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A METHOD FOR REDUCING FUZZINESS AND ACCELERATING NEW PRODUCT MODELLING IN CAD: THE CASE OF DESIGN FOR MANUFACTURING

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ABSTRACT

Improvements in product development can increase the competitiveness of firms. However, new product development in CAD systems involves difficulties and uncertainties that increase along with the pressure to develop the products. A distinct characteristic of CAD modeling for new product development is its uncertainty. This is because the information is usually approximate and incomplete during CAD modeling. Thus, the main objective of this paper is to propose a robust and flexible CAD approach to reduce uncertainty and accelerate new product modeling in the context of design for manufacturing. This methodology permits the convergence towards different product forms depending on the selected manufacturing process. Application of this approach has shown that when uncertainty is high, approving a complete CAD modeling results in a delay in product development. In contrast, CAD modeling using fuzzy models results in a gain of valuable development time because the model is completed when knowledge about manufacturing technologies, company fit and capabilities, and markets is available.

Keywords: Computer Aided Design (CAD), New product development, Design for X (DfX), Fuzzy modeling

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1 INTRODUCTION

Companies have continuously maintained strong innovation objectives in the face of a globalized and extremely segmented market. This allows them to offer products with increasingly shorter lead times while maintaining the same quality, cost, and delivery criteria (Garro et al., 1998). This run to innovation is also due to heightened competition among companies in most industrial sectors. The time factor is an essential element in achieving vital advances over competitors.

Under these working conditions, efforts can be made to shorten lead times either in production systems or in product design. Therefore, the focus is on freeing up time for innovation through the rationalization of certain design engineering tasks, primarily by means of automation using computer-aided design (CAD) tools with controlled parameters. Since the 1980s, knowledge-based engineering (KBE) (Sriram et al., 1989) (Rezayat, 2000) has been one of the scientific fields that supported this approach (Danjou et al., 2008) (Verhagen et al., 2012). The purpose of KBE is to be able to recycle existing knowledge for incremental innovation and to develop new material for radical innovation (Cooper et al., 1999) (Van der Laan, 2008) (Un, 2010). Through this, it is possible to automatically generate technical solutions from existing databases that are kept constantly updated. The new product development (NPD) process, which integrates knowledge management (Hoegl and Schulze, 2005), is useful for solutions that are integrated into environments where parameters can be completely delineated.

NPD in CAD systems involves difficulties and uncertainties that increase along with the pressure to develop new products. Improving the speed of CAD modeling using well-developed roadmaps can give a powerful competitive advantage.

A distinct characteristic of CAD modeling for NPD is uncertainty. Information is usually approximate and incomplete during CAD modeling. Fuzziness comes from the uncertainty about customer requirements, production technologies to process the product, evolving markets and demands, company fit, and capabilities (Kim and Wilemon, 2002). To improve the likelihood of successful CAD modeling for NPD, it is necessary to determine the main specific requirements of the product and reduce uncertainty step by step during CAD modeling.

Although the need for fuzzy logic in the development of CAD systems was identified more than 20 years ago (Pham, 1998), fuzzy CAD modeling has, until recently, been a neglected topic. Although some research has been conducted to develop and integrate AI techniques to enhance the intelligent modeling capabilities of CAD systems (R.W. Mann and Coons, 1965; Brown and Chandrasekaran, 1983; Rao et al., 1993; Fougères and Ostrosi, 2018). (Regassa Hunde and Debebe Woldeyohannes, 2022) proposes a process of merging CAD, called model-based reasoning (MBR), which is based on a litterature review of the both domains. In this synthetis, they identify 5 features defining a MBR: (1) the product parts should be stored in a hierarchical manner in order to know their relationship; (2) it is the designing experts who provide the knowledge-based reasoning and decision-making procedure, (3) the reasoning and the methodology define the rules for links of product parts (4); the cumulative analysis of the qualitative and quantitative simulation defines the efficiency of the product analyzed; (5) easy installation procedure in the database. Therefore, the development of robust and flexible CAD methods for reducing fuzziness has not received the needed attention.

A robust method can reduce uncertainty by taking the necessary steps to minimize the undesired effects of uncertainty. On the other hand, a flexible method is characterized by the ability to adapt or react when necessary.

The purpose of this article is to present a CAD methodology for NPD in the context of design process-oriented manufacturing, called design for manufacturing (DfM). The main objective of this methodology is to propose a robust and flexible CAD approach for reducing uncertainty, in particular about the choice of the manufacturing process in the early steps of the design process. In this case, a company will be able to confront directly several manufacturing process without increasing the CAD modeling time. Moreover a company will be able to take the CAD models created in the first project by this method and reuse them in subsequent projects. Therefore, this approach will help companies not only to ensure robustness by reusing proven CAD models but also to save modeling time. Also, as stated earlier, the CAD model will be the backbone of the design process. That is, the CAD model will "grow up" over the course of the product's lifecycle, from the fuzzy front end to the detailed modeling steps.

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This paper is structured as follows: Sections 2 and 3 present the methodology and the development of the approach. Section 4 presents a case study to validate the approach. Lastly, the discussion and conclusion analyze and summarize the findings.

2 GENERAL METHODOLOGY

As stated in the introduction, the main objective of this paper is to present a CAD methodology used in the context of DfM. Since the emergence of the design rationale concept (Cross, 1994); (Lee, 1997) and the application of knowledge engineering to CAD systems (Chapman and Pinfold, 1999), there have been a large number of attempts to accelerate the completion of routine tasks in order to free up time for innovation. Some examples include the work of (Jauregui-Becker et al., 2009), who concentrated on automating routine design tasks. Likewise, since the 1980s, most studies on the integration of routine process automation into knowledge-based CAD systems through KBE (Sriram et al., 1989) have involved mechanical systems based on primitive solids that can be fully controlled. This has enabled the automation of some design actions. Examples of this include (Hunter et al., 2006), (Kulon et al., 2006), and (Gil et al., 2011). Successful experiments using this approach have used basic repetitive tasks and a relatively stable environment (Le Masson and McMahon, 2016).

Figure 1 shows the potential design approaches in advanced parametric CAD systems. The design approach 7, named full Intelligent Computer Aided Design represents the generic model. It is characterised by a full control of computers entities called agents. A fuzzy agent-based system for Fuzzy Intelligent Computer Aided Design is given as (Ostrosi et al., 2021), (Fougères and Ostrosi, 2013):

$$\widetilde{M}_{\alpha} = \langle \tilde{A}, \tilde{I}, \tilde{P}, \tilde{O}, \Phi_{\tilde{A}} \rangle, \tag{1}$$

where $\tilde{A}, \tilde{I}, \tilde{P}, \tilde{O}, and\, \Phi_{\tilde{A}}$ are a set of fuzzy agents, a set of fuzzy interactions between fuzzy agents, a set of fuzzy roles that fuzzy agents can perform, a set of fuzzy organizations defined for communities of fuzzy agents, and a set of functions of fuzzy agents' generation, respectively.

The definition of a fuzzy agent $\tilde{\alpha}_i$, whose behavior is of feedback loop type <perceive, decide, act> in a fuzzy context, is given as

$$\tilde{\alpha}_i = \langle \Phi_{\Pi(\tilde{\alpha}_i)}, \Phi_{\Delta(\tilde{\alpha}_i)}, \Phi_{\Gamma(\tilde{\alpha}_i)}, K_{\tilde{\alpha}_i} \rangle, \tag{2}$$

where $\Phi_{\Pi(\tilde{\alpha}_i)}, \Phi_{\Delta(\tilde{\alpha}_i)}$ and $\Phi_{\Gamma(\tilde{\alpha}_i)}$ are function of observation, function of decision, function of action, and knowledge of a fuzzy agent $\tilde{\alpha}_i$, respectively. This knowledge includes decision rules, objects, characteristics of the domain (for instance, the geometric and topological attributes), acquaintances, and dynamic knowledge $Ks_{\tilde{\alpha}_i}, Kcad_{\tilde{\alpha}_i}, Ke_{\tilde{\alpha}_i}$ (Figure 1).

$$\Phi_{\Pi(\tilde{\alpha}_i)}: \left(E_{\tilde{\alpha}_i} \cup I_{\tilde{\alpha}_i}\right) \times \Sigma_{\tilde{\alpha}_i} \rightarrow \Pi(\tilde{\alpha}_i), \tag{3}$$

where $E_{\tilde{\alpha}_i}$,$I_{\tilde{\alpha}_i}$,$\Sigma_{\tilde{\alpha}_i}$,$\Pi(\tilde{\alpha}_i)$ are the finite sets of observed events, interactions, states, and perceptions of a fuzzy agent $\tilde{\alpha}_i$, respectively.

$$\Phi_{\Delta(\tilde{\alpha}_i)}: \Pi_{\tilde{\alpha}_i} \times \Sigma_{\tilde{\alpha}_i} \rightarrow \Delta_{\tilde{\alpha}_i}, \tag{4}$$

where $\Pi_{\tilde{\alpha}_i}$,$\Sigma_{\tilde{\alpha}_i}$,$\Delta_{\tilde{\alpha}_i}$ are the finite sets of perceptions, states, and decisions of a fuzzy agent $\tilde{\alpha}_i$, respectively.

$$\Phi_{\Gamma(\tilde{\alpha}_i)}: \Delta_{\tilde{\alpha}_i} \times \Sigma_{\tilde{\alpha}_i} \rightarrow \Gamma_{\tilde{\alpha}_i} \tag{5}$$

where $\Delta_{\tilde{\alpha}_i}$,$\Sigma_{\tilde{\alpha}_i}$,$\Gamma_{\tilde{\alpha}_i}$ are the finite sets of decisions, states, and actions of a fuzzy agent, respectively.

The definition of a fuzzy interaction $\tilde{t}_l \in \tilde{I}$ between two fuzzy agents is given as

$$\tilde{t}_l = \langle \tilde{\alpha}_s, \tilde{\alpha}_r, \tilde{\gamma}_c \rangle, \tag{6}$$

where $\tilde{\alpha}_s$ is the fuzzy agent source of the fuzzy interaction;$\tilde{\alpha}_r$ is the fuzzy agent destination, and $\tilde{\gamma}_c$ is a fuzzy act of communication ($\tilde{\gamma}_c \in \tilde{\Gamma}$and $\tilde{\Gamma}$={inform, diffuse, ask, reply, confirm}).

In this paper, our approach is based on the model of the Design Approach 2, which allows the CAD designer to integrate the knowledge of multi-view experts through the CAD system.

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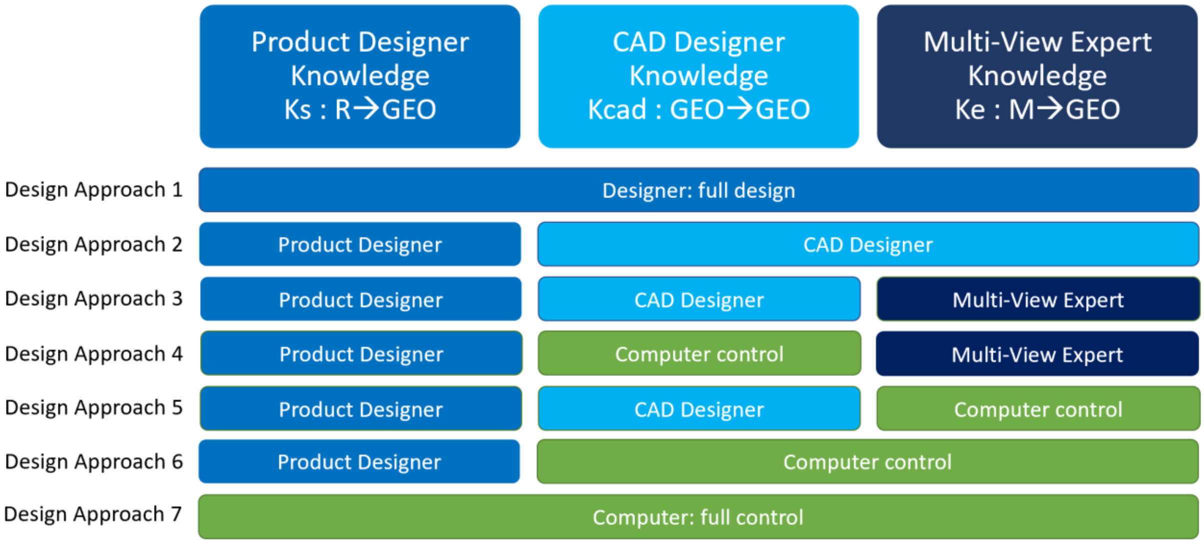

Figure 1. CAD model definition: Design approaches

In our approach, we are looking at existing methods and rules developed to support product designers to fulfil their requirements regarding a large number of different aspects, often addressed in the literature as design for X (DfX) (Gupta et al., 1997) (Lindemann, 2007). The manufacturing seems to be already taken into account as Design for Manufacturing - DfM. For example, other fields are using this approach, such as design for comfort (da Silva et al., 2012), ergonomics (Sang et al., 2013), acoustics and vibration reduction (Mohanty and Fatima, 2013), aesthetics (Bluntzer et al., 2014; Ranscombe et al., 2012), emotions (Herbeth and Blumenthal, 2013), and materials (Bluntzer et al., 2016).

When we focus on DfM, the main objectives of such approaches is to reduce the development time from the concept of the product to the manufacturable part, through a continuous improvement of the product and process. Therefore, a lot of method are developed in order to answer a specific kind of manufacturing process. For example, we can cite the additive manufacturing (Asadollahi-Yazdi et al., 2017), the machining processes (Aman et al., 2022), composite materials (Stojkovic and Butt, 2022) including defect prediction (Noevere et al., n.d.), plastic materials (Jha and Kumar, 2022) or assembly process (Bakhshi et al., 2022). We can also cite some works which exposes methodologies designing hybrid modular products. For exemple, (Kerbrat et al., 2011) see the product as 3D puzzles with modules., combining machining process and additive manufacturing.

However, the integration of specific CAD methodologies to support the DfM approach by confronting directly several manufacturing processin the early stages of the product design process has not beenproposed.

3 PROPOSED APPROACH

The inputs into the manufacturing view design process are the functional requirements and the fuzzy geometrical interfaces. Figure 2 illustrates our methodology.

- **Functional requirements.** Based on the specifications of the future product, the functional requirements are the characteristics needed to obtain the function in terms of its technical aspects, ergonomics aspects, styling aspects, etc.
- **Fuzzy geometrical interfaces.** Based on the specifications and the physical environment of the future product, this set is composed of simplified 2D and 3D features that represent the physical features of the interface with our future product.

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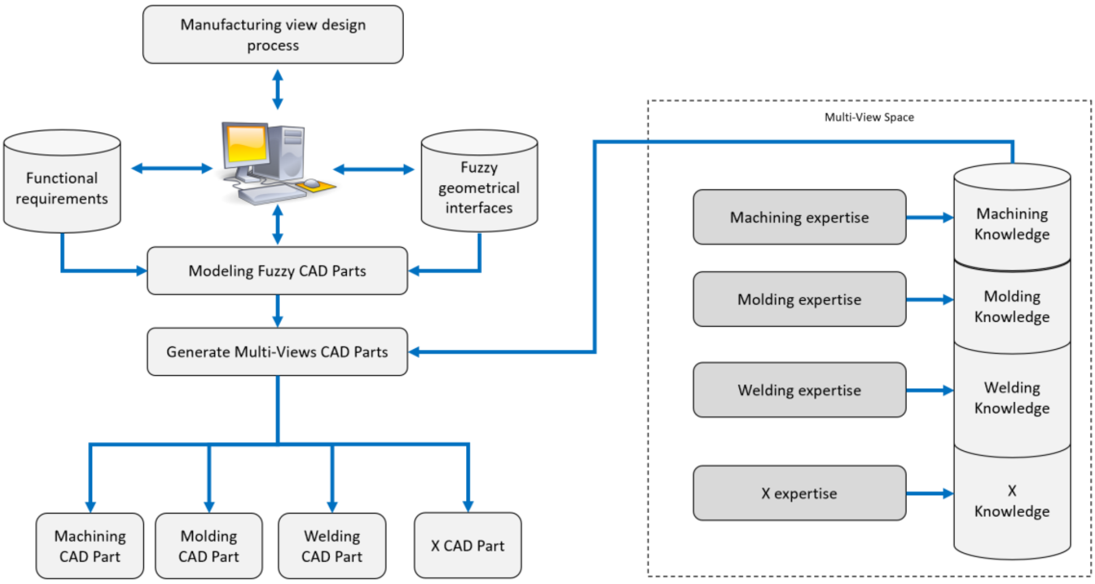

Figure 2. Manufacturing view design process

Phase 1. Modeling fuzzy CAD parts

This phase can be done at the early steps of the design process. The main objective is to generate a first CAD part containing the functional aspects of the future product. We need to extract the functional geometries in order to be in correlation with the technical specifications of the future product. This first model will be the "kernel" of our functional geometries.

Phase 2. Generate multi-view CAD parts

Based on the fuzzy CAD parts, the main objective is to generate a CAD model containing the expert aspects of the future product. We need to use the formalization of the expert rules in order to integrate it directly in the CAD model. For example, expert rules can be extracted from an expert area such as machining expertise, molding expertise, or welding expertise.

Figure 3 shows a simplified composition of multi-view CAD parts and how each expertise is abounded in the whole model.

Phase 3. Generate manufacturing CAD part

Through the multi-view CAD parts and the chosen manufacturing process, we are able to generate the good part automatically by switching from one process to another but without the need to redesign the process.

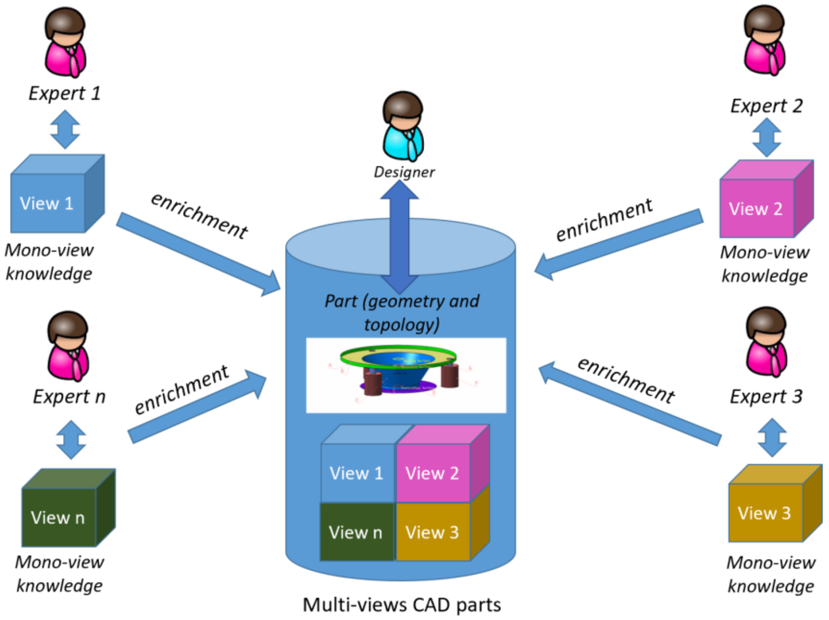

Figure 3. Multi-view CAD parts process

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4 APPLICATION

We will describe a case study for part of an oil pump. The selected part is a cover as shown in Figure 4.

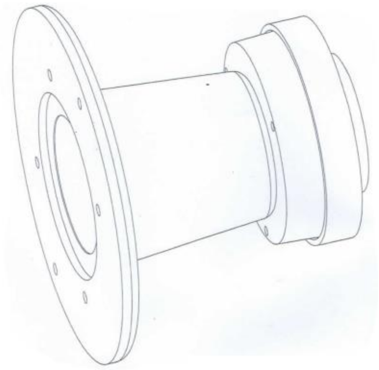

Figure 4. Oil pump with its cover

4.1 Functional requirements and fuzzy geometrical interfaces

The functional characteristics of the future product can be represented through a simplified section. In our example, first, we can define the functional surfaces that are the interfaces with the environment. Second, we can define the functional dimensions that will be set as parameters.

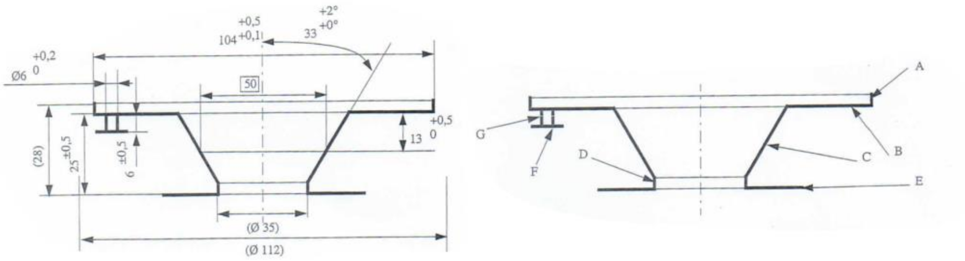

Figure 5. Functional parameters and surfaces

Figure 5 illustrates this section along with the functional geometries and parameters. Table 1 describes the retained surfaces.

Table 1. Definitions of the retained surfaces

Surface reference	Surface use	Surface categories
A	Cover cantering on the volute	Assembly help
B	Bearing surface on the volute	Bearing definition
C	Bounding surface of the volute	Assembly help
D	Joining surfaces between C and E	Assembly help
E	Bearing surface on the ventilation grill	Bearing definition
F	Bearing surface for assembly	Bearing definition
G	Bounding surface of the assembly screws	Bearing definition

4.2 Modeling fuzzy CAD parts

The main objective of this step is to propose to the designers a base for the detailed CAD model. Also, the fuzzy CAD part is considered as a CAD skeleton, which is built with specific constraints (Svensson et al., 2002). Many studies have already been carried out in skeleton-based modeling (Bley and Bossmann, 2006; Cluzel et al., 2012; Cornea et al., 2005; Lee et al., 2013; Ma and Choi, 2014; Ostrosi et al., 2020). Like the human body, where the skeleton holds muscles, a CAD skeleton holds the morphology, which is the topology-geometry (TG) of the future product. The main objective of the skeleton is to validate the major specification in the early phases of the CAD process, without wasting time to define a detailed CAD model, which will be a rework. The skeleton can be considered as a basic concept in CAD modeling of machines and mechanisms.

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Different types of skeletons and their roles in modeling have been introduced in CAD modeling: part skeleton, assembly skeleton, and motion skeleton. Depending on the level of conceptualization, these alternative solutions could be represented first as a simplified shape that is driven by material requirements and embeds the working principles.

Thus, in our approach, a simplified model, or a fuzzy CAD part, represents the functional parameters and surfaces of a part without the integration of the expert point of view. Figure 6 shows the simplified topology and morphology of the future part.

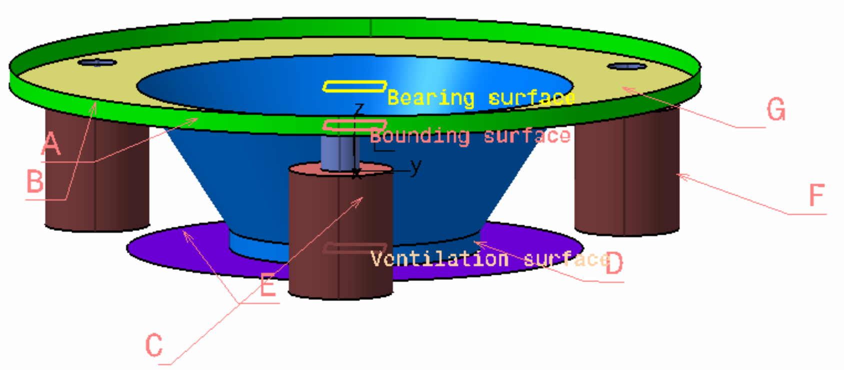

Figure 6. Fuzzy CAD part integrating functional parameters and surfaces

4.3 Manufacturing space: integrating expertise and knowledge

After the generation of a fuzzy CAD part, the final shapes of the future part can be directly generated on the bounding shapes by integrating the expert rules. Today, this step is done by an expert in direct collaboration with the CAD designer.

4.4 Modeling of CAD parts

Figure 7 shows an example of a fuzzy CAD part model completed by considering the knowledge of the machining view. The machining part model is an evolution of the fuzzy CAD part model by reducing the fuzziness. Similarly, Figure 8 shows the fuzzy CAD part model transformed into a stamping part, and Figure 9 shows the fuzzy CAD part model transformed into a moulding part.

5 DISCUSSION

Although the beginning fuzziness level is determined by the functional parameters (Table 1), the subsequent geometry is determined by internal and external developments, such as manufacturing technologies, company fit, capabilities, and markets.

When the fuzziness or the uncertainty is high—that is, when there are many unanswered questions in the design project—approving a complete CAD model will result in delays in product development. Application of the proposed approach has shown that CAD modeling using fuzzy models results in a gain of valuable development time because the model is completed when knowledge about manufacturing technologies, company fit and capabilities, and markets is available.

6 CONCLUSION

This paper presents a generic model for Fuzzy Intelligent Computer-Aided Design. A new CAD methodology for reducing fuzziness and accelerating new product modeling is then implemented. The main objective of this methodology is to propose a robust and flexible CAD approach by reducing uncertainty. The methodology is applied in the case of the DfM approach. The application has shown that a new part is driven by fuzzy functional parameters and fuzzy surfaces and is completed step by step using expert knowledge.

The beginning fuzziness level is determined by the functional parameters; the subsequent geometry is determined by manufacturing technologies. The fuzzy CAD part is completed according to expert knowledge when it is decided to process this knowledge based on a chosen technology. Thus, the concept of a multi-view CAD part as the output of a detailed design step is proposed and realized.

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Using this approach, we can conclude that the morphology of the part (geometry and topology) is driven by fuzzy functional parameters and fuzzy surfaces. As a result, depending on the selected manufacturing process, this methodology permits the convergence towards different product forms. Thus, the proposed method is robust because it can reduce uncertainty and is flexible because it is characterized by its ability to produce different morphologies.

As the generic model suggests, further developments include the development and the implementation of design approaches using fuzzy intelligent agent.

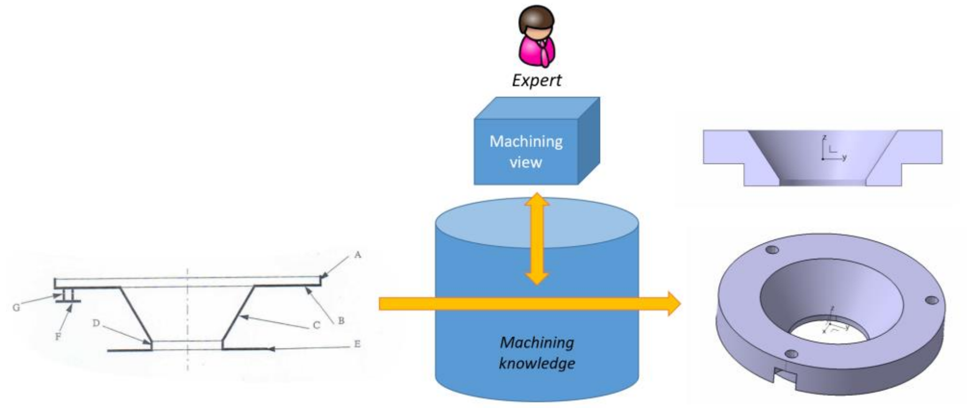

Figure 7. Machining-oriented part

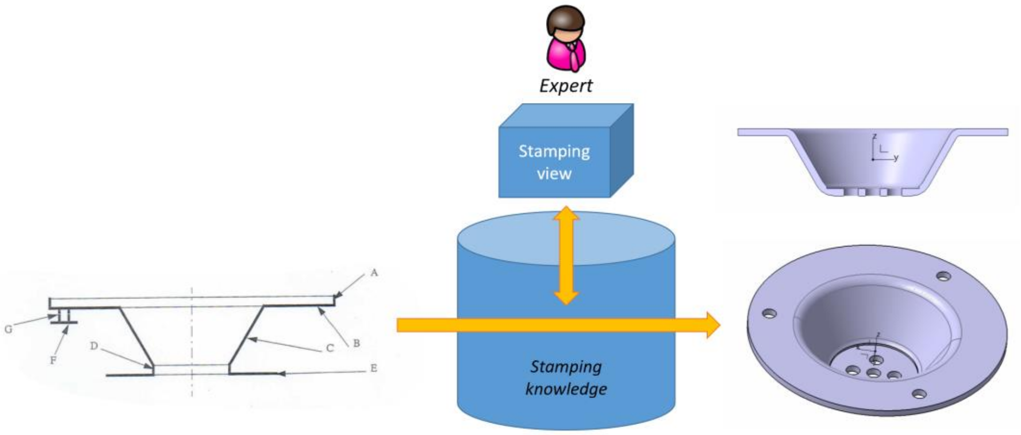

Figure 8. Stamping-oriented part

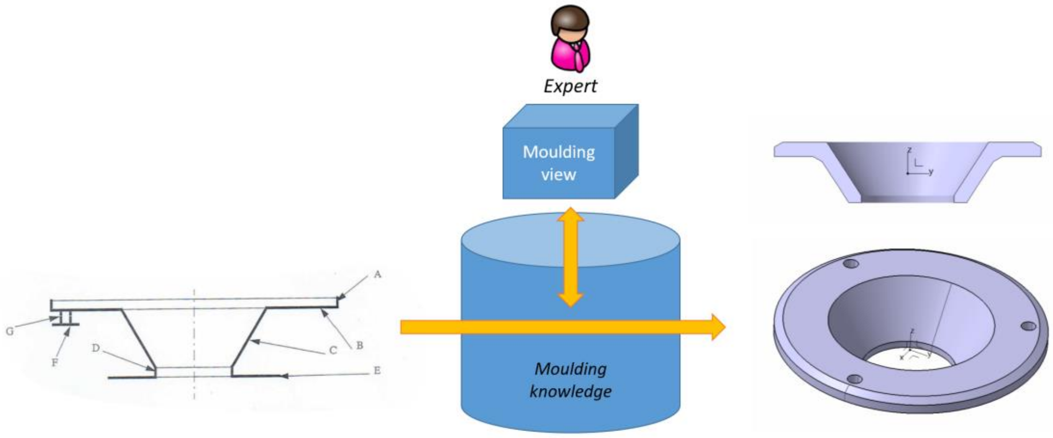

Figure 9. Moulding-oriented part

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REFERENCES

Aman, A., Bhardwaj, R., Gahlot, P. and Kumar Phanden, R. (2022), “Selection of cutting tool for desired surface finish in milling Machine using Taguchi optimization methodology”, Materials Today: Proceedings, https://dx.doi.org/10.1016/j.matpr.2022.10.253.

Asadollahi-Yazdi, E., Gardan, J. and Lafon, P. (2017), “Integrated Design for Additive Manufacturing Based on Skin-Skeleton Approach”, Procedia CIRP, Vol. 60, pp. 217–222, https://dx.doi.org/10.1016/j.procir.2017.02.007.

Bakhshi, S., Chenaghlou, M.R., Pour Rahimian, F., Edwards, D.J. and Dawood, N. (2022), “Integrated BIM and DfMA parametric and algorithmic design based collaboration for supporting client engagement within offsite construction”, Automation in Construction, Vol. 133, p. 104015, https://dx.doi.org/10.1016/j.autcon.2021.104015.

Bley, H. and Bossmann, M. (2006), “Automated Assembly Planning Based on Skeleton Modelling Strategy”, in Ratchev, S. (Ed.), Precision Assembly Technologies for Mini and Micro Products, Springer US, Boston, MA, pp. 121–131, https://dx.doi.org/10.1007/0-387-31277-3_13.

Bluntzer, J.-B., Ostrosi, E. and Niez, J. (2016), “Design for Materials: A New Integrated Approach in Computer Aided Design”, Procedia CIRP, Elsevier, Vol. 50 No. Supplement C, pp. 305–310.

Bluntzer, J.-B., Ostrosi, E. and Sagot, J.-C. (2014), “Car styling: a CAD approach to identify, extract and interpret characteristic lines”, Procedia CIRP, Vol. 21, pp. 258–263.

Brown, D.C. and Chandrasekaran, B. (1983), An Approach to Expert Systems for Mechanical Design., OHIO STATE UNIV COLUMBUS DEPT OF COMPUTER AND INFORMATION SCIENCE.

Chapman, C. and Pinfold, M. (1999), “Design engineering—a need to rethink the solution using knowledge based engineering”, Knowledge-Based Systems.

Cluzel, F., Yannou, B. and Dihlmann, M. (2012), “Using evolutionary design to interactively sketch car silhouettes and stimulate designer’s creativity”, Engineering Applications of Artificial Intelligence, Vol. 25 No. 7, pp. 1413–1424.

Cooper, S., Fan, I. and Li, G. (1999), Achieving Competitive Advantage through Knowledge-Based Engineering: A Best Practice Guide, Dept. of Enterprise Integration, Cranfield University, Cranfield [England].

Cornea, N.D., Silver, D. and Min, P. (2005), “Curve-skeleton applications”, VIS 05. IEEE Visualization, 2005., IEEE, pp. 95–102.

Cross, N. (1994), “Engineering Design Methods: Strategies for Product Design, 4th Edition | Wiley”, Wiley.Com, available at: https://www.wiley.com/en-us/Engineering+Design+Methods%3A+Strategies+for+Product+Design%2C+4th+Edition-p-9780470519264 (accessed 22 November 2022).

Danjou, S., Lupa, N. and Koehler, P. (2008), “Approach for Automated Product Modeling Using Knowledge-Based Design Features”, Computer-Aided Design and Applications, Vol. 5 No. 5, pp. 622–629, https://dx.doi.org/10.3722/cadaps.2008.622-629.

Fougères, A.-J. and Ostrosi, E. (2013), “Fuzzy agent-based approach for consensual design synthesis in product configuration”, Integrated Computer-Aided Engineering, Vol. 20 No. 3, pp. 259–274.

Fougères, A.-J. and Ostrosi, E. (2018), “Intelligent agents for feature modelling in computer aided design”, Journal of Computational Design and Engineering, Vol. 5 No. 1, pp. 19–40, https://dx.doi.org/10.1016/j.jcde.2017.11.001.

Garro, O., Brissaud, D. and Blanco, E. (1998), “Design Criteria”, IFAC Proceedings Volumes, Vol. 31 No. 15, pp. 743–748, https://dx.doi.org/10.1016/S1474-6670(17)40641-0.

Gil, M., Pokojski, J. and Szustakiewicz, K. (2011), “Extended KBE in Mechanical Engineering: Discussion of Concepts”, in Frey, D.D., Fukuda, S. and Rock, G. (Eds.), Improving Complex Systems Today, Springer, London, pp. 267–274, https://dx.doi.org/10.1007/978-0-85729-799-0_31.

Gupta, S.K., Regli, W.C., Das, D. and Nau, D.S. (1997), “Automated manufacturability analysis: A survey”, Research in Engineering Design, Vol. 9 No. 3, pp. 168–190, https://dx.doi.org/10.1007/BF01596601.

Herbeth, N. and Blumenthal, D. (2013), “Product appraisal dimensions impact emotional responses and visual acceptability of instrument panels”, Food Quality and Preference, Vol. 29 No. 1, pp. 53–64, https://dx.doi.org/10.1016/j.foodqual.2013.02.003.

Hoegl, M. and Schulze, A. (2005), “How to Support Knowledge Creation in New Product Development:: An Investigation of Knowledge Management Methods”, European Management Journal, Vol. 23 No. 3, pp. 263–273, https://dx.doi.org/10.1016/j.emj.2005.04.004.

Hunter, R., Rios, J., Perez, J.M. and Vizan, A. (2006), “A functional approach for the formalization of the fixture design process”, International Journal of Machine Tools and Manufacture, Vol. 46 No. 6, pp. 683–697, https://dx.doi.org/10.1016/j.ijmachtools.2005.04.018.

Jauregui-Becker, J.M., Tragter, H. and van Houten, F.J.A.M. (2009), “Structure and models of artifactual routine design problems for computational synthesis”, CIRP Journal of Manufacturing Science and Technology, Vol. 1 No. 3, pp. 120–125, https://dx.doi.org/10.1016/j.cirpj.2008.10.002.

Jha, N.K. and Kumar, V. (2022), “Design and Analysis of Injection Mold for Plastic Rivet with Buttress Thread Profile: DFM Approach”, CVR Journal of Science and Technology, Vol. 22 No. 1, pp. 84–89.

https://doi.org/10.1017/pds.2023.27 Published online by Cambridge University Press

Kerbrat, O., Mognol, P. and Hascoët, J.-Y. (2011), “A new DFM approach to combine machining and additive manufacturing”, Computers in Industry, Vol. 62 No. 7, pp. 684–692, https://dx.doi.org/10.1016/j.compind.2011.04.003.

Kim, J. and Wilemon, D. (2002), “Focusing the fuzzy front–end in new product development”, R&D Management, Vol. 32 No. 4, p. 269.

Kulon, J., Broomhead, P. and Mynors, D.J. (2006), “Applying knowledge-based engineering to traditional manufacturing design”, The International Journal of Advanced Manufacturing Technology, Vol. 30 No. 9, pp. 945–951, https://dx.doi.org/10.1007/s00170-005-0067-0.

Le Masson, P. and McMahon, C. (2016), “XXX. Armand Hatchuel et Benoit Weil. La théorie C-K, un fondement formel aux théories de l’innovation”, Les Grands Auteurs en Management de l’innovation et de la créativité, EMS Editions, Caen, pp. 587–613, https://dx.doi.org/10.3917/ems.burge.2016.01.0587.

Lee, J. (1997), “Design rationale systems: understanding the issues”, IEEE EXPERT, p. 8.

Lee, J., Son, H., Kim, C. and Kim, C. (2013), “Skeleton-based 3D reconstruction of as-built pipelines from laser-scan data”, Automation in Construction, Elsevier, Vol. 35, pp. 199–207.

Lindemann, U. (2007), “A Vision to Overcome ‘Chaotic’ Design for X Processes in Early Phases”, DS 42: Proceedings of ICED 2007, the 16th International Conference on Engineering Design, Paris, France, 28.-31.07.2007, pp. 231-232 (exec. Summ.), full paper no. DS42_P_320.

Ma, J. and Choi, S. (2014), “Kinematic skeleton extraction from 3D articulated models”, Computer-Aided Design, Elsevier, Vol. 46, pp. 221–226.

Mohanty, A.R. and Fatima, S. (2013), “An Overview of Automobile Noise and Vibration Control”, Noise & Vibration Worldwide, SAGE Publications, Vol. 44 No. 6, pp. 10–19, https://dx.doi.org/10.1260/0957-4565.44.6.10.

Noevere, A., Collier, C., Harik, R. and Halbritter, J. (n.d.). “Development of a Design for Manufacturing Tool for Automated Fiber Placement Structures”, AIAA Scitech 2019 Forum, American Institute of Aeronautics and Astronautics, https://dx.doi.org/10.2514/6.2019-0520.

Ostrosi, E., Bluntzer, J.-B. and Stjepandic, J. (2020), “A CAD Material Skeleton-Based Approach for Sustainable Design”, https://dx.doi.org/10.3233/ATDE200133.

Ostrosi, E., Fougères, A.-J., Zhang, Z.-F. and Stjepandić, J. (2021), “Intelligent modular design with holonic fuzzy agents”, Advances in Manufacturing, Vol. 9 No. 1, pp. 81–103, https://dx.doi.org/10.1007/s40436-020-00331-0.

Pham, B. (1998), “Fuzzy Logic Applications in Computer Aided Design”, in Reznik, L., Dimitrov, V. and Kacprzyk, J. (Eds.), Fuzzy Systems Design: Social and Engineering Applications, Physica-Verlag HD, Heidelberg, pp. 73–85, https://dx.doi.org/10.1007/978-3-7908-1885-7_5.

Ranscombe, C., Hicks, B. and Mullineux, G. (2012), “A method for exploring similarities and visual references to brand in the appearance of mature mass-market products”, Design Studies, Vol. 33 No. 5, pp. 496–520.

Rao, M., Wang, Q., Yuan, L. and Zuo, M. (1993), “Framework of computer integrated process systems”, Proceedings of IEEE International Conference on Control and Applications, presented at the Proceedings of IEEE International Conference on Control and Applications, pp. 697–702 vol.2, https://dx.doi.org/10.1109/CCA.1993.348322.

Regassa Hunde, B. and Debebe Woldeyohannes, A. (2022), “Future prospects of computer-aided design (CAD) – A review from the perspective of artificial intelligence (AI), extended reality, and 3D printing”, Results in Engineering, Vol. 14, p. 100478, https://dx.doi.org/10.1016/j.rineng.2022.100478.

Rezayat, M. (2000), “Knowledge-based product development using XML and KCs”, Computer-Aided Design, Vol. 32 No. 5, pp. 299–309, https://dx.doi.org/10.1016/S0010-4485(00)00013-0.

R.W. Mann and Coons. (1965), Computer-Aided Design, McGraw-Hill Book Co., New York, NY, USA.

Sang, C.L., Ren, J.D., Liu, Y.Q., Mi, M.D., Li, S.H. and Gao, X.X. (2013), “Development of an Adjustable Physical Mockup Used for Design Validation of Passenger Car Ergonomics and Interiors”, Advanced Materials Research, presented at the Advances in Materials Science and Engineering, Trans Tech Publications Ltd, Vol. 650, pp. 698–704, https://dx.doi.org/10.4028/www.scientific.net/AMR.650.698.

da Silva, L., Bortolotti, S.L.V., Campos, I.C.M. and Merino, E.A.D. (2012), “Comfort model for automobile seat”, Work, Vol. 41, pp. 295–302, https://dx.doi.org/10.3233/WOR-2012-0172-295.

Sriram, D., Stephanopoulos, G., Logcher, R., Gossard, D., Groleau, N., Serrano, D. and Navinchandra, D. (1989), “Knowledge-Based System Applications in Engineering Design: Research at MIT”, AI Magazine, Vol. 10 No. 3, pp. 79–79, https://dx.doi.org/10.1609/aimag.v10i3.758.

Stojkovic, M. and Butt, J. (2022), “Industry 4.0 Implementation Framework for the Composite Manufacturing Industry”, Journal of Composites Science, Multidisciplinary Digital Publishing Institute, Vol. 6 No. 9, p. 258, https://dx.doi.org/10.3390/jcs6090258.

Un, C.A. (2010), “An empirical multi-level analysis for achieving balance between incremental and radical innovations”, Journal of Engineering and Technology Management, Vol. 27 No. 1, pp. 1–19, https://dx.doi.org/10.1016/j.jengtecman.2010.03.001.

Van der Laan, A.H. (2008), “Knowledge based engineering support for aircraft component design”.

Verhagen, W.J.C., Bermell-Garcia, P., van Dijk, R.E.C., and Curran, R. (2012), “A critical review of Knowledge-Based Engineering: An identification of research challenges”, Advanced Engineering Informatics, Vol. 26 No. 1, p. 5.

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