ENHANCEMENT OF PRODUCT DEVELOPMENT PROCESS: AN ONTOLOGICAL APPROACH

SHUAIBU ALANI BALOGUN*[1], ADAMU MAKAMA PINDIGA[2], MURTALA UBA DISSINA[1], JAMILA ADAMU[1]

[1]Federal Polytechnic Bauchi, School of Engineering Technology, Department of Mechanical Engineering Technology, Bauchi, Nigeria [2]Federal Polytechnic Bauchi, School of Environmental Technology, Department of surveying and Geoinformatics, Bauchi, Nigeria

ABSTRACT

Information is vital at every stage of the product life. At the early-stage information about existing product is useful to enable setting of target during product definition. Furthermore, information about function, form and processing method are all important at the early stage. As the product becomes matured the information need is concern with its operation and disposal. For a successful product development process, there is need to study the product development process and the means of storing design information throughout the life span of the artifact. Ontology has proved to be one of the best tools for information storage indexing and retrieval. However, its use in product development process is not well emphasised. This paper scans through the existing ontology application to understand method applied to build them and the challenges and progresses register in them. It then proposed a need to deploy ontology for information capturing storage and retrieval at all stages of PDP. This can go a long way to assist new entrant into the industries to improve on their design capabilities.

INTRODUCTION

The goal of any industry is to produce artefacts that will satisfy the customers' needs and at the same time bring profit to the organisation. The customers' needs could entirely be new product or improvement on an existing one(Ullman, 2010). Besides, the time a product gets to the market from the time the idea to develop the product is conceived is paramount to the productivity of a firm. Product time to market has been reduced recently due to worldwide competition and technological improvement in Product Development Process (PDP). (Catalano, Camossi, Ferrandes, Cheutet, & Sevilmis, 2009). Therefore, for the product to satisfy customers' needs and be economically viable, developing the product must follow a well-planned process. In automobile industry for example, the part to be designed and manufactured are so many and the product is expected to reach the market as early as possible therefore it requires an effective and efficient decision-making method especially those based on tested and experienced approach.(Renzi, Leali, & Di Angelo, 2017)

A product that passes through a good design process is expected to bring better satisfactions to both the customers and the firm. A well-designed product has its manufacturing cost cut down by at least 30%. As such, modern industries take design as serious as manufacturing (Ullman, 2010). Design methods vary from industries to industries. From academic view, design process entails: product identification, project planning, product definition, conceptual design, embodiment and detail design(Pahl, Beitz, Feldhusen, & Grote, 2007).

At every stage in the design process, decisions are taken based on some criteria. Taking the right decision at the right time affects the time a product gets to the market and economy of design and manufacture (Ullman, 2010). For instance, to select bolt and nut for fastening, decisions must be made, and these decisions are compromises made on factors like weight, cost, strength and size. This could cost a lot of delay in design when there is no information repository where standard information could be elicited even if the designer is experienced but new in the organisation. More than 75% of engineering design activities entail reuse of knowledge from previous work. Hence a reliable source of information search, retrieval and indexing is essential as a support to design process (KingLim, Liu, & Chen, 2015). Design knowledge is helpful to both the novice and experienced designer at every level of product development (Ahmed, Wallace, & Blessing, 2003). Therefore, to enhance work capacity of new designers or experience designers that are new in a firm, a complete documentation of information that is related to products or the process of developing the products is necessary.

Recently, many researches were carried out on the use of EO in industries. Results of such researches have led to adoption of EO in many industries. Besides, many fields now develop ontologies for sharing and annotating their domain knowledge (KingLim et al., 2015). Information sharing between product developers and customers/suppliers becomes obviously necessary due to; complexity of product, increase in competition among firms, globalization of energy, and higher customers' focus. (Vegetti, Henning, & Leone, 2005). Knowledge-based system for design automation requires: knowledge formalisation, Integration with other software tools and Interoperability. Interoperability is the ability of a system to interchange and interpret shape knowledge with other system. (Furini et al., 2016) Information in a domain can be stored using ontology such that stakeholders in the domain can access the information by indexing, retrieving or reusing it. The main entities within the knowledge in a domain are called the root concepts. These root concepts are interdependent to each other therefore, the concepts are arranged in a hierarchical order such that the entities are considered as classes which have subclasses and supper-classes. Such hierarchical organisation of concepts into classes is called taxonomy (Ullman & D'ambrosio, 1995).

Ontologies have been developed for indexing, retrieval and reuse in several domains (Alizon, Nanda, Shooter, & Simpson, 2007) within product life cycle. Domains like the aerospace, general engineering devices manufacturing and materials which are all generic have been explored and included in the semantic web. However, in the area of product development process little work has been done. The work of Kerr, Roy, & Sackett (2004) is on specifications for selection of seats for vehicles while that of Sandkuhl & Billig (2007) is on management of electronics artefacts. Ontologies on design of the vehicle structures transmission systems and painting and decoration which are the main work in the automobile industries are yet to be created.

This paper therefore delved into the existing works on ontology of engineering design to ascertain the gap in knowledge and lay foundation for evoking domain knowledges from literature.

EXISTING WORK ON ONTOLOGY IN ENGINEERING

Generic component of engineering ontology is the concept of physical product that has assembly, component, feature etc and their relation rather than the definition of a physical product (Ahmed, Kim, & Wallace, 2005). Ullman & D'ambrosio (1995) developed taxonomy for classifying decision methods and tools. They identified four aspects of decision problems that form the root concept of the taxonomy which are: structure, focus, range and support. They rooted information for decision making from: operation research, psychology, optimisation, business and artificial intelligence. (Ullman & D'ambrosio, 1995). Meanwhile, this taxonomy does not make an explicit representation of the decision-making knowledge and cannot be used as a design information repository as it has a very minimal benefit to designers when it comes to design information seeking. Another taxonomy was developed by Smith (2000) for categorisation of engineering tasks. He considered three root concepts for the taxonomy and named them: repair task, engineering task and improve task; as shown in Figure I. Improve task was considered a hybrid of the first two tasks (Smith, 2000). The taxonomy is too general and the domains span over the entire product life. It is not explicit enough for design knowledge indexing.

Besides, The DesignExchange was built for storing information to aid collaboration amongst engineering design stake holders. The DesignExchange is more centred on conceptual design and it forms only taxonomy and not detailed specification of the knowledge in the domain to make an ontology (Roschuni, Agogino, & Beckman, 2011). Manufacturing Service Description Language (MSDL) is another ontology developed for mechanical machining domain (Ameri et al., 2012). MSDL is composed of five models that make the major classes of the ontology which are: Supplier, Shop, Machine, Device and Process (Ameri et al., 2012). Another effort is the PROTON which defines product ontology modelling within the domain of complex product related to the structure of product (El Kadiri & Kiritsis, 2015). Sanya & Shehab (2015) developed a methodology for building ontology for aerospace industries in the domain of combustor and casing design, which comprises of three

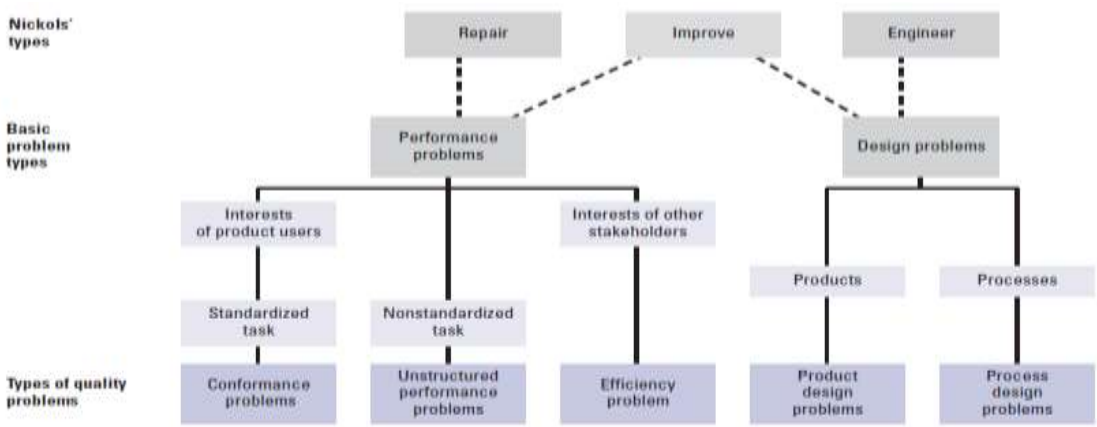

Figure II: Taxonomy of Quality problems (Smith, 2000)

Phases which are: design of the ontology, validation and implementation (Sanya & Shehab, 2015). The root concepts of the ontology are: Product, Engine, Assembly, Component, Feature, and Design style. The ontology was validated by experts within the domain (Sanya & Shehab, 2015). (Mori, Ceccarelli, Lollini, Bondavalli, & Frömel, 2016) developed a semiformal key concept for SoSs (System of Systems) and relationships using SyML (System Modelling Language)

Further, in the field of Biomedical engineering, Adamczyk et al. (2017) Built an ontology called MCDM/A (Multi-Criteria Division Making/Analysis) for decision making support in dental implant. They built the ontology on two models which root concept. The two models are: dental implant PDP and Medical sciences. Ernadote (2017) Developed an ontology-based pattern for system engineering. System engineering is a multidomain life-cycle of system or systems of system (Ernadote, 2017). Besides, Yuan et al. (2017) Used hierarchical material structure representation and that of shape graph to abstract the morphological properties of materials. Sanfilippo (2018) developed a feature-based ontology called FPRO (Feature-based Product ontology). they based it on the root concepts of form feature and function feature. The upper-level ontology consists of: object, process, description, quality and quality space as shown in figure III.

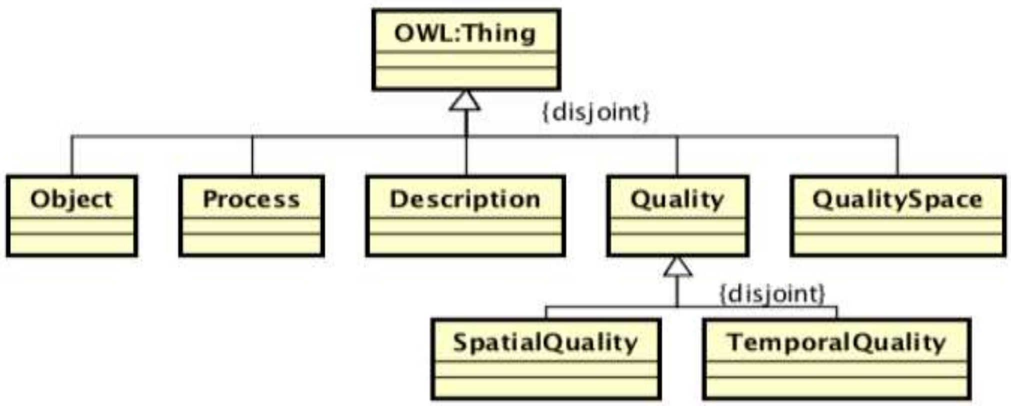

Figure III: Taxonomy for Feature-based Product ontology (Sanfilippo, 2018)

PRODUCT DEVELOPMENT PROCESS

Engineering design is a systematic intelligent process of generating, evaluating and specifying concepts for artefacts whose form and function ensure customers' needs and satisfy a set of constraints (Trevisan, Peruccio, & Barbero, 2018) Engineering design is a complex system that entails several decisions making and compromises. Decision making in design is to enable selection of the optimum alternative that will best suit the focus and desired value of a design process (Renzi et al., 2017) Design process models are edited and rationalized abstraction of realities. (Green, Southee, & Boult, 2014) In standard industries, the design process begins with product discovery, then project planning, product definition, conceptual design, embodiment design, detail design and product support. According to Ullman (2010), a complete design process can be represented as shown in Figure I.

The objective of conceptual design is to analyse the requirement of product to be designed and the design process to convert functional requirement into abstracted structures and then find the fundamental solutions(Yuan, Liu, Lin, & Zhao, 2017).Thomas, Stahovich, Randall, (1993) laid emphasis on the need for considering function in the conceptual design of devices and nomenclature of components or devices. For example, he defined a lever as “the transformation of a force which is not reactive force by means of a balanced moment (torque) about a pivot point”. Based on this definition, a lever is categorised based on function and any device that performs this function is considered a lever.(Thomas et al., 1993).

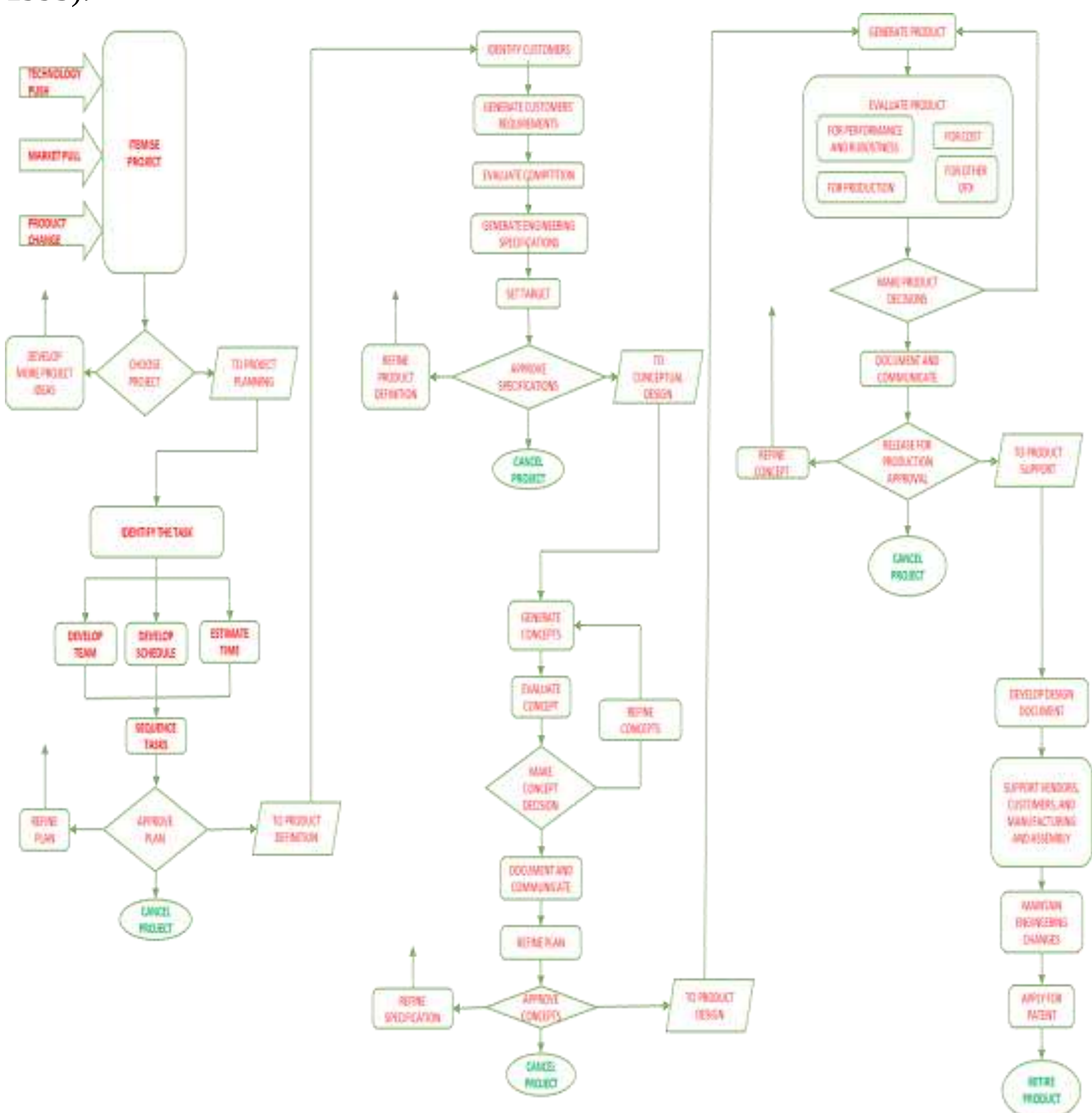

Figure I: Complete Design Process According to Ullman (Ullman, 2010)

Renzi et al., (2017) categorised the methods for automobile design problem (ADP) into: ADP related to uncertainty, ADP related to requirements, ADP related to customers' needs, ADP related to design alternative selection, ADP related to material selection and ADP related to process selection (Renzi et al., 2017).

Many tools have been developed to support both design process and analysis (Alizon et al., 2007). Designers both in the industries and research field use either Top-Down Design (TDD) or Modular Product Design (MPD) strategies (Chu, Chu, Li, Lyu, & Xue, 2016). Chu et al., (2016) hypothesised that the integration of TDD and MPD strategies would yield an optimum result by improving the quality and efficiency of products. Nevertheless, there are no existing tool that can handle the use of the two strategies simultaneously (Chu et al., 2016). Nearly 80% survey of businesses indicates that designers are good at their innovative activities but deficient in communicating the values of their design activities (Green et al., 2014). There is need for a good blend of relationship between members of a design team as the heterogeneity or homogeneity of the team may affect the output of their design work. Where there are differences among the team members in factors like: cultural background and demography,(Cash, Dekoninck, & Ahmed-Kristensen, 2017) are often responsible and as such a good information repository can bridge the gap.

ENGINEERING DEIGN INFORMATION

New methods and tools for design has evolved to support product family design. Because of this, design data has evolved and been reused. Therefore, issues on sharing and compatibility and the repository for supporting design data and description are of concern. The design data are being revised frequently to enhance issues of compatibility among the diverse design tools (Alizon et al., 2007). More than 75% of engineering design activities entail reuse of knowledge from previous work. Hence a reliable source of information search, retrieval and indexing is essential as a support to design process. (KingLim et al., 2015) Design information have been adopted in many fields due to its vast advantages (Alizon et al., 2007)

The best practices that ensures quality of engineering systems are available in standard such as 15015288. NIST, NCOSE Handbook e.t.c. These standards entail the activities of the system engineering process, the stake holders and their responsibilities regarding the activities. Standard metal models engineering such as: UML, SysML or NMM/NAF are typically used to describe the concept of the metamodels (Ernadote, 2017). Knowledge-Based Engineering (KBE) and Design Automation (DA) require good management of data and information. The main aim of adopting KBE system is to optimise time and cost in a design process (Furini et al., 2016). Both KBE and DA are used to integrate design data and information to facilitate the design tasks. Knowledge formalisation and integration with other software tools are the two critical steps in developing Design Automation or Knowledge-Based System (Furini et al., 2016). There are two main types of integration that can be distinguished generally: Functionality and data. Function integration is remedying the problems of composing local function from dissimilar existing systems. Data integration implies access to data from data heterogeneous or autonomous source via a homogeneous interface (El Kadiri & Kiritsis, 2015).

Design information is classified into five which include: location, interface features, design space, key features and kinematic constraints. Design information can be modelled using three types of skeletons which are: location skeleton, interface skeleton and published skeleton. (Chu et al., 2016) Researcher build ontologies using information gathered from literature and interview with practitioners in the industries (Celeste Roschuni et al., 2015).

MEANING OF ONTOLOGY

The term ontology is derived from Greek words ontos meaning being and logos meaning words (El Kadiri & Kiritsis, 2015). Ontology is concept of philosophy which implies systematic explanation of being and is used to describe the essence of the real world (Zhu & Li, 2018). One of the early definitions of ontology is that of Neches and colleague. They defined ontology as: “an ontology defines the basic terms and relations comprising the vocabularies of a topic area as well as the rules for combining the terms and relations to define the extension to the vocabularies (Corcho, Fernández-López, & Gómez-Pérez, 2003). Definition stated by Gruber is one of the most commonly used which states that: “Ontology is the explicit specification of shared conceptualisation and conceptualisation is an abstract model of concepts that describes the relevance of the concept in the domain” (Mario et al., 2008).

Studer and colleague later modified Gruber’s definition by viewing ontology as a formal specification of shared conceptualisation (Zhu & Li, 2018). In some other known definitions ontology is described as: 1- the representation of a sense making process which is the point of view of those who take part in the process (Cristani

& Cuel, 2004) 2- Classification of all entities explicitly in all domain of being (El Kadiri & Kiritsis, 2015) 3- formal knowledge model that defines concepts and relationship between concept and enable information search and reasoning. (Hammar, 2017) 4- specification of the conceptual information derived from real world systems, In the contest of artificial intelligence (El Kadiri & Kiritsis, 2015).

ONTOLOGY OF DESIGN PROCESS

Thomas et al. (1993)developed an ontology for mechanical devices knowledge base which is based on function. The ontology is not explicit enough for comprehensive design process since other aspects of design process like project planning and even conceptual design that require consideration for forms and other casual explanations are not captured in the ontology. Besides, the root concepts are too general therefore the ontology is not explicit as there are no specific instances. Another ontology built for engineering design is DO which was built on four root concepts: Design, lifecycle phase, life phase system, product assortment. (Ahmed & Štorga, 2009) [15] GDMS which was proposed by Mortensen was used as the basis and main source for extracting the content of the DO(Mario et al., 2008). Later, an empirical approach was used to develop an ontology named EDIT (Engineering Design Integrated Taxonomy). EDIT comprises of four root concepts- Design process, Physical product, function and issue- that form the individual taxonomy (Ahmed & Štorga, 2009). The ontology was constructed using a theoretical approach in which the concepts and relationship were elicited from engineering design theories and Design Ontology (DO). Design process has been described in literature, for knowledge indexing it needs to be more detailed (Ahmed et al., 2005). EDIT does not explicitly study the complex interrelation amongst the root concepts (KingLim et al., 2015). DO is modelled from Engineering design theories using top-down approach while EDIT was built using bottom up approach in the domain of aerospace with the application as indexing knowledge industry(Ahmed & Štorga, 2009). The taxonomy of the root concepts for both EDIT and DO are indicated in Figure IV. DO describes design as a product while EDIT describes same as an activity (Ahmed & Štorga, 2009). The ontologies ie both EDIT and DO, were merged to form a template ontology for the DO (Ahmed & Štorga, 2009). Ahmed & Štorga (2009) termed the merged otology MOED (Merged Ontology for Engineering Design).

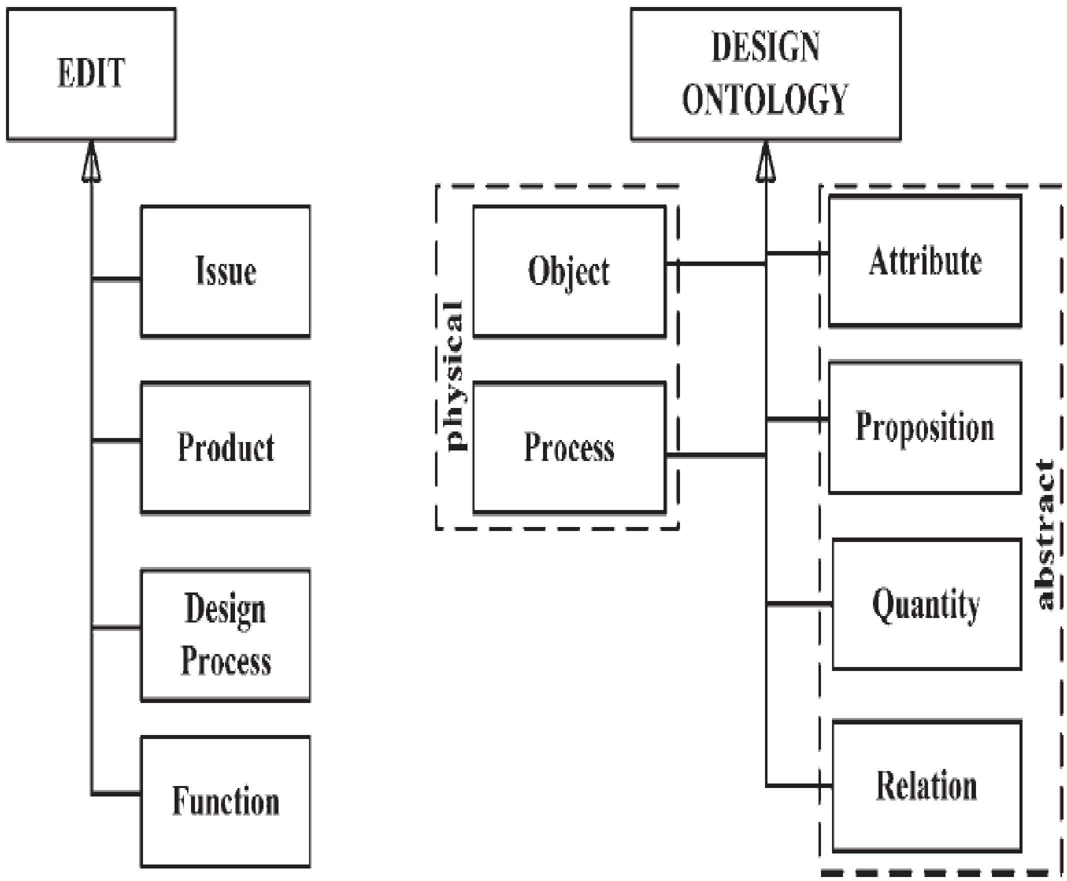

Figure IV: the root concepts of EDIT and DO (Ahmed & Štorga, 2009)

MOED (Merged Ontology of Engineering Design) which comprises of the four top classes: Physical object, Process, Abstract attribute, and relation (Ahmed & Štorga, 2009) [15]further,

Cardoso et al. (2008) developed a PFODM (Product Family Ontology Development Method). The ontology is a merger between product design information and the requirements of design tools. [51] Catalano et al. (2009) developed PDO (Product Design Ontology) the objective of the ontology is to provide medium for sharing and indexing information on shape processing of product. Catalano et al. (2009) considered only product behaviour. They used ontology to model PDO in combination with corresponding OWL plug-in (Catalano et al., 2009). The core root concept of the PDO are: shape type, shape processing tools, task, conditions and group (Catalano et al., 2009). Ostergaard & Summers (2009) develop an interdisciplinary taxonomy

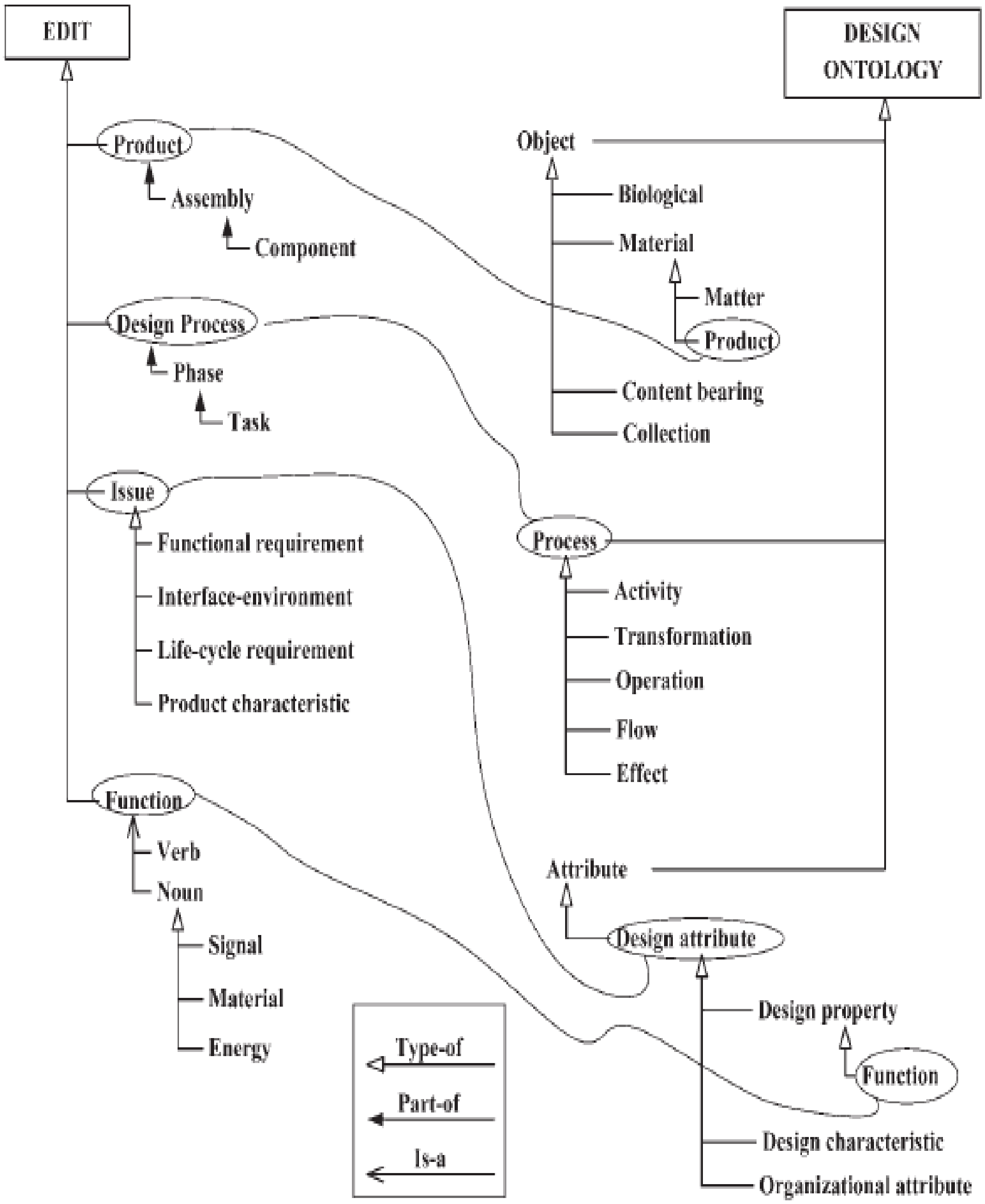

Figure V: Mapping of EDIT and DO to create MOED (Ahmed & Štorga, 2009).

For collaborative design using top-level method. Jain & Singh (2013) also built a design ontology with the aim of considering the effect of product on the environment. They used LCA to analyse the environmental impact of product development process.

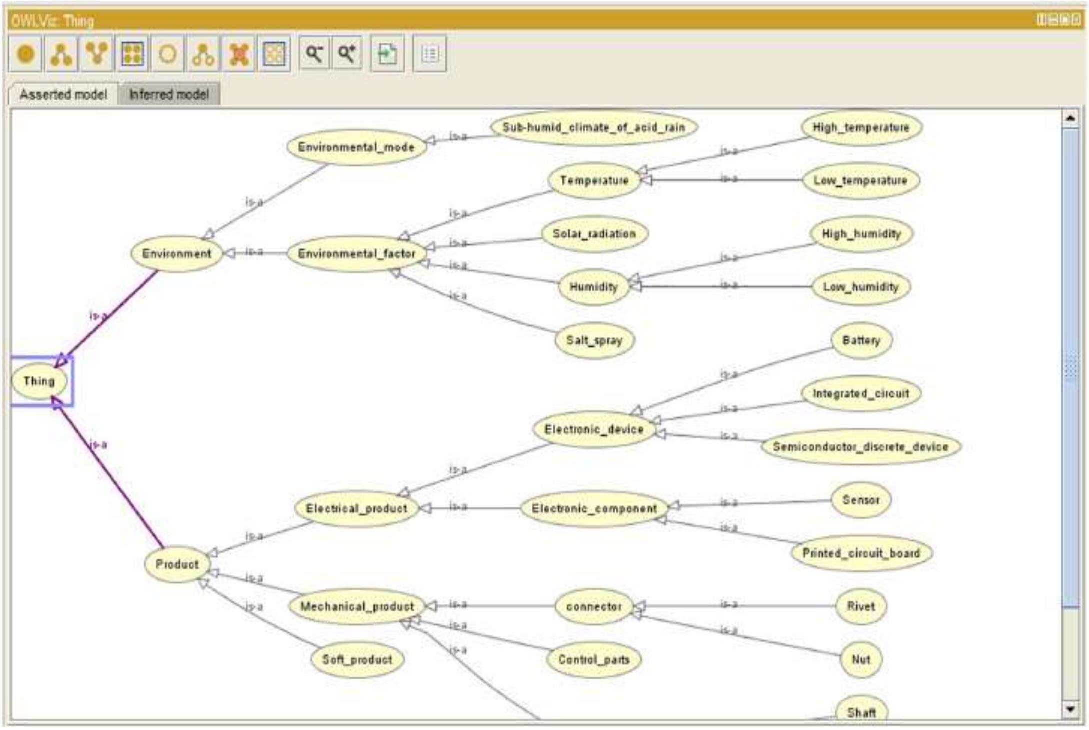

Figure: VI: ontology of environmental effectiveness in a reliability design analysis.(Li et al., 2016)

Aadil, Wakrime, Kzaz, & Sekkaki (2016) proposed an ontology for both need and data-oriented design. They verified applicability of the ontology in waste management. The ontology was first localised then globalised by aligning the various local ontologies (Aadil et al., 2016).

IMPORTANCE OF USING ONTOLOGY FOR DESIGN INFORMATION

Several industries are adopting ontology and semantic search in their design work. Many of such companies are drawing towards having a cloud-based application powered by semantic web technology. For example, Autodesk proposed the use of PLM360 which is a cloud-based approach for PLM. Dassault systems also developed EXALEAD cloud view which uses NLP (Natural Language Processing) (KingLim et al., 2015)[27]

Design ontology is a framework for more efficient product development in data, information and knowledge description, explanation understanding and reuse. (Mario et al., 2008)[16] The availability of domain vocabulary and the correct meaning definition to the vocabulary is important to the success in engineering knowledge exchange and management. (Mario et al., 2008). Availability and accessibility of engineering ontology is key to effective integration of product development resources. For example, accessibility to information on manufacturing and material can help the designer in considering the manufacturing of complex concepts or selection of materials that give a combination of properties. (Mario et al., 2008)[16] Ontology manages and states knowledge. It facilitates sharing and reuse of knowledge Determination of application domain and purpose of research (Zhu & Li, 2018). Ameri et al. (2012) observed how novice and experienced designers approach design work. Novice use trial and error method and are less confident of their decisions, while experienced designers consider issues and are more confident in their decision. Ontology plays a key role in a system by providing shared and machine-readable vocabulary for information exchange amongst the stake holders in the system (Ameri et al., 2012).

Experience and knowledge play important roles in the success of design task (Ahmed et al., 2003) Generally, ontology can be used to search, retrieve or index information. (Ahmed et al., 2005)[21] Ontology for indexing engineering design knowledge can help designers when searching for engineering design knowledge when the query is properly formulated.(Ahmed et al., 2005) Several industries are adopting ontology and semantic search in their design work. Many of such companies are drawing towards having a cloud-based application powered by semantic web technology. For example, Autodesk proposed the use of PLM360 which is a cloud-based approach for PLM. Dassault systems also developed EXALEAD cloud view which uses NLP (Natural Language Processing) (KingLim et al., 2015)[27] Advantages of using ontologies are: It enables information sharing amongst people within the same domain; Makes domain knowledge reusable, it enables corrections of domain information; It ensures separation of domain knowledge from operational information. (El Kadiri & Kiritsis, 2015)[37] Ontology has been adopted in product development to capture information that is related to the product and process form conceptualization to disposal of the product. Examples of product data are those in models that deals with the form of products which is exchangeable in the product development and maintenance process using (STEP/ISO10303)(El Kadiri & Kiritsis, 2015) [37] STEP- Standard for exchange of product model data. To enhance semantic modelling of products, the information in STEP is being translated from express to owl to develop a product model ontology called OntoSTEP.(El Kadiri & Kiritsis, 2015) [37] Generally, ontology assists designers to focus their queries through browsing or navigating an indexing structure. Besides, it helps to overcome the problems of search engines not understanding the context of a queries.

El Kadiri & Kiritsis, (2015) observed 7 roles of ontology as: trusted source of knowledge, database, Knowledge base, bridge for multiple domains, mediator for interoperability, contextual search enabler and linked data enabler. Besides, Knowledge sharing, and reuse can be effectively developed using ontology and the ability of ontology to integrate, interpreted or express knowledge is key to the success of semantic web (Li et al., 2016). Using ontology, domain concepts and their relationship can be expressed explicitly with machine readable language.(Li et al., 2016). This enables information representation to support knowledge modeling, communication, interoperability etc. in the form of semantic web (Adamczyk et al., 2017).

CONCLUSION

Inconclusion, the basic information that are retrieved, processed, and stored during product development process are very vital just as the design process is vital. This study has unveiled the importance of using ontology in PDP. With such information management systems design process especially the early part of it will be adequately supported.

REFERENCES

Aadil, B., Wakrime, A. A., Kzaz, L., & Sekkaki, A. (2016). Automating Data warehouse design using ontology. *Proceedings of 2016 International Conference on Electrical and Information Technologies, ICEIT 2016*, 42–48. https://doi.org/10.1109/EITech.2016.7519618

Adamczyk, B. S., Szejka, A. L., Canciglieri-Junior, O., & Rocha-Loures, E. D.-F. (2017). Towards interoperability semantic model to support design for dental implant decision-making. *Advances in Transdisciplinary Engineering*, *5*, 941–948. https://doi.org/10.3233/978-1-61499-779-5-941

Ahmed, S., Kim, S., & Wallace, K. M. (2005). A Methodology for Creating Ontologies for Engineering Design. In *Proceedings of IDETC/CIE 2005 Conference ASME 2005 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference September 24-28, 2005, Long Beach, California USA* (pp. 1–12). Retrieved from www.proceedings.asmedigitalcollection.asme.org/

Ahmed, S., & Štorga, M. (2009). Merged ontology for engineering design: Contrasting empirical and theoretical approaches to develop engineering ontologies. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, *23*(4), 391–407. https://doi.org/10.1017/S0890060409000146

Ahmed, S., Wallace, K. M., & Blessing, L. T. M. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*, *14*(1), 1–11. https://doi.org/10.1007/s00163-002-0023-z

Alizon, F., Nanda, J., Shooter, S. B., & Simpson, T. W. (2007). Ontology-based models for design retrieval and analysis. *Proceedings of ICED 2007, the 16th International Conference on Engineering Design*, *DS 42*, 1–11.

Ameri, F., Urbanovsky, C., & McArthur, C. (2012). A systematic approach to developing ontologies for manufacturing service modeling. *CEUR Workshop Proceedings*, *886*, 1–14.

Buchenau, M., & Suri, J. F. (2000). Experience Prototyping. In *DIS '00 Proceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques* (pp. 424–433). New York City. https://doi.org/10.1145/347642.347802

Cardoso, J., Hepp, M., & Lytras, M. D. (2008). *The Semantic Web: Real word Appl]cstion from Industry*. (J. Cardoso, M. Hepp, & M. D. Lytras, Eds.). New York City: springer science business media LLC233.

Cash, P., Dekoninck, E. A., & Ahmed-Kristensen, S. (2017). Supporting the development of shared understanding in distributed design teams. *Journal of Engineering Design*, *28*(3), 147–170. https://doi.org/10.1080/09544828.2016.1274719

Catalano, C. E., Camossi, E., Ferrandes, R., Cheutet, V., & Sevilmis, N. (2009). A product design ontology for enhancing shape processing in design workflows. *Journal of Intelligent Manufacturing*, *20*(5), 553–567. https://doi.org/10.1007/s10845-008-0151-z

Cheng, Z., & Ma, Y. (2017). Explicit function-based design modelling methodology with features. *Journal* *of Engineering Design*, *28*(3), 205–231. https://doi.org/10.1080/09544828.2017.1291920

Chu, D., Chu, X., Li, Y., Lyu, G., & Xue, D. (2016). A multi-skeleton modelling approach based on top-down design and modular product design for development of complex product layouts. *Journal of Engineering Design*, *27*(10), 725–750. https://doi.org/10.1080/09544828.2016.1227428

Ciavola, B. T., & Gershenson, J. K. (2016). Affordance theory for engineering design. *Research in Engineering Design*, *27*(3), 251–263. https://doi.org/10.1007/s00163-016-0216-5

Corcho, O., Fernández-López, M., & Gómez-Pérez, A. (2003). Methodologies, tools and languages for building ontologies. Where is their meeting point? *Data and Knowledge Engineering*, *46*(1), 41–64. https://doi.org/10.1016/S0169-023X(02)00195-7

Cristani, M., & Cuel, R. (2004). A Comprehensive Guideline for Building a Domain Ontology from Scratch. *Proceedings of I-KNOW '04*, 206–212. https://doi.org/10.1.1.91.2557

El Kadiri, S., & Kiritsis, D. (2015). Ontologies in the context of product lifecycle management: State of the art literature review. *International Journal of Production Research*, *53*(18), 5657–5668. https://doi.org/10.1080/00207543.2015.1052155

Ernadote, D. (2017). Ontology-Based Pattern for System Engineering. *Proceedings - ACM/IEEE 20th International Conference on Model Driven Engineering Languages and Systems, MODELS 2017*, 248–258. https://doi.org/10.1109/MODELS.2017.4

Furini, F., Rossoni, M., & Colombo, G. (2016). Imece2016-67292 Knowledge Based Engineering and Ontology Engineering Approaches for Product Development : Methods and Tools for. In *Proceedings of the ASME 2016 International Mechanical Engineering Congress and Exposition IMECE2016 November 11-17, 2016, Phoenix, Arizona, USA IMECE2016-67292* (pp. 1–7). ASME Engineering Technical Conferences. Retrieved from proceedings.asmedigitalcollection.asme.org/pdfaccess.ashx?url=/data/conferences/asmep/91001/

Green, S., Southee, D., & Boult, J. (2014). Towards a design process ontology. *Design Journal*, *17*(4), 515–537. https://doi.org/10.2752/175630614X14056185480032

Hammar, K. (2017). *Content Ontology Design Patterns Qualities, Methods, and Tools*. Linkoping University. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-139584/%0Ahttps://liu.diva-portal.org/smash/get/diva2:1131672/FULLTEXT02.pdf

Hirtz, J. M., Stone, R. B., McAdams, D. A., Szykman, S., & Wood, K. L. (2001). (Hirtz) Evolving a functional basis for engineering design.pdf. In *Proceedings of DETC01 2001 ASME Design Engineering Technical Conferences September 9-12, 2001- Puttisburgh, PA* (pp. 1–11). Pittsburgh: ASME Engineering Technical Conferences. Retrieved from https://pdfs.semanticscholar.org/b5eb/afd5d9c470c7b470af234117d8087a0764eb.pdf

Jain, V., & Singh, M. (2013). Ontology Development and Query Retrieval using Protégé Tool. *International Journal of Intelligent Systems and Applications*, *5*(9), 67–75. https://doi.org/10.5815/ijisa.2013.09.08

Kerr, C. I., Roy, R., & Sackett, P. J. (2004). A Product Ontology for Automotive Seat Specification. In *ASME 2004 Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 1–8). Salt Lake City, Utah, USA,. https://doi.org/10.1115/DETC2004-57071

KingLim, S. C. J., Liu, Y., & Chen, Y. (2015). Ontology in Design Engineering : Status and Challengies. In *International Conference on Engineering Design, ICED15 27-30 JULY 2015, Politecnico Di Milano, Italy O* (pp. 1–10).

Li, Y., Sun, B., Wang, Z., & Ren, Y. (2016). Ontology-Based Environmental Effectiveness Knowledge Application System for Optimal Reliability Design. *Journal of Computing and Information Science in Engineering*, *17*(1), 011005. https://doi.org/10.1115/1.4034129

Ma, Z., & Liu, Z. (2018). Ontology- and freeware-based platform for rapid development of BIM applications with reasoning support. *Automation in Construction*, *90*(January), 1–8. https://doi.org/10.1016/j.autcon.2018.02.004

Mario, S., Mogens, M. A., & Dorian, M. (2008). The design ontology : foundation for the design knowledge exchange and management. *Journal of Engineering Design*, *00*(0), 1–28. https://doi.org/10.1080/09544820802322557

Mori, M., Ceccarelli, A., Lollini, P., Bondavalli, A., & Frömel, B. (2016). A Holistic Viewpoint-Based SysML Profile to Design Systems-of-Systems. *Proceedings of IEEE International Symposium on High Assurance Systems Engineering, 2016–March*, 276–283. https://doi.org/10.1109/HASE.2016.21

Ostergaard, K. J., & Summers, J. D. (2009). Development of a systematic classification and taxonomy of collaborative design activities. *Journal of Engineering Design*, *20*(1), 57–81. https://doi.org/10.1080/09544820701499654

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). *Engineering Design a Systematic Approach*.

Renzi, C., Leali, F., & Di Angelo, L. (2017). A review on decision-making methods in engineering design for the automotive industry. *Journal of Engineering Design*, *28*(2), 118–143. https://doi.org/10.1080/09544828.2016.1274720

Roschuni, C., Agogino, a M., & Beckman, S. L. (2011). The DesignExchange: Supporting the Design Community of Practice. *Proceedings of the 18th International Conference on Engineering Design (ICED11)*, (August), 255–264.

Roschuni, C., Kramer, J., Qian, Z., Zakskorn, L., & Agogino, A. (2015). Design Talking: an Ontology of Design Methods To Support a Common Language of Design. *Proceedings of the 20th International Conference on Engineering Design (ICED 15)*, 285–294.

Sandkuhl, K., & Billig, A. (2007). Ontology-based artefact management in automotive electronics Ontology-based artefact management in automotive electronics, *3052*(June), 627 – 638. https://doi.org/10.1080/09511920701566467

Sanfilippo, E. M. (2018). Ontological foundations for feature-based modeling. *Procedia CIRP*, *70*, 174–179. https://doi.org/10.1016/j.procir.2018.03.002

Sanya, I. O., & Shehab, E. M. (2015). A framework for developing engineering design ontologies within the aerospace industry. *International Journal of Production Research*, *53*(8), 2383–2409. https://doi.org/10.1080/00207543.2014.965352

Schuh, G., Riesener, M., Mattern, C., Linnartz, M., & Basse, F. (2018). Evaluating collaboration productivity in interdisciplinary product development. *Procedia CIRP*, *70*, 211–216. https://doi.org/10.1016/j.procir.2018.02.024

Smith, G. F. (2000). Too Many Types Of Quality Problems Categorizing your problems in solution relevant ways. Retrieved from www.quality-texas.org/wp-content/uploads/2014/11/Quality-process-problems.pdf

Thomas, F. S., Davis, R., & Howard, S. (1993). *An Ontology of Mechanical Devices*. https://doi.org/10.1.1.16.8107

Trevisan, L., Peruccio, P. P., & Barbero, S. (2018). From engineering to industrial design: Issues of educating future engineers to systemic design. *Procedia CIRP*, *70*, 319–324. https://doi.org/10.1016/j.procir.2018.02.014

Ullman, D. G. (2010). *The Mechanical Design Process*. *Mechanics of Materials McGraw-Hill Science-Engineering-Math*. https://doi.org/10.1017/CBO9781107415324.004

Ullman, D. G., & D'ambrosio, B. (1995). Taxonomy for classifying engineering decision problems and support systems. *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing*. https://doi.org/10.1017/S0890060400002742

Vegetti, M., Henning, G. P., & Leone, H. P. (2005). Product ontology: definition of an ontology for the complex product modelling domain. *2nd Mercosur Congress on Chemical Engineering 4th Mercosur Congress on Process Systems Engineering*, (September 2015), 1–10. Retrieved from http://www.enpromer2005.eq.ufrj.br/nukleo/pdfs/1016_productontology.pdf

Yuan, L., Liu, Y., Lin, Y., & Zhao, J. (2017). An automated functional decomposition method based on morphological changes of material flows. *Journal of Engineering Design*, *28*(1), 47–75. https://doi.org/10.1080/09544828.2016.1258459

Yuan, L., Liu, Y., Sun, Z., Cao, Y., & Qamar, A. (2016). A hybrid approach for the automation of functional decomposition in conceptual design. *Journal of Engineering Design*, *27*(4–6), 333–360. https://doi.org/10.1080/09544828.2016.1146237

Zhu, H., & Li, J. (2018). Research on three-dimensional digital process planning based on MBD. *Kybernetes*, *47*(4), 816–830. https://doi.org/10.1108/K-05-2017-0170