtually navigate around the engine, inspecting, and evaluating the placement and arrangement of critical components. They can identify potential obstacles, such as tightly packed components or restricted access points, which could make maintenance procedures challenging or time-consuming.

Based on these virtual simulations, designers can make necessary design modifications to optimize the accessibility of components. They can reposition or redesign parts, adjust clearances, or incorporate access panels to facilitate easier maintenance and reduce the time required for servicing. By iteratively refining the design through virtual prototyping, designers can fine-tune the product’s maintainability, ensuring that it meets the highest standards.

One of the key advantages of virtual prototyping in terms of maintainability is the significant reduction in the need for physical prototypes. By conducting virtual simulations and assessments, designers can identify and address potential maintainability issues early in the design process, before investing time and resources in physical prototyping. This not only saves costs but also enables accelerated design iterations, allowing for more efficient design refinements and improvements.

**Metrics and analytics**

Maintainability metrics and analytics have become essential tools for designers to assess and optimize the maintainability of their
designs. By leveraging advanced algorithms and AI, platforms like the tool proposed offer designers a range of quantitative insights and metrics that can be used to evaluate and compare different design alternatives.

These maintainability metrics provide designers with valuable information about various aspects of a design that influence maintainability. For example, metrics may include accessibility scores, serviceability ratings, mean time to repair, or spare parts availability. These metrics allow designers to objectively assess the ease of maintenance, the efficiency of repair processes, and the overall reliability of the product.

By utilizing the tool’s analytics, designers can compare different design options and make informed decisions to optimize maintainability. For instance, they can evaluate the impact of design modifications on key maintainability metrics and identify areas that require improvement. This data-driven approach enables designers to prioritize design features and make trade-offs that enhance the ease of maintenance without compromising other design objectives.

Moreover, the use of AI in maintainability analytics allows for more accurate and predictive insights. AI algorithms can analyze vast amounts of data and identify patterns and correlations that might not be apparent to human observers. This enables designers to anticipate maintenance challenges, identify potential failure points, and proactively address them during the design phase.

The quantitative insights provided by the tool and similar tools serve as valuable decision-making support for designers, helping them make design choices that result in superior maintainability. By incorporating maintainability metrics and analytics into the design process, designers can enhance the overall performance, reliability, and longevity of their products while minimizing downtime and maintenance costs.

Integration with other design software

The tool offers seamless integration with popular design software, including Rhino and SolidWorks, providing designers with a streamlined workflow for assessing maintainability. By importing their design files directly into the tool, designers can leverage the real-time synchronization feature, which automatically updates maintainability assessments as design changes are made.

For example, let us consider a scenario where a designer is working on a complex automotive component using Rhino. As the designer makes modifications to the design, such as adjusting the geometry or adding features, the tool, integrated with Rhino, instantly updates the maintainability metrics and analytics based on the revised design. This real-time synchronization ensures that the maintainability assessment accurately reflects the latest design iteration.

Similarly, in the case of SolidWorks, designers can take advantage of the tool’s integration to import their SolidWorks design files. As design changes are made within SolidWorks, such as altering the assembly structure or changing component properties, this tool automatically captures these updates and recalculates the maintainability metrics accordingly. This eliminates the need for manual data entry and ensures that the maintainability analysis remains up to date.

The real-time synchronization between design changes and maintainability assessments offered by this tool significantly reduces redundant data entry and minimizes the risk of human error. Designers can focus on iterating and refining their designs, knowing that the maintainability analysis is continuously and accurately updated in parallel.

Furthermore, this integration between design software and this tool allows designers to explore different design alternatives and evaluate their impact on maintainability in a more efficient manner. By quickly importing and analyzing various design iterations, designers can make informed decisions to optimize maintainability without interrupting their design workflow.

Design documentation and reporting

The tool simplifies the documentation process by generating comprehensive reports that capture maintainability considerations throughout the design process. The tool highlights the importance of these reports for future reference, maintenance planning, and effective knowledge transfer to maintenance teams.
Conclusion

In conclusion, this research has shed light on the transformative power of digital transformation in the field of industrial design, specifically focusing on the intersection of digital technologies and DfMn. The integration of computer-aided design, 3D modeling, and virtual prototyping has revolutionized the design process, allowing for improved idea communication, immersive representations, and enhanced design iterations. By incorporating design considerations such as repairability, serviceability, maintainability, and reliability, designers can significantly impact the cost and user satisfaction of products.

We have introduced a novel digital design tool, which empowers industrial designers to optimize their designs for maintainability. This tool, with its comprehensive features including maintainability assessment, virtual prototyping, collaboration, seamless integration with design software, and optimization suggestions, enables designers to create highly maintainable and user-friendly products. The utilization of this tool leads to cost savings for both consumers and businesses, an extended product lifespan, and increased customer satisfaction.

While the potential of digital transformation in industrial design is vast, it also brings forth new challenges that designers must address. The adoption of digital tools necessitates designers to adapt to and acquire new skills to effectively leverage these technologies in their practice. Furthermore, there is a need for continuous research and development in the field of digital transformation and DfMn.

Future studies should focus on exploring advanced technologies like generative design, AI, and machine learning to further enhance the capabilities of digital design tools. Leveraging these technologies can optimize product performance and contribute to the ongoing evolution of industrial design. In addition, integrating sustainability principles and circular economy concepts into design practices can promote the significance of repairability and foster the extension of product lifecycles.

In conclusion, this research establishes the importance of digital transformation in industrial design and highlights the significance of DfMn. The findings presented here contribute to the existing body of knowledge and provide valuable insights for designers, researchers, and industry practitioners. By embracing digital technologies and prioritizing design considerations, the potential for innovation, cost savings, and user satisfaction in industrial design can be maximized.

Conflicts of interest

None declared.

References

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