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Smart Product Design Ontology Development for Managing Digital Agility

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ABSTRACT

Digital agility is a critical dynamic capability that is becoming increasingly important in the context of collaborative product development processes (PDPs). This paper aims to address the complexity of today's PDPs by considering various quality aspects including safety, environment, and the entire lifecycle, along with diverse dynamic capabilities such as digital agility and circular economy. The authors employed a semantic web methodology and created an ontology-based knowledge model. The proposed ontology uses Design for X techniques, circular economy, digital agility, and the semantic web under the PDP perspective to increase performance and cooperation between designers and the project team. To validate the ontology, measures for domain ontology evaluation have been used. The paper presents a detailed guide for ontology engineering and evaluation for collaborative smart PDP, which incorporates digital agility as a critical dynamic capability. The proposed ontology can help boost PDP performance and increase customer satisfaction.

KEYWORDS

Circular Economy, Collaborative Product Development Process, Design for X Techniques, Digital Agility, Ontology Development, Semantic Web

1. INTRODUCTION

Over the last decades, organizations have faced significant challenges because of volatile market demand, rising product variability, process complexity, individual customer demands, and the specialization of competencies in the product development process (PDP) (Ahmed et al., 2019;

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Arromba et al., 2020). These frequent and unpredictable market changes driven by the fourth industrial revolution have transformed the way we develop, interact, connect, and do business across the world (Birkel and Müller 2021). In this dynamic and complex environment, digital agility has become a critical dynamic capability for organizations, enabling them to respond quickly and effectively to changes in the digital landscape (Gong & Ribiere, 2023; Grover, 2022). Moreover, with the emergence of concurrent engineering and the use of IoT tools, even if designers intend to design for simplicity, the work they must complete is intrinsically difficult (Cherrafi et al., 2022). Thus, complexity has increased continuously, leading design project management to shift from a sequential to an iterative, holonic, and concurrent model with a lifecycle perspective (Benabdellah, Benghabrit, & Bouhaddou, 2020).

Designing a composite (complex) product that considers cost, assembly, security, functionality, serviceability, reliability, quality, and environmental challenges throughout the product lifecycle has special features that directly impact how knowledge is used (Benabdellah et al., 2021a). This complexity can be handled by implementing Design for X (DFX) methodologies, which allow businesses to examine the influence of design decisions on different elements such as cost, safety, quality, agility, sustainability, and manufacturing (Benabdellah et al., 2019; Chaouni Benabdellah et al., 2021). Besides, achieving the balance that promotes social and environmental sustainability requires flexibility, agility, willingness to take risks, careful planning, effective implementation, and continuous improvement to be able to adapt to changes in the market, technology, and other environmental factors (Awan et al. 2021; Du et al. 2020). This is where dynamic capabilities come into play. More clearly, dynamic capabilities are a collection of skills, procedures, and practices that enable businesses to respond quickly and efficiently to changes and uncertainties (Al-Shami and Rashid 2022; Zekhnini et al. 2021). Therefore, in a complex and volatile market demand, dynamic capabilities such as circular economy (CE) and digital agility are crucial for developing innovative products that are flexible, adaptable, and satisfy changing consumer and market demands (Al-Shami & Rashid, 2022; Salmela et al., 2022). In fact, by embracing the circular economy approach, organizations can ensure resource efficiency and minimize waste, while digital agility empowers them to swiftly navigate the digital landscape, capitalize on emerging opportunities, and overcome potential hurdles. In addition to that, as the number of diverse actors participating in the PDP grows, the need to reduce confusion, share information, competencies, and resources, and acquire the correct information in the right format at the right time in the composite industry become crucial (Benabdellah, Benghabrit, Bouhaddou, et al., 2020; Benabdellah et al., 2021a). Consequently, it becomes imperative to embrace knowledge management practices (Benabdellah et al., 2021b; Martins et al., 2019; Zbuchea et al., 2019) . In fact, Knowledge management supports digital agility and dynamic capabilities by facilitating the capture, sharing, and utilization of knowledge and insights (Benabdellah et al., 2021b). Therefore, effective knowledge management practices enhance decision-making, problem-solving, and continuous improvement in product development (Martins et al., 2019). To do so, ontologies emerge as a relevant technique for describing the required knowledge to support flexibility, interoperability, decision-making, modularity, optimal solution, and lift ambiguity of PDP systems with a connection with Semantic Web (Benabdellah et al., 2021a; Kendall & McGuinness, 2019; Klašnja-Milićević et al., 2017; Mohammed et al., 2021). Thus, by leveraging digital agility, dynamic capabilities, Design for X techniques and knowledge management practices (ontologies), organizations can successfully navigate volatile market conditions and adapt their product development processes to meet changing requirements according to a specific feature X.

By using ontologies in the context of PDP, some researchers describe only the concepts related to enterprise memory (Sadigh et al., 2017; Uschold & Gruninger, 1996). Others focus on the development of ontologies for the beginning of the product lifecycle (Fortineau et al., 2013; Petrovan & Lobontiu, 2018). Further ones integrate the concept related to the product and its manufacturing process while considering the supply chain process in their ontologies (M. Das et al., 2015; Garcia et al., 2023; Kaar et al., 2018; Z. Li et al., 2018; Mohammed et al., 2021). Other researchers have proposed ontologies that combine product concepts with the assembly requirements (S. K. Das &

Swain, 2021) or with quality requirements, or even environmental requirements (Benabdellah et al., 2021a; Fakhfakh et al., 2021; Yan et al., 2010). A significant gap exists in the current body of research regarding the integration of digital agility, Design for X techniques, dynamic capabilities, and knowledge management practices, particularly ontology, within the context of developing complex products in the face of volatile market demand. The scarcity of literature exploring the synergistic application of digital agility, dynamic capabilities, knowledge management practices, Design for X techniques and ontology hampers our understanding of how organizations can effectively navigate the challenges posed by a rapidly changing market landscape while developing complex products. Addressing this research gap would provide valuable insights and guidance for organizations seeking to enhance their adaptive capabilities, leverage knowledge assets, and exploit digital technologies to respond agilely to volatile market demand in the product development process. Another gap is related to how to express semantically the different quality attributes that need to be considered to satisfy customers' needs during the collaborative PDP such as environmental concerns, quality concerns, and safety concerns with several dynamic capabilities such as circular economy and digitalization. Further gap remains in the consideration and implementation of these different quality attributes using Design for X techniques and ontology.

Given the limitation of existing research and practice, this paper aims to design, conceptualize, and implement a holistic ontology, that combines Design for X technique, dynamic capabilities such as circular economy and digital agility and Semantic Web to enable engagement between designers and the whole project team throughout the product's lifecycle while considering different virtues X's. More clearly, following a detailed proposed guide for ontology engineering, the proposed ontology presents the logical relations between designers' and logisticians' requirements in the whole product lifecycle while considering different X such as quality, safety, manufacture, service, assembly, and environment while considering circular economy and digital agility capabilities. Therefore, the proposed ontology offers a generic architecture addressed by international standards IATF 16949 (Benabdellah, Benghabrit, Bouhaddou, et al., 2020; Laskurain-Iturbe et al., 2021) able to be employed in many forms of automotive mechanical machines of various types of manufacture. To that end, the authors suggest a taxonomy of the smart collaborative PDP represented as well as a method for modeling it into an ontology. Additionally, to verify the reasoning, logic, adequacy, and clarity of the proposed ontology, a set of measures for domain ontology evaluation (validation, verification, and assessment) about the stated goal, and context have been used. More clearly, this article discusses the following research questions (RQ):

- **RQ1.** What is the suitable methodology needed to engineer an ontology of smart collaborative PDP for managing digital agility?
- **RQ2.** How to semantically describe the knowledge needed to consider quality attributes, product lifecycle and digital agility during the development of a product?
- **RQ3.** How to assess, validate and verify the expressivity, extensibility, and clarity of the ontology?

The remainder of this paper is organized as follows: Section 2 presents related works of the existing ontologies for collaborative product as well as for digital agility in PDP and provides as such the research gap. Section 3 describes the ontology development methodology undertaken in this paper. Section 4 presents the development steps of the Project Memory and its ontology. Section 5 presents the implementation of the ontology using Semantic Web language. Section 6 provides a set of metrics for ontology validation. Section 7 discusses the findings and presents the implications for both researchers and practitioners. The final section contains the findings and future works. Appendix A showcases the abbreviations used in this study.

2. RELATED WORKS

Digital agility, Design for X (DFX) techniques, and ontology are essential for collaborative product development processes (PDP) in today's fast-paced business environment. In this section, an analysis of research papers split into three subsections in which each paradigm is thoroughly evaluated.

2.1 Digital Agility for PDP

Digital agility pertains to the capacity of an organization to react to the challenges and opportunities presented by generative digital technologies within limited or emerging timeframes. The term describes the organization's ability to respond to these opportunities and challenges within these specific time constraints (Grover, 2022). It is closely linked with IT artifacts, as these digital resources and tools allow organizations to improve their digital agility (K\Ho et al., 2022). Through harnessing cutting-edge IT artifacts, organizations can leverage the transformative potential of technology to swiftly navigate the digital landscape, capitalize on emerging opportunities, and surmount potential obstacles (Salmela et al., 2022). Therefore, the effective utilization of IT artifacts enables organizations to bolster their digital agility, empowering them to adapt, innovate, and thrive in an increasingly digital-driven world (Grover, 2022; Mangalaraj et al., 2023).

In the context of product development, digital agility can be defined as an organization's capacity to respond quickly and efficiently to changes in the market, customer needs, or emerging technologies (Kretschmer et al., 2017; F. Tao et al., 2018). In this regard, there has been a growing interest in understanding the role of digital agility in PDP and how it can improve the overall product development process. (Salmela et al., 2022) defined digital agility as an organization's capacity to adapt promptly and efficiently to shifts in the market and technology. The study concludes that digital agility is crucial for successful PDP because it enables businesses to quickly innovate, adapt to new trends and technologies, and retain an advantage over competitors. (H. Li et al., 2021) investigated the connection between digital mobility and the efficiency of product development. The findings demonstrated that the efficacy of product development, including product quality, development time, and cost effectiveness, benefits from digital agility.

Additionally, several studies have looked at how digital technologies have affected PDP. For instance, Jia et al. (2019) investigated how PDP uses digital technologies like modeling and 3D printing. According to the study, the use of digital technologies increased PDP's efficiency and effectiveness, which sped up product development and cut expenses. The application of digital twin technology in PDP was studied by (Lo et al., 2021). The research revealed that by enabling real-time monitoring and optimization of the product development process, digital twin technology can increase PDP efficiency. (G. Tao et al., 2021) investigated how Virtual Reality could be used in PDP. The research discovered that VR could enhance teamwork and communication between various PDP teams, leading to quicker product development and better product quality. In (Xiao et al., 2021) study, 3D printing technology was used in PDP. The research discovered that 3D printing, which enables quick prototyping and testing, can cut the time and expense of product development.

As a result, the literature review focuses on digital agility, which involves an organization's ability to respond swiftly to challenges and opportunities presented by digital technologies. IT artifacts play a crucial role in enhancing digital agility and navigating the digital landscape effectively. Studies emphasize the importance of digital agility in successful product development, leading to innovation, adaptability, and competitive advantage. Research explores the impact of digital technologies, such as modeling, 3D printing, digital twin technology, and Virtual Reality, on product development efficiency and effectiveness. Integration of digital technologies in PDP results in faster development, cost savings, improved teamwork, and enhanced product quality. However, implementing knowledge management practices like ontologies may present challenges, including ontology development complexity, ensuring semantic consistency, and integrating diverse knowledge sources. Organizational factors like resistance to change and limited resources may affect successful ontology adoption. Addressing these limitations requires further investigation and practical strategies to fully harness the benefits of digital agility, digital technologies, and knowledge management practices in PDP.

2.2 DFX for Smart PDP

Digital technologies and the industry's rapid growth have sparked significant improvements in industry growing technology. Concurrent Engineering, initially introduced as a business strategy in 1989, encompasses the integration of multiple factors throughout the entire product lifecycle, as highlighted by (Benabdellah, Benghabrit, Bouhaddou, et al., 2020). As a result, to effectively overcome the challenges presented by diverse variables, businesses are increasingly embracing DFX approaches as a powerful and feasible remedy. These approaches empower organizations to proactively assess multiple facets, leading to enhanced efficiency and successful implementations. The objective of DFX is to enhance product performance by optimizing its suitability for all stages of its life cycle and elevating its overall qualities and virtues. (Kuo et al., 2001). From the standpoint of the Triple Bottom Line (TBL), DFX techniques were devised to actively enhance the efficiency of product development, minimize cost errors, and accelerate the process. These techniques, such as Design for Manufacture (DFM), Design for Assembly (DFA), Design for Manufacture and Assembly (DFMA), Design for Supply chain (DFSC), Design for Quality (DFQ), Design for Maintenance (DFMt), and Design for Cost (DFC), play a pivotal role in achieving economic objectives. They collectively contribute to streamlining production, optimizing the supply chain, ensuring high-quality output, and reducing maintenance costs. Subsequently, companies have become increasingly attentive to environmental issues, prompted by legislation changes, inadequate environmental records, and shifts in consumer attitudes. This motivation has led to the development of new DFX techniques aimed at minimizing the environmental impact of products. Key techniques for achieving ecological objectives include Design for Recycling (DFRcy), Design for Remanufacture (DFRem), Design for Reuse (DFRu), and Design for Environment (DFE). These techniques collectively focus on creating products that are more environmentally friendly, facilitating recycling, remanufacturing, reuse, and overall sustainability. More recently, In more recent times, another DFX technique, known as Design for Social Responsibility (DFSR), has emerged to address the dimension of social equity. (Wan et al., 2023) providing opportunities for the world's poorest residents. An analysis of a wide variety of DFX techniques can be found in (Benabdellah et al., 2019; Moreno et al., 2016). Moreover, with a strong emphasis on Industry 4.0 (I4.0) from a DFX standpoint, several researchers have introduced novel DFX approaches. These include "Design for cyber-security" (Lesjak et al., 2016), "Design for Data analytics" (F. Tao et al., 2018), "Design for changeability"(Zallio & Berry, 2017), and "Design for product-in use feedback" (Mulder et al., 2015). Additionally, studies have explored the impact of I4.0 on design through the lens of the Triple Bottom Line (TBL), considering both technological advancements and societal developments (Bag et al., 2021; Junior et al., 2018; J. Lee, 2020; Pereira Pessôa & Jauregui Becker, 2020).

As a result, incorporating DFX techniques for a smart Product Development Process (PDP) is crucial. These techniques include Design for Empowerment, Design for Product-in-Use Feedback, Design for Accessibility, and Design for User Experience, which involve users and foster collaboration among multi-disciplinary teams. Design for Changeability and Design for Scalability address resource scarcity and obsolescence concerns. Additionally, Design Emotional Interaction and Design for Security establish connections between users and products, understanding the purpose behind smart device usage, data collection, management, programming, and education. Furthermore, Design for Data Analytics, Design for Cyber Security, and Design for Internet of Things ensure secure handling and storage of data from diverse sources, guaranteeing safety, security, and privacy aspects. Integrating these DFX techniques is essential to develop successful and efficient smart products. However, while incorporating multiple virtues like environmental, social, and economic considerations into smart Product Development Process (PDP) is crucial, it presents challenges. Integrating diverse DFX techniques for various virtues may increase complexity and require careful management to ensure synergies between different objectives. Balancing these different aspects in PDP may require specialized expertise, and a comprehensive approach to smart PDP that considers the entire product lifecycle and multiple virtues may require coordination across various teams and stakeholders. Overcoming these challenges and effectively implementing such a holistic approach can lead to more sustainable and socially responsible product development.

2.3 Circular Economy for PDP

The Circular Economy (CE) is a social and industrial concept, frequently described as a closed-loop economy, that embraces a waste-free culture to achieve comprehensive sustainability goals. It employs mechanisms that reduce pollution, waste, and energy loss by effectively closing, slowing, and narrowing material flows. Over time, the CE has evolved beyond a narrow focus solely on waste and has encompassed a wide spectrum of economic activities, promoting a closed raw material cycle that encompasses production, distribution, and consumption processes. (Urbinati et al., 2017). Companies adopting a CE approach primarily reap the benefits of material savings, reduced supply and production risks, improved consumer satisfaction, and the exploration of new revenue streams. (Prieto-Sandoval et al., 2018). Thus, the design domain is acknowledged as a key catalyst in facilitating the transition towards a CE (Wastling et al., 2018). Nevertheless, the majority of research tends to concentrate solely on the technical aspects. It is essential, however, to not only consider how design standards aid in fitting products into a Circular Economy (CE) system but also to account for how products align with people's needs, preferences, and behavioral patterns. In light of this perspective, the "Ellen MacArthur Foundation and IDEO" propose strategies and mindsets to guide designers in adopting design thinking and circular design principles, known as Circular Design (CD). This approach emphasizes a more comprehensive consideration of human-centric factors alongside technical aspects to foster successful implementation of CE principles (Ratum et al., 2020). Circular design seamlessly incorporates human-centered thinking into the creation of circular products and services, facilitating a profound comprehension of how customers interact with the system and how their behavior can be influenced by thoughtful product, service, and system design. (Wastling et al., 2018). More clearly, the CD entails improving product design and material selection through component standardization and modularization, promoting cleaner material flows, and adopting Design for Disassembly (DFD) principles. (Ratum et al., 2020).

As a result, through closed-loop economic activities, reducing pollution, waste, and energy leakage by closing material loops. Its implementation in companies results in material savings, decreased supply and production risks, improved consumer satisfaction, and the generation of new revenue streams. Design plays a crucial role in facilitating the transition to a Circular Economy, encompassing considerations of how products align with people's needs, preferences, and behavioral trends, in addition to technical aspects. Circular Design (CD) incorporates human-centered thinking into the design of circular services and products, promoting standardization, modularization, and purer material flows. Leveraging the Circular Economy, Design for X (DFX), and ontologies in the PDP provides a comprehensive and sustainable approach to product design, aligning with consumer needs, circular principles, and industry objectives.

2.4 Ontologies for PDP

Ontology is one of the most important knowledge models used in Knowledge engineering (Gemmeke et al., 2017; Montali et al., 2018), Artificial Intelligence (Demertzis et al., 2017), and Computer science, in which semantics is represented as machine-readable information. Because the ontology's major need is to be simply intelligible and changeable, it should enable linkages to other ontologies to enhance and expand the semantic domain (Kendall & McGuinness, 2019). An analysis of the literature shows that there are ontologies that have been proposed to support the product information, especially in different phases of its life cycle with a PLM perspective (Fortineau et al., 2013; Koomen, 2020; Matsokis & Kiritsis, 2010; Matta et al., 2011). Some others have represented information and knowledge related to the various links of the supply chain such as architectures, structures, resources, capacities, and activities (M. Das et al., 2015; Madni et al., 2001; Sulaeman & Harsono, 2021; Yan et al., 2010; C. Zhang et al., 2017). Further ones have proposed ontologies for the collaborative development of products by integrating information about the products and production process by considering logistics constraints (Benabdellah et al., 2021a; Bock et al., 2010; Bolek et al., 2023; Fakhfakh et al., 2021; Monticolo et al., s. d.; Yan et al., 2010).

In summary, ontologies have been proposed to support a variety of PDP-related elements, such as product development processes, design activities, product qualities, and manufacturing capabilities. These ontologies provide a common language for all parties involved to communicate ideas and connections, allowing for more efficient collaboration and interaction. They have been used to facilitate virtual workplace collaboration, automate design processes, make decision-making easier, and enable design for manufacture.

In summary, ontologies play a crucial role in various fields like Knowledge Engineering, Artificial Intelligence, and Computer Science, representing semantics as machine-readable information. Their primary purpose is to provide easily understandable and adaptable linkages to other ontologies, expanding the semantic domain. The literature analysis reveals that ontologies have been proposed to support different aspects of PDP. Nonetheless, when dealing with collaborative PDP, it becomes essential to account for different virtues, each generating a wealth of knowledge that should be effectively leveraged to facilitate seamless communication and collaboration among team members. To achieve this, the incorporation of diverse virtues through DFX techniques, while also considering the entire product lifecycle, is crucial. By integrating these virtues, collaborative PDP can harness valuable insights, leading to informed decisions, adaptability to changing demands, and an environment conducive to innovation and excellence throughout the product development journey.

2.5 Research Gaps

Digital agility, DFX techniques, and ontology are essential for collaborative PDP in today's fast-paced and rapidly changing business environment. In fact, "digital agility is the capacity of an organization to react swiftly and successfully to changes in the market and in technology" (Salmela et al., 2022). It enables businesses to rapidly innovate, adapt to new trends and technologies, and maintain an advantage over rivals. Design for X techniques are a set of practices that ensure that products are designed to be efficient, reliable, and easy to manufacture, assemble, use, and dispose. By incorporating these factors into the PDP, companies may enhance product quality, lower costs, and increase customer satisfaction, as well as enable a more agile development process, as feedback can be collected and responded on quickly, reducing time to market (Benabdellah, Benghabrit, Bouhaddou, et al., 2020). On the other hand, an ontology is a framework for presenting and organizing knowledge in a specific field. It offers a standardized vocabulary as well as a collection of guidelines for describing the relationships between ideas, entities, and attributes. It can assist organizations in better understanding the complexities of their goods and services, improving team communication, and fostering innovation (Fakhfakh et al., 2021). As a result, the incorporation of these three concepts (DFX, digital agility, ontology) in PDP can enable organizations to develop more innovative, agile, and customer-focused products. However, the analysis of the literature demonstrates several gaps:

- There is a lack of an integrated framework that incorporates all three concepts into a single framework for PDP. While there are studies on each concept individually, there are no study that provide a comprehensive framework that considers DFX techniques, digital agility capability and ontology benefits. This article aims to bridge this gap by presenting the development of an ontology for collaborative PDP that unifies these concepts, providing a holistic and synergistic approach to enhance product development practices. Through this integration, our research seeks to offer valuable insights and practical applications to support more efficient and effective PDP in today's dynamic and technology-driven landscape.

- There is a lack of semantic explanation of many different quality criteria (any features of a product which are needed to satisfy customers' needs or achieve the non-functional requirements) related to product design (Benabdellah, Benghabrit, Bouhaddou, et al., 2020; Benabdellah et al., 2019). Thus, as far as we know, there is no integrated ontology explaining the quality, safety, environment, assembly, and product service while developing a product through the whole lifecycle was found. To address this void, the present paper takes an innovative approach by integrating diverse concerns using Design for X (DFX) techniques. By incorporating Design for Environment, Design for Assembly, Design for Service, Design for Safety, and other relevant DFX methodologies, our research aims to develop a unified ontology that elucidates the intricate relationships among these critical aspects. This integrated ontology will offer valuable insights and a standardized knowledge representation for enhancing product design and development practices, enabling organizations to make well-informed decisions while ensuring product quality, safety, and environmental sustainability.
- A gap between the use of several DFX techniques while considering different quality requirements and PDP ontology was noticed. Several ontologies have concepts that may be utilized to describe a virtue such as a manufacture or an assembly in a specific phase of the product lifecycle. In contrast, some other ontologies integrate concepts related to all the product lifecycle but ignore the environment, safety, quality, and serviceability challenges. Addressing this gap, our article takes a comprehensive approach by encompassing all product development phases, including the end-of-life considerations in the context of circular economy capability. This integrative approach ensures that all concepts are meticulously explained and provides a holistic framework that embraces various DFX techniques. By bridging this gap, our research contributes to a more robust and unified ontology that can effectively support product development endeavors with clear and well-defined knowledge representations throughout the entire lifecycle.
- Interdisciplinary cooperation between various teams and departments within a company is necessary for an integrated approach to PDP that considers DFX, digital agility, and ontology. Research is lacking, though, on how to make it easier for the various PDP teams to collaborate and communicate effectively. This article addresses this crucial question by proposing an ontology that serves as a facilitating tool to enhance collaboration and communication across various PDP teams. By offering a structured and standardized representation of knowledge, this ontology streamlines information exchange, promotes a shared understanding, and fosters efficient decision-making processes. Through the development of this ontology, our research aims to bridge the gap and pave the way for successful interdisciplinary cooperation in PDP, ultimately leading to more effective and innovative product development outcomes.

In conclusion, more studies are required to fully understand how DFX, digital agility, and ontology are integrated into PDP. An integrated framework should be established. Practical implementation strategies should be investigated. Cultural aspects should be considered. Collaboration between disciplines should be made simpler. To this end, this study aims to address all the limitations discussed above and exploit simultaneously the different potentialities that an ontology can offer. More clearly, the proposed ontology aims at supporting, sharing, and reusing the massive volume of data produced by PDP concerning the (1) sixth DFX methods namely Design for Service, Design for Quality, Design for Safety, Design for Manufacture, and Assembly, Design for Supply Chain and Design for Environment that have been presented in paper (Benabdellah et al. 2020b) as the prominent ones for collaborative PDP while taking IATF 16949 requirements; (2) eleventh DFX methods for smart PDP identified in the literature review analysis and (3) PDP design factors in general for the whole product lifecycle. By doing so, the proposed ontology can help organizations enhance their digital agility and respond quickly and effectively to changes in the digital environment. In addition to that, this article addresses the gap in the field regarding the lack of a clear and concise guide for engineering an ontology from scratch. The identified gap pertains to the absence of comprehensive resources that practitioners and managers can readily follow to develop ontologies tailored to their specific needs. In this respect, the article proposes a comprehensive guideline that offers clear instructions and best practices for ontology development. This user-friendly framework empowers individuals with the necessary tools to create ontologies effectively, enhancing knowledge management, collaboration, and decision-making processes within their domains. Through this contribution, the article bridges the gap and promotes a more accessible and practical approach to ontology engineering, facilitating ontology integration across various domains and industries.

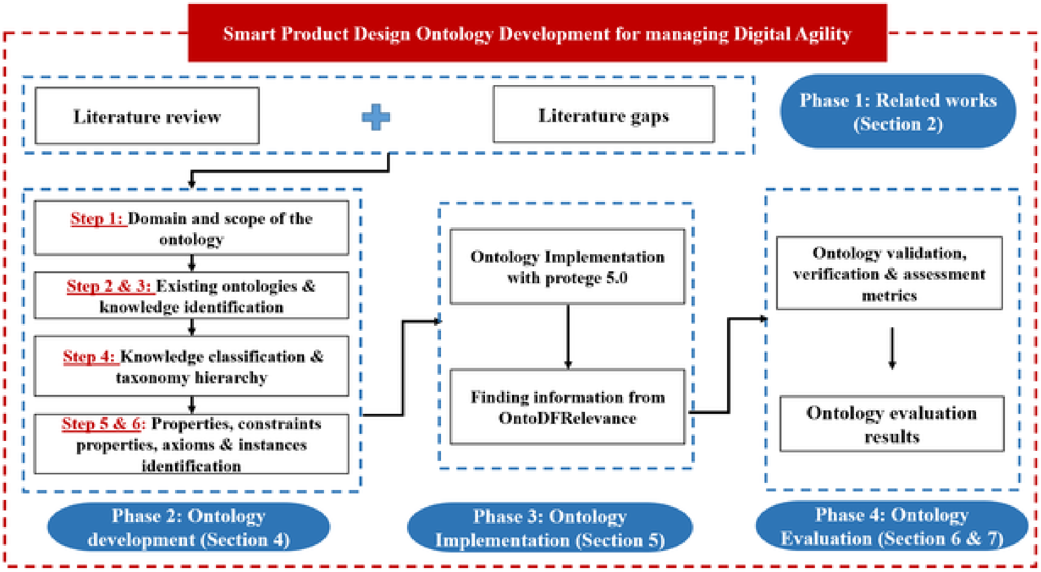
3. RESEARCH METHODOLOGY

For the last century, the creation of ontologies has progressed from the world of Artificial Intelligence research to the desktops of domain experts for them to exchange and annotate material in their disciplines. However, when creating Semantic Web applications, a substantial amount of time and effort must be spent on constructing ontologies. Unfortunately, there is no “correct” way for designing ontologies (Yu, 2011). After an analysis of the literature, the Noy and McGuinness’ iterative methodology has been chosen since it is cited in several research articles and is the only one that discusses naming standards. It incorporates existing ontologies in the early stages of ontology development and provides a precise explanation for each step. Therefore, as this method is lacking the consideration of the evaluation and maintenance phases of the ontology, which is very important to validate the purpose, we have gathered this step from (Öhgren & Sandkuhl, 2005) methodology. Figure 1 presents the methodology for developing ontology:

Phase 1: Related works. During this step, a literature review was conducted to search for the existing ontologies related to the studied field. By doing so, the literature gaps were identified (see Section 2).

Phase 2: Ontology development. In the first step, the domain, purpose, scope, and who will use the proposed ontology is defined. The second and third steps involve collaboration with automotive experts to propose a framework and identify important terms (design factors) for designing a

Figure 1. Research methodology (authors’ own compilation)



smart collaborative product while considering all the selected DFX techniques as well as digital agility and circular economy capabilities. In the fourth step, a knowledge taxonomy is developed based on the similarities of the concepts, and in the fifth and sixth steps, an ontology is developed to make the information and knowledge contained in the project memory comprehensible and easy to manage for the agents. The resulting ontology includes classes, properties, and their constraints to capture, represent, and integrate the key concepts and practices related to digital agility, collaborative product development, and DFX techniques. By doing so, organizations can create a shared understanding of these concepts, facilitate collaboration and communication, and develop more agile and adaptable processes and systems, leading to better overall performance outcomes.

Phase 3: Ontology implementation. Once the hierarchy classes and their interactions have been determined, the first step is that the ontology is implemented using Protégé (Gennari et al., 2003) to visualize and develop the proposed ontology. In the second step, a code for finding the relevant information needed using the SPARQL queries was also presented.

Phase 4: Ontology evaluation. To evaluate the clarity, consistency, and reusability of the implemented ontology, different validity metrics have been used such as the number of concepts, the average number of sub-concepts, measures for the cohesion of the ontology, and so on to validate, verify & assess the proposed ontology. Once the different metrics have been identified, the evaluation results are discussed.

4. ENGINEERING THE ONTOLOGY FOR SMART COLLABORATIVE PRODUCT DESIGN

Since ontology has grown in importance, the ontology engineering process must be viewed as a project and therefore should be addressed as such (Kendall & McGuinness, 2019). Therefore, ontology engineering should use project management strategies and software engineering methodologies that have been developed and used. In this respect, the methodology described in the previous section has been followed. The detail of each step is presented in the following sub-sections.

4.1 The Domain and Scope of the Ontology

The ontology development begins with identifying the domain and scope. To determine these objectives and the boundaries of an intervention, the following questions must be answered:

"What is the domain the ontology will cover?" *The ontology will consider all the important concepts and relations needed in the development process of a mechanical product or more specifically an automotive product. We notice that the PDP development considered here includes all the product lifecycle phases from feasibility to end of life. In addition to that, the concepts of the most prominent DFX techniques needed to satisfy most of the non-functional requirements of IATF standards as well as smart design are considered in this ontology. In fact, IATF 16949 is a globally recognized standard developed by the International Automotive Task Force (IATF) to establish a comprehensive quality management system specifically tailored for the automotive industry. It provides a framework for automotive manufacturers and suppliers to meet customer requirements, enhance product quality, and drive continual improvement throughout their operations (Laskurain-Iturbe et al., 2021). The design factors needed for the incorporation digital agility and circular economy are also considered. By doing so, an ontology model to fully understand how DFX and digital agility are integrated into PDP is presented.*

"For what purpose the ontology is going to be used?" *The proposed ontology is used to (1) Capture knowledge from heterogeneous and distributed resources; (2) Enable the reuse of product and process knowledge; (3) Facilitate the semantic description of terms used in PDP; (4) Lift ambiguity*

by providing a consensual vocabulary in which one can build descriptions and communications acts between designers and logistician actors; (5) Share a clear understanding of the information structure; (6) Provide a vocabulary for annotating, manipulating, and inferring information from PDP to build an operational process; and (7) Enable informed decision-making and enhancing their digital agility.
"Who will use and maintain the ontology?" *Collaborators, professional experts, and administrators of the system as well as the actors involved in the PDP. Each of these actors has an identifier that gives him access to limited knowledge in depends on his status.*
"What is the Scope of the ontology?" *One method for determining the scope of an ontology is to create a list of questions, which are defined as competency questions. In this respect, the proposed ontology should be able to answer different questions such as:*

1. CQ1: Which logistics services are required to realize a flow of goods?
2. CQ2: What aspects are critical to selecting a logistics service?
3. CQ3: Which are the main design factors needed to address digital agility?
4. CQ4: What is the main component of the project glossary?
5. CQ5: What aspects are critical to evaluating an argument?
6. CQ6: Which members are involved in designing a product?
7. CQ7: What skills are important to realize an activity?
8. CQ8: What is the required information needed to add new information to the project?
9. CQ9: What kind of criteria do professional experts need to evaluate knowledge?
10. CQ10: What kind of issues are used to make a decision?

By answering all these questions, 'the purpose and scope of the ontology are specified.

4.2 Step 2: Considering Reusing Existing Ontology

Before defining the important terms in the proposed ontology and based on the literature review gathered in section 2, the key terms that will drive our conception have been chosen. They have some terms that have the same name with different meaning and other with different names and means the same thing. However, to achieve interoperability between the heterogeneous ontology analyzed previously, the meaning of each concept in each ontology is explained and analyzed. The key terms used for from the existing ontologies are presented in Table 1.

4.3 Step 3: Defining Important Terms in the Ontology

Data collecting is a common action in the community of knowledge acquisition. There are several data gathering approaches available, including data obtained from individual or group interviews, data created through observation of individuals, and the way they operate on a real job or simulated scenario. It can also be focused on other indications such as papers, organization, and acquaintance networks, among others. The data can be generated from document analysis such as raw material, normalization, or even from the questionnaire. Our cartography of knowledge uses most of these techniques.

By adding all the design factors needed to consider the selected DFX techniques, circular economy and digital agility, not only the data generated from smart PDP are considered but also the important terms needed to consider the functional requirements of designers and logisticians in terms of "supportability", "flexibility", "cost", "quality", "timely delivery", "safety", "order frequencies", "volumes changes", "digital agility", "circular economy" and "sustainability". Therefore, by combining all these techniques and approaches with concepts identified in step 2, a list of design factors is created that has been presented to professional actors. After that and to regroup them into homogenous categories, the clustering algorithm was used to facilitate the simultaneous consideration of different

Table 1. Key concepts used in OntoDFRelevance

Category	Reference	Name	Concepts Used in OntoDFRelevance Ontology
Enterprise	(Grüninger & Fox, 1995)	***TOVE***	Component; Constraints; Parameter, Requirements; Part
	(Uschold & King, 1995)	***ENTERPRISE***	Activity specification, Sub-activity, Process specifications, Machine, Purpose, Assumption, Objective, Customer, Product, Sale price, Skill, Resource, Planning
	(Gandon et al., 2000)	***O'COMMA***	Document; tasks; group; professional actors
Product	(Vegetti et al., 2005)	***PRONTO***	Product Variants, Constraints
	(Monticolo et al., 2015)	***InDesign***	Tasks, prototype, design rule, element, phase, Activity, tool, Raw material, Organization, project process, successes, failures, difficulties, origin, specific techniques, specific activities, functions, product cost, prototype, project glossary, organizational constraint
	(Matsokis & Kiritsis, 2010)	***SOM***	Document, Equipment, property, physical product, condition, duration time, File, activity
	(Assouroko et al., 2014)		Stakeholders, customers, design team members, artifacts, Entity
	(Miled et al., 2020)		Tasks, prototype, design rule, element, phase, Activity, tool, Raw material, Organization
Collaborative Product	(Kim et al., 2006)	***AsD***	Product, Assembly, Part, Assembly features, Joint, Joint feature, Mating features, Form Feature
	(Abdul-Ghafour et al., 2007)	***CDFO***	Product parameters, constraints, features
	(C.-S. Lee et al., 2008)	***OIDSA***	Behavior, Entity, Properties
	(Catalano et al., 2009)	***PDO***	Shape, tasks
	(Rockwell et al., 2008)	***DSO***	Requirements, constraints, Issues, Alternatives, Decisions, Preferences, Evaluation Information
	(Ostermeyer et al., 2018)	***PARO***	Activity, Resources, Organization, Product, Human material
	(Rao et al., 2012)		Resources, Decisions, tasks, roles, organizational goals, knowledge, skills, Group
	(Benabdellah et al., 2021a)	***Design for Environment***	Environmental consideration, Environmental requirements, Environmental indicators, Environmental issues, Recycling & Disassembly criteria
Supply Chain	(Madni et al., 2001)	***IDEON***	Organization, logistics processes, logistics resources, Storage space, capacity, warehouse length, warehouse height
	(Himoff et al., 2006)		Real-time, schedule analysis
	(Chandra & Tumanyan, 2007)		Resources, Materials, Information, Customer, Objectives, Agent, Product
	(Ye et al., 2008)	***SCO***	Supply chain, Role, Purpose, Activity, Resource, Performance metric
	(Zhang & Tian, 2010)	***LDOM***	Organization, supplier, constraint, Sender, Receiver, Invoice, Arrival date, arrival time
	(Scheuermann & Hoxha, 2012)		Logistics resources, logistics service, logistics control, lead time, delivery quality, delivery flexibility, delivery reliability, logistics process, performance
	(Lu et al., 2015)	***SCOR***	Customer, sales function, control function, maintenance function, promotion function
	(Zekhnini et al., 2021a)		Resilience criteria, Sustainability criteria, digitalization criteria, profile criteria, and primary criteria.
	(Chaouni Benabdellah et al., 2021)	***Design for Circular SCOR***	Plan, Source, Make, Deliver, Use, Return, Recover, Enable

issues and facilitates the manipulation and the validation of each concept. After this step, a list of concept groups that should be capitalized is obtained and have been validated with professional experts.

4.4 Step 4: Defining the Hierarchy of Classes

Ontology often comprises a taxonomy of knowledge. It is defined as a classification or categorization based on similarities between classes (Gandon, 2002). The activity modeling allows to distinguish between two sorts of knowledge (Benabdellah, Benghabrit, Bouhaddou, et al., 2020):

- **“Knowledge related to the history of the project”,** which represents the “project progress” and creates a reference system for locating professional information. Therefore, to present the “project progress”, two aggregates of knowledge need to be capitalized: “**Project Context** that brings all the knowledge characterizing the project gathered in two classes: *Product* and *Organization”*; and “**Project evolution** that describes all the project stages by including three classes: *Activity*, *Actual progress,* and *Phases”*.
- **“Knowledge related to competencies used in the project”** which demonstrates an individual’s ability to use his education and grow his know-how within a professional framework. It comprises the assessment of collective competence gained via contact with professional actors involved in the same project. By using Monticolo classification which considers “**Project Experience”**, “**Project Glossary”** and “**Project Process”**, this model is enhanced by including the “**Project Decision”** composed of four classes: *Argument, Constraint, Decision,* and *Issue* and also by adding “**Project Evaluation”** that is composed of four distinct classes: *Knowledge state, Knowledge parameter, knowledge validation,* and *knowledge added* and “Project requirements” that is composed of nine distinct classes: *Digital Agility, Assembly, Market Assessment, Needs, Product constraints, Rules, Supply chain, Technical factors, lean/green.*

In terms of the real-world entities’ assumed connections, that each category represents, and by considering the similarities of the information concepts, the knowledge has been structured into a taxonomy that represents the structure of the project memory presented in Figure 2. The subsumption relationship is fundamental to taxonomy, which incorporates a concept under a more general one. For example, “concept C subsumes concept D only if all instances of D are necessarily instances of C”. The term subsumes simply means is *sub-class of.* After structuring the project Memory, the knowledge is stored. For example, to anticipate the study planning, project evolution needs to be consulted. To investigate the definition and representation of a technical word used in the project, the project glossary needs to be checked when the definition of all terms is stored. Furthermore, when incorporating new knowledge into the project’s memory, it is necessary to determine its consistency. This involves initially adding the new knowledge to Project Evaluation, followed by the expert assigning weight to the knowledge, utilizing a comparison matrix, and subsequently calculating the efficiency index. Another example is when considering Design for Safety that ensures the quality and risk-free utilization of the product, it comprises four modules that quantify risks, guiding designers to avoid risks, evaluate unavoidable ones, combat risks at their source, adapt work conditions to individuals, keep up with technical progress, replace hazardous elements, utilize collective and protective measures, and implement a prevention policy with proper training and instructions for employees.

4.5 Step 5: Defining the Concepts, Their Attributes, and Relations

To specify the ontology concepts and their relations (Objects and Datatype relations), the methodology proposed by (Gandon, 2002) is used, which uses three tables to specify them:

- For the specification of concepts: Table 2 presents some of the concept ID, their linkages (Parent ID), and a natural language statement of the concept underlying the concepts to represent their intention (Natural Language Definition).

Figure 2. Part of the taxonomy of the considered concepts (authors' own compilation)

Table 2. Specification of concepts

Concept ID	Parent ID	Natural Language Definition
Elements	Specification	Component of a product
Engineering	Specification	Methods, technics, and tools used during the project
Market_ assessments	Requirements	A comprehensive and impartial evaluation of the possibilities of a new product, new business concept, or new investment is referred to as a market assessment.
Value_analysis	Professional_ methods	The method used to simplify products and processes by resolving problems, encouraging innovation, and improving communication across the organization
Functional_ analysis	Professional_ methods	The method used for analyzing and developing a function structure.
Atomic_process	Process	Correspond to the activities that a service can undertake when it is engaged in a single encounter.
Simple_process	Process	Simple processes provide an abstraction method that allows many views of the same process to be provided.
Parameters	Project_process	Measurable variable, property, or value which characterizes a system or parts.

- For the specification of objects' properties: Table 3 displays a list of some of the Relation ID, the concepts they connect (Domain and Range), and a natural language statement of the concept underlying the relation to reflect their intention (Natural Language Definition).

Table 3. Specification of object properties

Relation ID	Domain	Range	Natural Language Definition
Has for evaluation	Requirements	Knowledge evaluation	Specifies the evaluation in which the requirement is used for
Has evaluation	Decision	Knowledge_ evaluation	Specifies the evaluation data that was utilized to make this choice.
With components	Issue	Components	Specifies the components to which this problem is directly connected.
Measures	Knowledge evaluation	alternatives	Specifies the alternative under consideration.
Has for issue	Decision	Issue	Describes the problem at hand.
Has tradeoff considered	Decision	Trade_off	Describes a tradeoff involved with this decision. The tradeoff must take place between the goal parameters defined in the preference model.
Has objective function	Preferences	Main function	Describes an objective function.
Has objective parameter	Preferences	Rules of design	Design characteristics that can be utilized to characterize an aim are specified.

- For the specifications of Datatype properties: Table 4 presents examples of the unique name of the potential attribute (Attribute ID), their associated concept (Concept), and the value of the attribute (Value type) used in the proposed ontology.

Once, the identification of the main components of proposed ontology is finished, the axioms that guide the inference of the ontology need to be added. It defines the semantics of concepts and relations (El-Gohary & El-Diraby, 2010) by providing a compact, intuitive, and accessible representation of the concepts and their relations. The axioms include the consideration of (1) “property domains and ranges for sub-class type expressions”; (2) “property hierarchies”; (3)” disjointness”; (4) “inverse properties”; (5) “symmetry and asymmetric properties”; (6) “transitivity properties”; (7) “functional and inverse functional properties”; and (8) “irreflexive properties” (Völker et al., 2007). Table 5 presents a list of some of the axioms used in the proposed ontology.

Table 4. Specification of datatype properties

Attributes ID	Concept	Value Type
Organization Name	Organization	String
Task Name	Task	String
Has value	Warehouse_capacity	Boolean
Invokable	Composite_process	Boolean
Has transport order number	Transport_order_process	Integer
Has client name	Transport_order_process	String
Has loading unit	Transport_order_process	Integer
Has delivery bill	Transport_order_process	Literal
Has phone Number	Members	Integer
Has value	Warehouse_capacity	Boolean

Table 5. Specification of axioms

Relation ID	Domain	Range	Axioms
Assigned by	Specifical_activity	Organization	Inverse functional
Need	Roles_skills	Resources	Functional
Has Input	Activity	Input_parameters	Functional
Has output	Activity	Output_paramters	Inverse Functional
Includes	Project	Process	Functional
Has for result	Tasks	Documents	Functional
Quantified by	Knowledge_evaluation	Number of stars	Inverse Functional
Has as maturity	Knowledge_evaluation	Evaluation percentage	Inverse Functional
Has a positive evaluation	Knowledge_evaluation	Number of positive evaluations	Transitive
Has as communication	Members	Role communication Link	Functional
Consume	Activity	Resources	Functional
Evoke	Argument	Knowledge Evaluation	Disjoint With
Has argument	Knowledge evaluation	Argument	
Collapse to	Composite_process	Simple_process	Disjoint With
Expand to	Simple_process	Composite_process	
Quantify	Competitive analysis	Commercial_cost	Functional

4.6 Step 6: Create an Instance

To define an individual instance of a class, first, it is crucial to choose a class, then construct an individual instance of that class, and then populate it with attribute values. However, determining whether a notion in an ontology is a “class” or an “individual instance” is reliant on the ontology’s potential applications. The first step in defining where classes end, and individual instances begin is to define the lowest degree of granularity. The amount of granularity is determined by the ontology’s potential use. What are the most precise entities that will be represented in the knowledge base, to put it another way? If we return to the competence questions mentioned earlier, the most particular concepts that would form the answers to these questions are excellent candidates for becoming individuals in the knowledge base.

Following the completion of the first six phases of ontology development, the validation of the implemented ontology is the next step in the development process. To do so, the proposed ontology needs to be implemented, which entails converting the ontology’s conceptual model into a formal model that machines can understand. To accomplish this, the ontology must be formalized into a language. To formalize the proposed ontology, the OWL-DL language is used. This is due to the language’s excellent balance of expressiveness and reasoning abilities. In addition, the OWL language contains a rather extensive collection of operators for defining both primitive and complicated ideas. “OWL Lite”, “OWL DL”, and “OWL Full” are the main three sub-languages with rising expressiveness (Klašnja-Milićević et al., 2017). “OWL DL” can be thought of as an extension of OWL Lite, whereas “OWL Full” might be viewed as an expansion of “OWL DL”. The implementation phase of the proposed ontology is described in the next section.

5. IMPLEMENTATION OF SMART PRODUCT DESIGN ONTOLOGY FOLLOWING THE SEMANTIC WEB STANDARD

The activity of implementing ontologies, proposed by most methodologies, consists in building a formal model represented in an ontological language. Representation languages, in particular RDF and OWL, allow on the one hand to exploit knowledge by providing functionalities such as research, extraction, maintenance, reasoning, and representation of information. On the other hand, they also make it possible to make web pages interpretable not only by humans but also by programs, for better human-machine cooperation, following the vision of (Berners-Lee et al., 2001).

5.1 Use of an Ontology Editor for the Implementation of the Ontology

The size of the ontology and the need to change the number of its relations according to the knowledge consultation justify the use of an ontology editor. Many software platforms using various formalisms and offering various functions have been created to assist ontologists in the various tasks of the ontology life cycle (DOE (Differential Ontology Editor), OntoEdit, or OILED (OIL Editor), Protected and WebODE). The two main tools emanating from research groups active in ontology engineering are Protégé (Gennari et al., 2003) and WebODE (Arpírez et al., 2001). To this end, the Protégé 5.0 tool is used. Thus, the previously developed concepts and relations were converted into "Classes", "object properties", and "data properties" to model ideas, relations, and attributes in a formal ontology. Concerning the axioms, it was done on Protected by the definition of a set of OWL restrictions, the different characteristics of the object properties, and by the restrictions of the data types. Figure 3 presents a part of the ontology defined in Protégé 5.0, as well as its implementation in OWL-DL.

5.2 Finding Information Using SPARQL Queries

RDF annotations contain a "series of triples". Each triple represents a sequence of the "Subject/Predicate/Object". The subject represents a structure that can be identified by a URI. Predicate on the other hand is a specification reused and identified by the URI of the relation. Object defines a resource or constant to which the subject is bound. In this context, to search for information from our ontology, SPARQL language is used as an efficient language allowing to apply queries on RDF triples, as recommended by the W3C. SPARQL queries are built according to structures close to the SQL language by using the SELECT and WHERE clauses (Figure 4). The WHERE clause uses a syntax composed of three elements using the question marks in front of the variables.

Therefore, once the ontology is implemented, the next step is to evaluate it. To do so, the next section details the evaluation process that includes the verification, validation, and assessment of the implemented ontology.

6. ONTOLOGY EVALUATION (VERIFICATION, VALIDATION, AND ASSESSMENT)

Rapid progress has been made in the creation of ontologies aimed to capture and represent parts of the actual world in recent years. Because ontologies vary, there is no standardized, objective, and widely accepted method to evaluate and perform ontology evaluation. In other words, we have no idea of their coverage, intelligibility to human users and administrators, validity and soundness, consistency, the kind of inferences that may be made with the ontology, or their capacity to be altered and reused for broader purposes (Gómez-Pérez, 2004; Mc Gurk et al., 2017).

6.1 Ontology Evaluation Metrics

The evaluation of ontologies is a critical phase in the development of an ontology. which refers to "the assessment of the quality and the adequacy of an ontology or parts of it regarding a specific aim, goal or context" (Gangemi et al., 2006). More clearly, it shows a "judgment of the ontology content concerning a particular frame of reference" (Sánchez et al., 2015). Given the importance of this

Figure 3. OWL implementation of smart product design ontology using Protége (authors' own compilation)

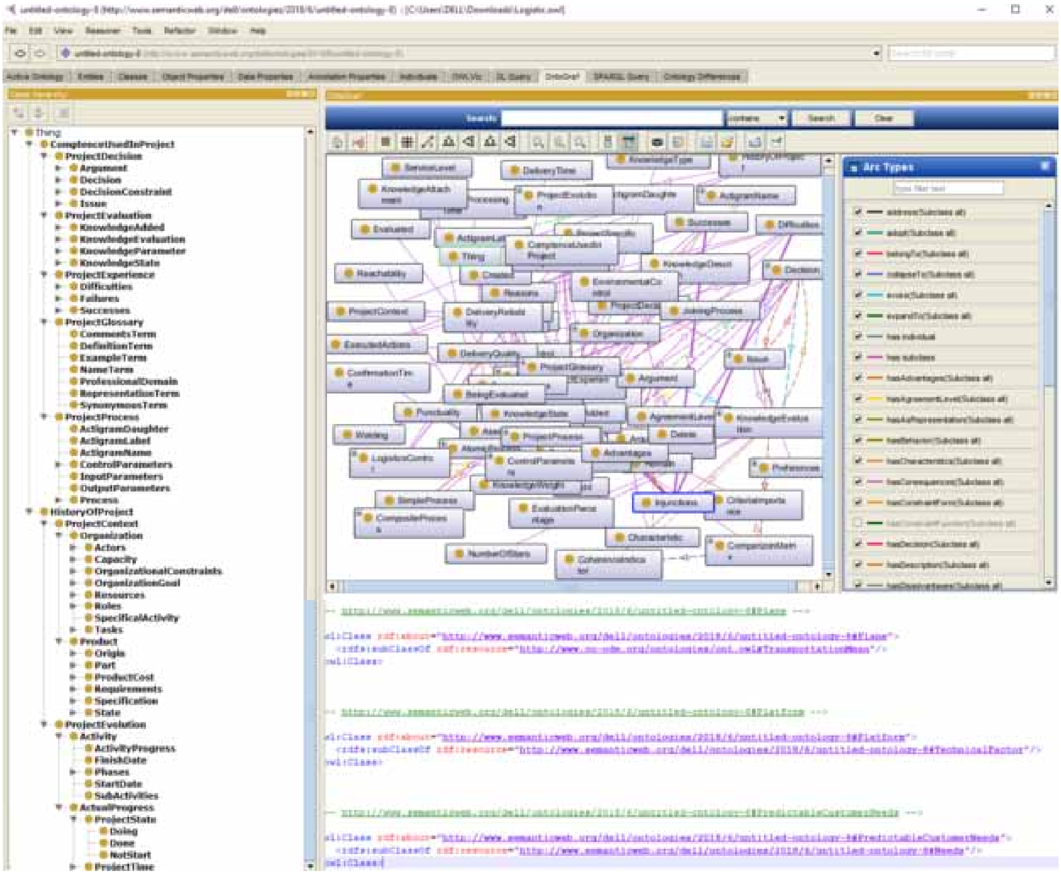
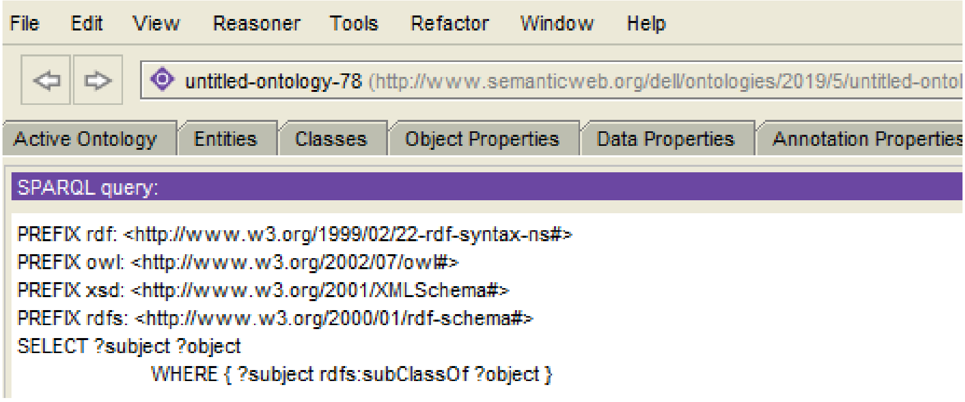


Figure 4. SPARQL query (authors' own compilation)



```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT ?subject ?object
                WHERE { ?subject rdfs:subClassOf ?object }
```

step, many studies held by different researchers address different methods and approaches to assist developers of ontologies in the process of evaluating their ontologies (Gangemi et al., 2006; Gómez-Pérez, 2004; Mc Gurk et al., 2017; Sánchez et al., 2015). In this regard, to obtain reliable ontology, a combination of different metrics used in the literature has been considered that respond holistically to the third ontology evaluation aspect which is (Table 6): validation, verification, and assessment.

6.2 Ontology Evaluation Results and Discussion

In terms of structural aspects, the ontology reveals complexity. It has 544 relations (NOR), 350 of which are hierarchical relations (H) and 194 of which are other types of connections (P). Besides, ontology contains 299 classes (NOC). The result in terms of richness of the inheritance (IR) is a real number that represents the subclasses on average, and which is calculated by a ratio of hierarchical relations (H) of several class NOC is 85%. This indicates that the ontology is horizontal, implying that it encompasses a broad range of general knowledge. This is the purpose of smart product design ontology, designed as a "general-purpose domain ontology" capable of specialization in many automotive industries.

Consistency of the ontology (Automated Consistency Checking) A consistent ontology is an ontology that does not involve contradiction (Wang & Xu, 2008). The inconsistencies of the ontology make the reasoning impossible to perform and thus no new information can be deduced at the level of the ontology (Mc Gurk et al., 2017). For the proposed ontology, the consistency was checked iteratively using the Pellet reasoner throughout the process of building and implementing the proposed ontology (Sirin et al., 2007). The latter is open source, integrated with Protégé, and represents several competitive advantages compared to other reasoners, particularly regarding the time it requires to check ontologies for consistency and, more importantly, the vast inference services it enables. More clearly, at each iteration, the inconsistent classes were marked for us in red at the level of Protected. These are then corrected and checked again until a consistent ontology is obtained.

Correctness of ontology: To examine the Correctness of Ontology, a logical specification query technique is used to generate and implement competency questions (Seaborne et al., 2008). When you apply the reasoning mechanism, you get useful knowledge at the end of the procedure. Validation is confirmed by the accuracy of the obtained results. The SPARQL language makes queries also known as "query classes", whose instances satisfy the query's membership condition. Table 7 presents the

Table 6. Ontology validation, verification, and evaluation criteria

Aspects	Attribute Type	Metrics	Definition	Source
Ontology validation	Semantic quality	Consistency	If it is unable to extract conflicting output outcomes from all valid input words, this value is set to false.	(Burton-Jones et al. 2005; Gómez-Pérez 2004; Obrst et al. 2007 Gangemi et al. 2006; Mc Gurk et al. 2017; Sánchez et al. 2015)
Ontology verification	Pragmatic quality	Correctness	Refers to whether the modeled ideas, instances, connections, and attributes correspond to those in the world being represented.	
Ontology assessment	Syntactic quality	Richness	Refers to the quantity and type of ontology language characteristics that have been employed in a certain ontology.	
		Structure	The number of connections between classes and subclasses in the ontology.	
	Semantic quality	Interpretability	Refers to the ontology's definition of terms (e.g., names of products and class properties).	
	Pragmatic quality	Extendibility	Refers to whether a user may create new terms for applications based on an ontology's current vocabulary in a way that does not need the rewriting of existing definitions.	
		Clarity	Refers to whether an ontology successfully communicates the intended meaning of its specified concepts and provides objective definitions that are not context-dependent.	
		Completeness	Refers to whether an ontology's definitions are sufficient for all potential domains.	

Table 7. SPARQL query execution results

Competencies Questions	Response	Correctness
CQ1: Which logistics services are required to realize a flow of goods?	List the logistics providers that offer storage, package, storage, transportation, and handling services.	Yes
CQ2: What aspects are critical to selecting a logistics service?	Show the name, description, Transport Service, Delivery Size, and website of the logistics companies	Yes
CQ3: Which information is required to provide adequate logistics service?	List of the logistics control parameters and lead time parameter	Yes
CQ6: What are relevant metrics to measure service performance?	List of service control parameters: Confirmation time, delivery time, order processing time, punctuality	Yes
CQ9: What aspects are critical to evaluating an argument?	Advantages, agreement level, argument description, characteristics, and disadvantages of each argument	Yes
CQ11: What skills are important to realize an activity?	Answerability, duty, flexibility, liability, loyalty, and responsibility	Yes
CQ12: What are the characteristics of an activity?	Activity progress, start date, finish date, a list of sub-activities	Yes
CQ15: What is the required information needed to add new information to the project?	attachment, description, type, specification, and the stage	Yes
CQ16: Which resources are required to realize the product?	Financial resources, information resources, logistics resources, materials resources, and software resources.	Yes

execution of certain SPARQL queries to answer certain questions among those previously defined. The results show the adequacy of the answers with the objective of the ontology.

Extensibility of the ontology: This criterion anticipates future uses of the ontology. Indeed, during the construction of the ontology, it is necessary to ensure that it is possible to define new terms without questioning or modifying the meaning and the definition of the existing terms in the model (Gómez-Pérez, 2004). The proposed ontology was developed to support different collaborative design processes belonging to different industries and applications. This was one of the main requirements that we imposed during the specification phase. For this purpose, it contains only the basic and common concepts and relationships between different industries. It thus leaves out the details of domains to ensure its extensibility and to facilitate its reuse for various applications. The terms (concepts and relations) of the proposed ontology are generic. To this end, the extension of the proposed ontology can be done easily without questioning or modifying the definitions of the current terms of the ontology.

Clarity of the ontology: To satisfy this criterion, the definitions of all the concepts of the ontology must be defined in the most objective way possible. To do this, it is important to define each concept in a natural language and to specify the necessary and sufficient conditions to say that an instance belongs to it. Gruber has defined three requirements elementary essentials to satisfy to meet this criterion of clarity (Gruber, 1991): (1) The ontology's terms must be formally specified without subjectivity; (2) the ontology should be described using natural language; and (3) the terms must correspond perfectly to their meaning rather than varying based on context. However, during the development of smart product design ontology, this criterion as well as its various requirements have been considered since the phase of the conceptualization. Indeed, most of the ideas have been simplified to ensure the ontology's clarity. relating to the PDP as well as to the various DFX techniques considered were inspired by the various existing projects and models in the literature. In addition, all the concepts have been defined formally and clearly. To do this, ontology has been enriched with comment annotations. For more details, see Table 2 of concept and relationship specifications.

Completeness of the ontology: This criterion states that the ontology must encompass all the information and knowledge that is either explicitly defined in the ontology or can be obtained thereby inference (Obrst et al., 2007). The verification of this criterion's compliance is challenging because neither the "completeness" nor the "incompleteness" of an ontology can be proven. Therefore, according to (Guo & Goh, 2017) "an ontology is considered semantically complete if it meets these two requirements: Each definition, which it includes, is complete and the ontology contains and explicitly includes everything it is supposed to be included". In our case, the "completeness of the classes" is examined before checking the completion. Then, the "domains" and ranks of all the "relations" between classes are double-checked (i.e., object properties) as well as their appropriate definitions. Finally, we verified that the class hierarchy is verified to be complete.

Exhaustivity of the ontology: When developing the ontology, the semantics of all its root concepts must be complete. They must make it possible to cover and represent all the information required for the modeling of the domain considered. To ensure the completeness of the proposed ontology and, its coverage of all of the product development process, the different "classes", "object properties" and "data properties" have been extracted and inspired, as mentioned above, from publications and standards concerning collaborative and integrated design. All the relevant terms (concepts and relationships) identified have been manually to meet the different requirements and objectives established in the specification phase. Thus, the completeness and coverage of the whole design process have been enhanced by adding missing subclasses, "object properties" and "data properties".

7. DISCUSSION AND IMPLICATIONS

Due to the rapid pace of technological change and the need for organizations to be able to rapidly adjust to changing market conditions, digital agility is becoming increasingly essential in today's PDP (Bouguerra et al., 2022; Grover, 2022). Organizations that are digitally agile have the capacity to respond immediately to market shifts and customer needs, enabling them to remain ahead of the competition and keep a competitive edge (Salmela et al., 2022). In fact, organizations can quickly develop and test new product concepts using digital tools and technologies, allowing them to iterate and improve on their ideas in a more efficient way (Gong & Ribiere, 2023). Digital agility can help to reduce time-to-market and improve customer satisfaction by allowing organizations to respond to customer needs and feedback more rapidly (Chan et al., 2019; Salmela et al., 2022). Another advantage of digital agility in PDP is having the capacity to collaborate and interact more efficiently across departments and teams (Lo et al., 2021; Neira-Rodado et al., 2020). Organizations can more easily share ideas and knowledge, cooperate on development and design, and implement modifications and improvements as required with digital tools and platforms (Huang et al., 2022; Xie et al., 2022). This can aid in the reduction of errors, delays, and misunderstandings during the PDP, resulting in a more efficient and streamlined process (Bertoni & Bertoni, 2022).

Therefore, by providing a standardized structure for organizing and representing knowledge in a specific area, ontologies can assist organizations in managing digital agility. In fact, ontologies can help an organization capture and formalize its knowledge and experience, making it more accessible and shareable across teams and divisions (Trappey et al., 2021; C. Zhang et al., 2017). It helps organizations to ensure that their product development process is able to respond quickly and effectively to changes in the market and technology, leading to more innovative and competitive products (Abou-Zeid, 2002; Yan et al., 2010). Besides, ontologies can help organizations adapt to fluctuating marketplace circumstances and consumer demands more effectively, allowing them to remain competitive and keep a competitive edge (Benabdellah et al., 2021a; Zekhnini et al., 2021b). Thus, when developing the ontology for digital agility, additional properties, constraints, and classes can be incorporated to characterize the organization's ability to respond swiftly and successfully to changes. This could include for example "agile development methodologies", "rapid prototyping", and the "ability to integrate customer feedback" into the PDP rapidly. However, the suggested ontology not only offers significant benefits, but it also emphasizes the importance of digital agility in the context of CE and DFX techniques through the consideration of the whole product lifecycle requirements such as sustainability, assembly, manufacture, service, safety, quality and so one. As a result of incorporating digital agility into the proposed ontology, organizations will have a better grasp of how to improve their DFX and circular economy efforts, resulting in the production of more environmentally friendly and effective products. Thus, the proposed ontology represents an important step toward realizing the full promise of CE, digital agility and DFX in the digital era. It provides a considerable advancement in resolving previously identified constraints. It can successfully manage the huge amounts of data created by PDP by leveraging the many capabilities of an ontology. Furthermore, by enabling more effective integration of DFX methods with PDP, the framework ensures that product development is guided by accurate, comprehensive, and up-to-date information. Furthermore, it allows for the sharing and reuse of information gained during the integration of these complex processes, which has the potential to save significant money and shorten product development schedules. It enables organizations to make better-informed decisions and promote innovation while decreasing time-to-market and development costs by simplifying the integration of multiple DFX approaches with PDP. As a result, the suggested ontology framework provides a comprehensive and strong answer to the problems that businesses encounter when dealing with huge volumes of data created during the product development process.

However, automotive companies must ensure that their products meet essential requirements in terms of safety, reliability, maintainability, occupant protection, and environmental impact throughout their lifecycle. To stay competitive, it is crucial for automotive manufacturers to have a deep understanding of customer preferences and consider multiple objectives when designing their products (Delic & Eyers, 2020; Kamble et al., 2021). In this regard, ontologies, can first improve Computer-Aided Design (CAD) systems by providing a systematic representation of automotive design information. The suggested ontology, for example, can record the interactions among various design factors, materials, and production processes. This enables CAD systems to offer creative design recommendations, automate design checks, and facilitate optimization of designs based on established objectives and constraints. Second, designers may easily retrieve and search relevant design knowledge by creating an ontology that defines the links between various vehicle components and their design specifications. This encourages information exchange, cuts down on unnecessary design work, and enhances design consistency across many vehicle variants and models. Third, decision support systems can use structured knowledge representation to deliver smart insights and suggestions by combining an ontology with data analytics and machine learning approaches. A decision support system based on ontologies, for example, can assist designers in picking appropriate materials, manufacturing techniques, or safety features based on preset design restrictions, cost considerations, and regulatory needs. Thus, with ontological representations of design knowledge, automotive companies can develop intelligent design decision support systems. These systems can provide recommendations, perform automated design checks, and optimize design parameters to improve product performance, quality, and efficiency. Fourth, ontologies can aid in interoperability and standardization during the product development process for automobiles. Multiple stakeholders, such as engineers, designers, manufacturers and suppliers, may interact and work together more efficiently by building domain-specific ontologies that define common vocabulary, connections and concepts. Furthermore, automotive businesses can use existing ontologies and data bases to speed up product development, minimize redundancy, and promote continuous learning. Lessons learned from previous projects can be captured in ontologies and shared across teams, leading to improved efficiency and innovation.

In terms of theoretical implications, the proposed ontology provides several advantages. First, it aids in the systematization of knowledge of the specified set of ideas as well as the structured representation of knowledge. Second, it provides transversal opportunities for collaboration between actors and systems. The hierarchy of the ontology allows for logical thinking about domain ideas. Third, the proposed ontology can be a guide for researchers to provide an overview of how to design innovative product when considering digital agility and CE capabilities under the umbrella of DFX techniques. The research contributes to the literature by being the first research paper that concentrates on integrating the DFX, CE, and digital agility in PDP field. Thus, by integrating DFX techniques, circular economy principles, and digital agility concepts, the ontology provides a comprehensive framework for exploring new design possibilities and consider the holistic impact of their decisions on product quality, sustainability, and efficiency. Fourth, the ontology implementation incorporates a wealth of knowledge encompassing various aspects of design, including Design for Manufacture and Assembly, Design for Safety, Design for Quality, Design for Supply Chain, Design for Environment, and other DFX techniques. This knowledge can be leveraged to interact with databases, information systems, or other ontology bases, facilitating knowledge reusability and interoperability across different platforms and applications. Fifth, integrating DFX techniques and digital agility into the product development process can have substantial environmental and economic benefits. By considering aspects such as material recovery and recycling, product durability, and resource efficiency, the proposed ontology promotes sustainability and contributes to lowering costs and waste while improving product quality and efficiency. Sixth, the proposed ontology can contribute to standardization efforts by providing a common framework for representing and organizing knowledge related to DFX techniques, circular economy, and digital agility. It establishes a foundation for defining best practices and industry standards, promoting consistency, efficiency, and quality in product development processes across different organizations and sectors.

In terms of managerial implications, the proposed ontology can help managers make better decisions about product development and obtain essential data and insights more efficiently by arranging and presenting knowledge in an organized manner. This can aid in analyzing design possibilities, considering the impact of digital agility and the circular economy on product creation, and making informed decisions that are in line with organizational goals and market expectations. Furthermore, the incorporation of DFX methodologies, circular economy and digital agility concepts via ontology can stimulate organizational innovation and creativity. Managers ought to motivate designers and academics to investigate new design possibilities, consider product development holistically, and offer innovative solutions that correspond with sustainability goals. This can lead to the development of products that are more competitive, sustainable, and aligned with customer needs. Furthermore, managers can use this data to connect their planning for strategy with market trends and client expectations. This can aid in the identification of potential for innovation, distinction, and sustainability, allowing the organization to remain competitive in a continually changing business environment.

8. CONCLUSION

The development of ontologies for collaborative product development processes is an active research area that has gained significant attention in recent years. These ontologies aim to support different stages of the product lifecycle with varying levels of detail, improving system interoperability and collaborative processes (Benabdellah et al., 2021a). The use of ontologies can facilitate knowledge sharing and integration among different stakeholders, promoting digital agility and circular economy principles (Trappey et al., 2021). Design factors such as data management, modular design, resource efficiency, digitalization, supply chain optimization, and collaboration and knowledge sharing are critical for enabling digital agility and circular economy principles (Chan et al., 2019; Varela et al., 2019). Therefore, it is essential to continue exploring the use of ontologies and design factors for collaborative product development to drive innovation, sustainability, and competitiveness in various industries.

However, this work goes first beyond the usual industrial application of ontologies, which relies solely on their expressivity to tackle semantic interoperability issues. Second, extend the existing ontologies by considering new dynamic capabilities such as circular economy and digital agility. Third, to answer the subject of how designers may effectively share, capitalize, and re-use knowledge, as well as how designers might become context-aware and deliver added-value information to improve operations monitoring and performance, the proposed ontology is developed, implemented, and evaluated. Fourth, the proposed ontology's uniqueness derives from the fact that it considers the customer's requirements derived from the "IATF/ ISO 16949" standard represented by different factors X's while considering at once the entire product lifecycle from conception, manufacture, used to disposal/recycle and dynamic capabilities such as digital agility and circular economy.

As a result, the proposed ontology, with its modular architecture, provides a critical link for organizations to integrate DFX methodologies into product lifecycle management to manufacture safe, environmentally friendly, economically successful goods while remaining adaptable to changing market and technological conditions. Additionally, the inclusion of digital agility in the ontology provides a means to effectively manage and integrate various organizational variables such as "safety", "service", "assembly", "quality assembly", "supply chain", and "environmental" factors in the automotive manufacturing industry. In other words, the proposed ontology has several distinctive characteristics:

- Reuse of fragments of existing ontologies.
- Integration of most of the customer's requirements derived from "IATF/ ISO 16949" standard represented by different factors X's while considering at once the entire product lifecycle and circular economy and digital agility capabilities.
- The ontology is adaptable and can be modified to meet the specific requirements of various organizations. This guarantees that the ontology is useful and applicable to a broad range of automotive manufacturing businesses.
- Use of Protégé throughout the development process to make use of its large selection of plug-ins and language formats, such as "XML" and "OWL".
- Establish a formal and accepted vocabulary for the field of automotive design, particularly mechanical design.
- The ontology is based on the most recent studies and company standards, ensuring that it is up-to-date and applicable in today's rapidly changing business environment. This gives companies trust as well as confidence that they are using a solid and efficient strategy for managing their operations.
- Standardize design reports to avoid misunderstandings caused by inconsistencies in terminology and assumptions.

The absence of agreement on quality limits the utility of ontologies. In this paper, automated consistency checking, "competencies question checking", and "criteria-based evaluation" have been utilized to test and prove the competency of the proposed ontology effectively.

Nonetheless, there are several limits to this study as well as some directions for further research. The manual approach used to develop the ontology captures the most precise concepts, but the outcome is less structured, with fewer complex axioms and relations. Using a broader variety of knowledge acquisition approaches to elicit more sophisticated information structures from documents and domain experts could improve this strategy. The use of ontology assessment methods would be another avenue for future research. While the smart product design ontology was reviewed objectively using "automated consistency checking" and "task-based evaluation", the "criteria-based evaluation" was primarily subjective due to the difficulty of quantifying criteria like clarity, extendibility, and completeness are hard to quantify. Coverage, on the other hand, maybe objectively assessed by comparing an ontology to a corpus of data. "Number of overlapping" terms, "vector space" similarity, "accuracy", "recall", and the "F-measure" can all be used to quantify "coverage". Besides, high-quality ontologies are challenging to create because they involve not only a thorough understanding of a topic, but also rationality, reasoning, and clarity regarding the data's intended purpose. Attempts to retrieve ontologies from existing Web documents have also been made. Because the quality of these ontologies varies so much, prospective users cannot be sure of their coherence, completeness, consistency, or suitability for a certain purpose.

DECLARATION OF COMPETING INTEREST

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

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APPENDIX A.

Abbreviation list

PDP	Product Development Process
DFX	Design for X
KM	Knowledge Management
CE	Circular Economy
TBL	Triple Bottom Line
DFM	Design for Manufacture
DFA	Design for Assembly
DFMA	Design for Manufacture & Assembly
DFC	Design for Cost
DFMt	Design for Maintenance
DFQ	Design for Quality
DFSC	Design for Supply Chain
DFRcy	Design for Recycling
DFRem	Design for Remanufacture
DFE	Design for Environment
DFRu	Design for Reuse
DFSR	Design for Social Responsibility
IATF	International Automotive Task Force
CQ	Competency Question
DOE	Differential Ontology Editor
OILED	OIL Editor

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