J. Pokojski et al. (Eds.)

doi:10.3233/ATDE200122

Robust CAD Modelling: Concepts and Principles for Industrial Applications

Egon OSTROSI[a,1], Josip STJEPANDIĆ [b] and Žarko TOMASIĆ [c]
[a] *ERCOS/ELLIADD EA4661, Univ. Bourgogne Franche-Comté, UTBM, F-90010 Belfort, France*
[b] *PROSTEP AG, Germany*
[c] *Croatian Academy of Sciences and Arts in Diaspora and Homeland (HAZUDD), St. Gallen, Switzerland*

Abstract. During product design, when many design aspects still must be understood by the design team, it is necessary to apply robust modelling approaches in order to describe the properties of the product according to the functional requirements, employing CAD system. High sensitivity to change of a CAD model can lead to unstable and unpredictable model behaviour which hinders the daily work of engineers and causes significant rework in downstream stages. Engineers need a methodology which enables them to evaluate and reduce the geometrical sensitivity of a product assembly, what the sources of variation are, their importance for the overall robustness and in what order to improve the overall design. Robustness is meant that the model structure is adjusted to react less sensitive to changes in design and model update. Robust CAD models are suitable for both downstream processes and collaboration. In this paper, we illuminate the background of CAD modelling and introduce the term robust modelling for the industrial purpose. We highlight the specific needs and expectations of the manufacturing industry. In a practical study, the application of robust modelling is shown in the design of complex machines.

Keywords. CAD, Parametric modelling, Robust modelling

Introduction

CAD systems have become indispensable tools in the product development of discrete products. As standard, modern 3D CAD systems are used as authoring tools for the design of products on a scale from screw to airplane [1]. The market is dominated by a dozen CAD systems that are usually fully integrated into holistic Product Lifecycle Management (PLM) concepts [2]. Sophisticated application methods have been developed for high-end CAD systems that need to be learned in weeks-long training courses. However, it is worth the effort because professional CAD application is an engineer's skill that has a significant impact on product development productivity [3]. This is not just about learning certain CAD functions and modules, but also about generating CAD models according to the process requirements so that they can be used without rework in the downstream processes in the entire supply chain [4]. The process compatibility of the CAD models can be assessed using various metrics [5].

[1] Corresponding Author, Mail: egon.ostrosi@utbm.fr.

The provision of high-quality CAD data for downstream processes is the prerequisite for the process integration in the manufacturing supply chain [6]. The fundamental vision seeks to achieve a continuous flow of information in all stages of the product lifecycle [7]. This vision affects three layers as illustrated in Figure 1. Integration is a widely requested "digital data" lever for digital transformation. It describes a product holistically with (1) domain-specific application models. It demands cohesive communication in the (2) supply chain based on CAx data streams with partners, in joint ventures and across factory plants [8]. It finally realizes (3) a fusion between up and downstream in the entire lifecycle, where digital aspects of the product solely are used as engineering, manufacturing and service bridges [6].

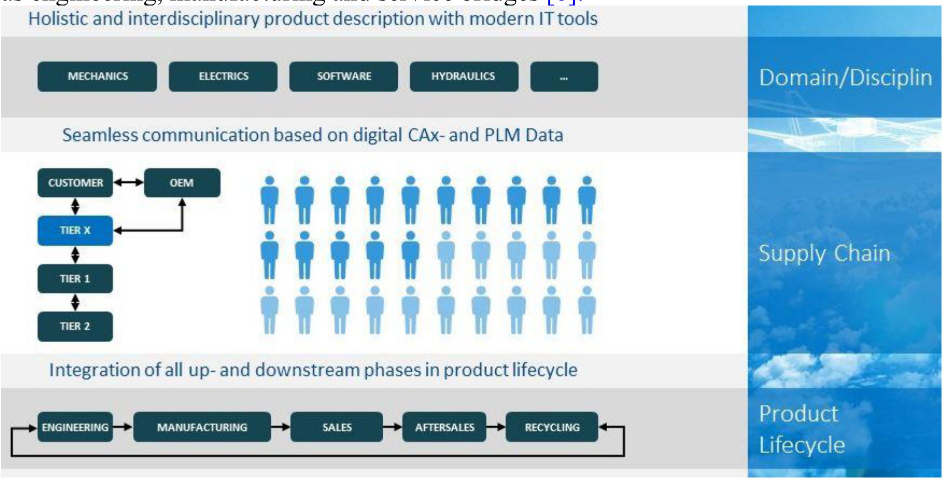


Figure 1. The integration vision in the automotive industry [6].

Thus, thanks to the consideration of inputs coming from the different disciplines, a CAD model as a multi-view object requires interdisciplinary engineering. Indeed, during the design process in the product lifecycle, a CAD model is subject of a frequent change by many stakeholders. The collaboration of various stakeholders with different points of view can lead to conflicts and misunderstandings due to, for instance, differences among domains' vocabulary [9]. Therefore, cross-modification is an important property of CAD designs. This is, in particular, the case if the CAD entities with the content of knowledge are used such as a Knowledge-based Engineering (KBE) template [10]. During the CAD design process, a tremendous issue can occur for every designer how to improve the efficiency of modification in the product design and avoid the model failure from a weak design procedure [11][12]. Several reports have been published to provide a robust design method [13][14]. It shortens the period of subsequent improvements effectively and assures product updating [15][16][17]. From this perspective, CAD modelling should reformulate its basic concepts in order to take into account the problems raised in this interdisciplinary perspective. Coping with complexity in the CAD modelling and in its conceptualization implies first to enlighten concepts and principles generally hidden in the industrial practice that can lead to a robust modelling.

The remainder of this paper is structured as follows: Section 1 provides an insight into the background of robust modelling, followed by section 2, where the conceptual principles are presented. In section 3 the method and principles of modular design are highlighted. The practical procedure is presented in section 4, followed by conclusions and outlook in section 5.

1. Background

A CAD model is a meaningful engineering representation of some product that is to be produced. A CAD model can be traced to the functional requirements and can be assessed for quality against predefined criteria. The robust product modelling consists largely of three activities: Architectural modelling, detailed component modelling and model testing [18][19]. The input into the CAD modelling is the functional model, a description of what the product is supposed to do. During CAD modelling, the functional specifications are transformed into CAD models that describe the details of the data structures, product architecture, interface, and components. The output is the CAD model which describes how the product is to achieve its functions. Essentially each CAD model produces a product.

In many development projects, CAD modelling is still an adhoc process. Normally the requirements, usually expressed in natural language, are used to make an informal design. Words have definitions but, at the same time, have no clear-cut boundaries to their meanings. In natural language, the capacity for many possible meanings is intrinsic, and the unfolding form has fuzzy boundaries and many possibilities for meaning. During CAD modelling, typically, there is little or no formal change control or design management. Thus, by the time the implementation is complete, the design has usually changed so much from the initial specifications that the original functional specification document becomes an incorrect and incomplete description of the product. Therefore, the control loop is necessary: *chaining from requirements to the CAD model*. It also means expanding this process through formalization a language of specification suitable for CAD modelling. Again the emphasis is on quality which can be checked easily [5].

The CAD modelling process is very important because it is the only phase in which the functional requirements can be accurately translated into a finished product. CAD modelling serves also as the foundation for all product engineering steps that follow regardless of which process model is being employed. Without a proper CAD modelling, we risk designing an unstable product: one that behaviour is unpredictable during changes. Or the design is a change process, one that may be difficult to test, one whose overall quality cannot be assessed until late in the production process. Each design product is reviewed for quality before moving to the next phase of product development [20]. Quality refers to both internal (e.g. modularisation) and external (visible to the other applications: e.g. Manufacturing or Finite Element Analysis.). As a consequence: a substantial rework later in the process chain could be imposed by unstable models [12].

CAD modelling assistance, as well as the translation of technical texts into the form of semi-formal or formal diagrams, can be achieved by a process of semantic analysis and representation of these texts, using previously acquired linguistic and conceptual knowledge. To analyse is to construct successive formal representations more or less dependent on a set of statements, which are, then, translated into computational treatments. Analysis modelling uses a combination of text and diagrammatic forms to depict the requirements for data, function and behaviour in a form that is relatively easy to understand, and more importantly, straightforward to review for correctness, completeness and consistency. Analysis modelling involves: a) Data modelling which defines data objects (Morphology, Material etc…) attributes (dimensions etc…) and relationships (surface, volume, speed…); b) Functional modelling, which describes how information is transformed within each module using design parameters and c) Behavioural Modelling which depicts the impact of events on the product. In essence behavioural models are used to describe the overall behaviour of the product and may use Finite Element Analysis (FEA), Failure Modes and Effects Analysis (FMEA) or Product Risk Management.

The afore-mentioned design activities essentially form four main areas of concern for designers which are: *data model*, *architectural model*, *interface model* and *component model*. In the case of an existing product, the outputs of analysis modelling are transmitted to each to each model in CAD-BOM. In the case of a new product, CAD-BOM is also created from the outputs of the analysis modelling. Thus modelling results can be classified as follows: a) *Data CAD model* which are created by channelling or transforming the function model (functional requirements) into data structures required to model the product (attributes and relationships); b) *Architectural CAD model* which defines the relationships among the structural elements of the product; it is derived from the product specifications, the analysis model (graphs, diagrams), and the interactions of the components defined in the analysis model; c) *Interface CAD model* which describes how the product elements communicate with each other, with other products, the data flow provides much of the necessary information and d) *Component CAD model* which is created by transforming the structural elements defined by the product architecture into CAD descriptions of product components.

The use of structured methods normally involves the use of graphical system models and results in a large amount of design documentation. The use of CASE tools make this process easier, results in cost reductions and because they use standard notations, it ensures that standard design documentation is produced. A structured method includes a design process model, notations to represent the design, report formats, rules, and design guidelines [21]. A given method may use one or more of the following models to represent the system: a) Data-flow model – where the system is modelled using the data transformations which take place as it is processed; b) Entity-Relationship model – describes the basic entities in the design and the relationships between them. These are popular with Database system design; c) Structural model – documents system components and their interactions; d) Object-Oriented Model – UML; e) State Transition diagrams – Models how the system reacts to (external) events.

Data-flow diagrams (DFD) are used to describe primarily data-driven systems. They are controlled by the data inputs to the system with very little external event processing. System-flow diagrams (SFD) are used to represent event-driven systems (e.g. real-time) where there is minimal data processing. In some instances, one may have to use both types of models.

2. Conceptual principles

Robust CAD modelling should satisfy many criteria (Table 1). Furthermore, consistency and completeness should characterise a robust CAD modelling. Consistency across design means that all CAD models should be carried to the same depth level. Though product modelling is the result of a team of designers, it should exhibit uniformity. It means that CAD interfaces between CAD modules should be well defined and the product should look like it was designed by one individual. Also, CAD architectural structure should describe the relationship between modules and components that exhibit independent functional characteristics i.e. low coupling and high cohesion. Completeness means that a CAD model should be rational and complete, which signifies that all requirements are accounted for and all CAD models are carried to its rational completion, to the same depth level.

Table 1. Criteria for robust modelling.

Criteria and explanation
Traceability: should be traceable and connected to the analysis model.
Multi-views: should consider design multi-views (assembly, maintenance, materials…etc) that is, should not suffer from the tendency to focus exclusively on a single or limited view.
Conformity virtual-real: should maximise the conformity between the CAD model and the physical solution as it exists in the real world.
Uniformity and integration: should exhibit uniformity and integration.
Stability: should be structured to provide stable changes coming from the variation of functional requirements.
Quality:should be assessed for quality as it is being created.
Rationality: should be assessed for rationality: every CAD element should justify its existence.
Semantic content: should minimize semantic errors.

Ideally, a CAD model should be self-sustaining. CAD modularity is a way in which a product and its model can be designed such as they are self-sustaining, self-standing and suited for integration. Hence, a CAD model is divided into separately named and addressable components called modules that are integrated to satisfy design requirements. These CAD models should be capable of adapting to new design situations. CAD models are adaptive if they are composed of modules whose self-existence enhances the probability of the integration, survival and diversification. In CAD modelling, another motivation for the modularization comes from the fact that a designer cannot easily manage large CAD models comprised of a single module as the number of variables, control paths and complete complexity would make understanding virtually impossible. Consequently, a modular approach would allow for the CAD model to be intellectually manageable.

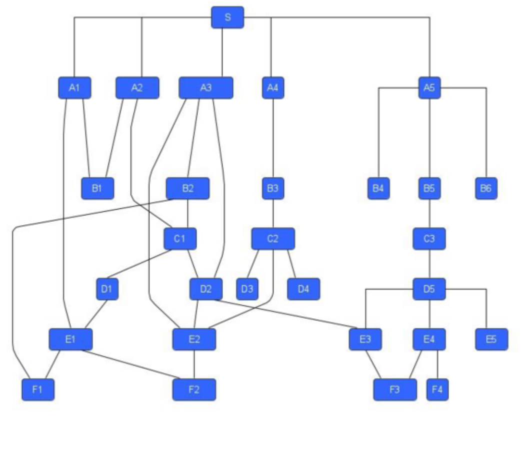
CAD model	Control Indicators
	*The span of control*: number of levels of control within a CAD model; *Depth*: the distance between the top and bottom modules in CAD model structure; *Fan-out*: number of modules directly controlled by a particular module. It represents the number of inter-modular flow out of a model; *Fan-in*: number of modules that depend on a particular module. It represents the number of inter-modular flow into a CAD model; *Connectivity*: the set of CAD components that are related directly by a given CAD component; *Indirect Connectivity*: the set of CAD model components that may be related by a given CAD component.

Figure 2. Tree diagram of CAD model and Indicators.

However, one cannot subdivide CAD product indefinitely to make the effort required to understand or develop it negligible [22]. This is because as the number of increases (causing the effort to develop them to decrease), the effort (cost) of the associated integration process increases. The main principles for CAD modularity are: a) Modular decomposability - provides systematic means for breaking product into modules; b) Modular composability - supports adaptability, reuse and integration of existing modules in new systems; c) Modular understandability - module can be understood as a stand-alone unit; d) Modular continuity - side-effects due to module changes minimised; e) Modular protection - side-effects due to processing errors minimised.

CAD modelling deals with changes – changes in product morphology, changes in product behaviour. Smooth and continuous changes should be planned. Abrupt changes, followed often by the destruction and the redefinition of the whole model, should be avoided. Therefore, CAD modelling should clearly define the scope of the effect of all modules. The scope of the effect of a module is defined as all the other modules that are affected by a decision made by that module. During the progress of the CAD model, several control indicators need to be continuously monitored (Figure 2).

3. CAD Modular Design and Complexity

The aim of CAD modular design is high cohesion and low coupling which ensure the functional independence of modules. The cohesion of a CAD model of a module measures the degree of relatedness of functions within the module. It gives the qualitative indication of the degree to which a module focuses on just one function or task. A cohesive module performs ideally a function. Coupling expresses the qualitative indication of the degree to which a module is connected to other modules. Coupling measures also the relative interdependence among functions. A CAD modelling method is proposed for successful modular design (Figure 3). It comprises the principle of decomposition-composition (modules may be exploded e.g. one becomes two modules or imploded to reduce coupling and improve cohesion) and the principle of factoring: determining what properties belong to a given module and closely related properties should be grouped together .

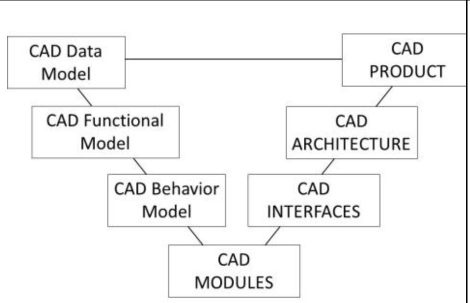
<table>
<tr><th>Proposed CAD modular design method</th><th>Rules for modular design</th></tr>
<tr><td>
</td><td>(a) define modules whose function is controlled from functional requirements;
b) ensure controlled entry modules from functional requirements, avoid uncontrolled connection e.g. uncontrolled relationships into another CAD module;
c) keep the scope of effect of a module within the scope of control for that module defined from functional requirements;
d) design and evaluate module interfaces to reduce complexity and improve consistency;
e) optimize the number of fan-out and fan-in.</td></tr>
</table>

Figure 3. Proposed CAD Modualr Design.

Models should be continuously tested and evalauted during CAD modelling to ensure that the functional specifications have been accurately and completely incorporated into the design [5]. The quality of the CAD model depends strongly on its complexity. Coupling and cohesion are two functional characteristics which impact the complexity of a CAD model. Functional coupling and functional cohesion are two metrics to measure the complexity of a CAD model (e.g. module or component) defined as:

Functional coupling = (number of inter-signature)/(total number of data signature)
Functional cohesion = (number of data signature)/(total number of data signature)

where: a *data signature* is any occurrence of elements (geometry and constraints) in a model; a *feature* within a model is the collection of all the elements that can affect the values of some function of interest; a *data feature* is the collection of all the data signature in the feature that will affect a specific function of interest; an *inter-signature* are the data signature in the model that lies in more than one data feature.
Other metrics vocabulary complexity, which measures the volume and the effort of the CAD model implementation can be introduced to measure the complexity of the CAD model. To measure the control flow and the inter-modular flow in a CAD model, the cyclomatic complexity and information flow complexity can be used. Cyclomatic complexity depends on the number of CAD elements and its topology.

4. Practical procedure

The robustness of a CAD model needs to be incorporated from the first sketch on, avoiding an unstable model basis. Otherwise, the time saved upfront by fast, "free" modelling by generating a flow of features in an intuitive, creative, but arbitrary order is eventually spent later by either a lower ability for collaborators to interrogate and rework models due to unclear design intent, or a lower changeability of the model by many failures which occur during an update on changes because such a model is not stable enough. A practical example is the design of complex industrial equipment such as production lines [23]. The implementation of a new production line for innovative composite boards starts with the analysis of customer-specific data and customer production requirements which lead to a 2D layout (Figure 4). With these defined processes and created functional sketches, the individual machines are implemented by 3D CAD modelling. The production possibilities of individual manufacturing companies are taken into account, such as, for example, the bending machine and tools, cutting equipment and in the CAD software some settings are already taken into account (Figure 5). The 3D data obtained from individual machine components are read directly in the production machine without further processing and automatically translated into machine language. This saves programming time and machine changeover time, and the components can be quickly and productively produced.
Basically, there are few approaches to implement or facilitate robust modelling: modular structure (1), use of component interfaces (2) and intelligent naming (3).

4.1. Modular structure

Modular structure (1) can be achieved in different ways [24]. A CAD system-independent method basically combines multiple, simple (10 – 15 entities) sketches with just a few references as a basis for features in a model tree which propagate the parameters and describe the progression of the design. In such a way, the sketches control the features. Otherwise, sketches become unruly and hard to modify. Keeping sketches lean helps avoid model failures in case of change and update. At general, chamfer or blend features should be added afterwards, outside the sketch to don't impact the model basis. This detail geometry should not impact the structure of the model and can be easily suppressed or excluded when the model needs to be simplified. Alternatively, a model can be created with the fewest number of features possible which provides a flat, robust structure with a low number of interdependencies. The drawback of this approach is that each of these features tends to get more and more complex. The robustness issue is moved to such features which are difficult to modify due to the unpredictable model behaviour. Their design intent is not obvious. If features are subdivided based on their function, the model tree becomes more clear.

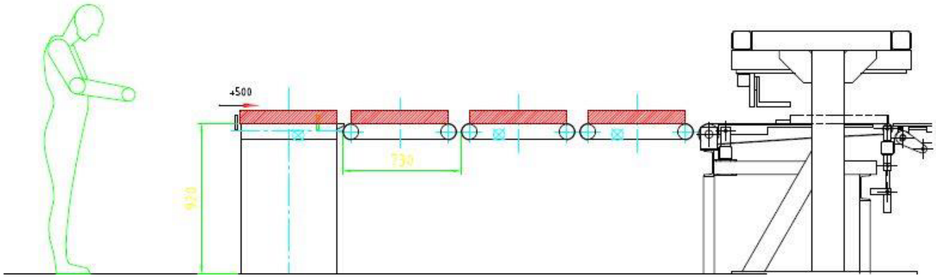


Figure 4. Sketch of the modular structure.

4.2. Use of component interfaces

Use of component interfaces (2) describes an approach to assemble predefined library components which can be singular features or patterns of features (transversal, circular etc). This can drastically reduce the number of references and constraint, and, therefore, increase the stability of the model. Such an approach impose a significant pre-work in the creation of a library and its elements. At general, interfaces require adaption of each library component. On the other side, less experienced users get a good hint to deal successfully with such designs. It can be combined with the publish function which exists in all leading CAD systems and provides just an explicit part of a CAD model or a feature to be used as a reference od constraint. This is particularly beneficial either to share the same geometry in multiple downstream components or to distribute such geometry with an owner of the source geometry among team members in a concurrent engineering team. The published geometry is set to read-only and an invariant which improves the model robustness.

4.3. Intelligent naming

With intelligent naming (3) an advanced technique is meant to give appropriate names to the generic names. It can be used additionally to support both previous approaches in order to achieve better transparency of complex CAD models. If the user omits to define his own nomenclature, the model tree becomes a mess of generic features which are hard to distinguish and, therefore, hard to edit because no one can recall singular one. Such a circular renaming can be supported by macros. Additional way to mark features is to use annotations which are available in all CAD systems. This can help to later identify the function of a feature or group of features. Use of groups and layers can also improve the readability of a CAD model. Depending on the CAD systems, groups can be built according to several criteria (function, reference, entity). Grouped features must be sequential in the tree.

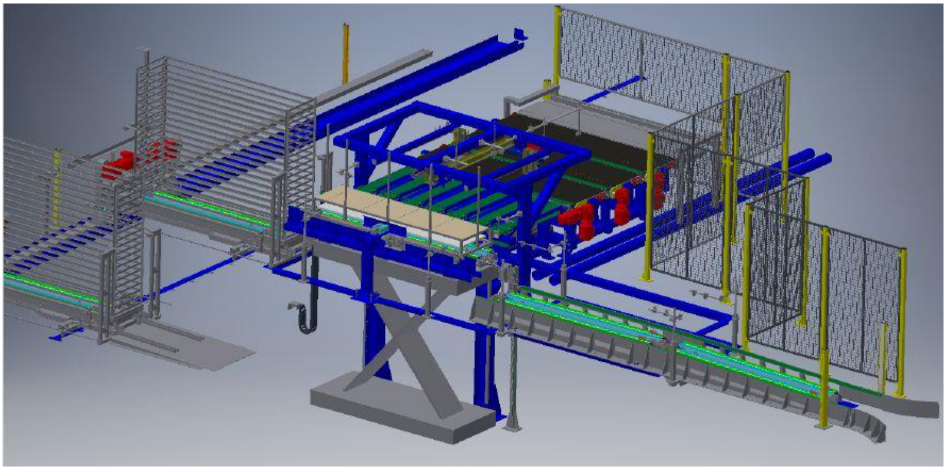


Figure 5. CAD model of the complete machine.

5. Conclusions and outlook

The article presented here has illustrated how robust modelling is a substantial method of CAD design and can be achieved efficiently by applying appropriate techniques. It was explained how the required input parameters impact the design process. Conceptual principles of modelling were analyzed too. Afterwards, the whole process with quality metrics was explained in detail. Impact factors for effective modular design were described. Such improved process reduces the effort to generate CAD models so that the utilization can be beneficial for downstream processes in the supply chain [23]. It is important to say that such generic approaches basically don't require specific CAD licenses and, therefore, can be included in the basis of CAD training. Most recommendations are CAD system independent.

Practical application was demonstrated based on complex industrial equipment (product line for composite boards). Based on robust modelling, various methods of detail design can be implemented e.g. high-fidelity definitions of aircraft external shapes [26]. This approach also emphasizes the role of the object-oriented approach and of well-established software design patterns in the development of a modular software library independent of low-level geometric modelling kernels. This can enhance modularity further.

Robust modelling is a good basis for further process improvements. The use of intelligent templates, on the one hand, achieved a high degree of automation and on the other hand, created the possibility of expanding the CAD environment for specific downstream processes [10] (e.g. automated provision of visualization data [4]). As a long-term solution, the use of comprehensive skeletons can be beneficial for a family of design problems. Based on robust modelling, such an approach can be also adapted to various expert areas and implemented as specific workbenches.

References

[1] C.M. Hoffman, R. Joan-Arinyo, CAD and the product master model, *Computer-Aided Design*, Vol. 30, 1998, No. 11, pp. 905 – 918.

[2] R. Riascos, J. Stjepandić, L. Levy, A. Fröhlich, Digital Mock-up, in: J. Stjepandić et al. (eds.): *Concurrent Engineering in the 21st Century: Foundations, Developments and Challenges*, Springer International Publishing Cham, 2015, pp. 355–388.

[3] J. Ríos, F. Mas Morate, M. Oliva and J.C. Hernández, Framework to support the aircraft digital counterpart concept with an industrial design view, *International Journal of Agile Systems and Management*, Vol. 9, 2016, No. 3, pp. 212–231.

[4] C. Emmer, A. Fröhlich and J. Stjepandić, Advanced engineering visualization with standardized 3D formats, *IFIP Advances in Information and Communication Technology*, Vol. 409, Springer, Berlin Heidelberg, 2013, pp. 584-595.

[5] S. Bondar, C. Ruppert and J. Stjepandić, Ensuring data quality beyond change management in virtual enterprise, *International Journal of Agile Systems and Management*, Vol. 7, 2014, Nos. 3/4, pp. 304–323.

[6] A. Biahmou, C. Emmer, A. Pfouga and J. Stjepandić, Digital master as an enabler for industry 4.0, *Advances in Transdisciplinary Engineering*, Vol. 4, 2016, pp. 672-681.

[7] A. Pfouga and J. Stjepandić, Leveraging 3D geometric knowledge in the product lifecycle based on industrial standards, *Journal of Computational Design and Engineering*, Vol. 5(1), 2018, pp. 54-67.

[8] H. Shen, T. Bednarz, H. Nguyen, F. Feng, T. Wyel, P.J. Hoek, E.H.S. Lo, Information visualisation methods and techniques: State-of-the-art and future directions, *Journal of Industrial Information Integration*, Vol. 16, 2019, 100102.

[9] F. Elgh, Automated Engineer-to-Order Systems A Task Oriented Approach to Enable Traceability of Design Rationale, *Int. J. Agile Systems and Management,* vol. 7, Nos 3/4, 2014, pp 324–347.

[10] O. Kuhn, H. Liese and J. Stjepandic, Methodology for knowledge-based engineering template update, *IFIP Advances in Information and Communication Technology,* Vol. 355, Springer, 2011, pp. 178-191.

[11] M. Hassannezhad, P.J. Clarkson, Internal and External Involvements in Integrated Product Development: A Two-Step Clustering Approach, *Procedia CIRP*, Vol. 60, 2017, pp. 253 – 260.

[12] T. Fischer, H.P. Martin, M. Endres, J. Stjepandić and O. Trinkhaus, *Anwendungsorientierte Optimierung des Neutralen CAD-Datenaustausches Mit Schwerpunkt Genauigkeit und Toleranz*, VDA, Frankfurt, 2000.

[13] F. Mandorli, H.E. Otto and R. Raffaeli, Explicit 3D functional dimensioning to support design intent representation and robust model alteration, *Computer-Aided Design and Appl.*, 2016, 13:1, 108-123.

[14] R. Soderberg and L. Lindkvist, Computer Aided Assembly Robustness Evaluation, *Journal of Engineering Design*, 1999, 10:2, pp. 165-181.

[15] K. Al-Widyan, J. Angeles, A Model-Based Formulation of Robust Design, *Journal-of-Mechanical-Design,-Transactions-of-the-ASME*, 2005, Vol. 127, pp. 388-396.

[16] L. Sun, B. Zhang, B. Li, W. Yin, CATIA V5 Robust Design Method to Prevent Feature Failure, *International Conference on Automation, Mechanical Control and Computational Engineering*, 2015, pp. 422-427.

[17] H. Liese, J. Stjepandić and S. Rulhoff, Securing product know-how by embedding IP-protection into the organisation, *2010 IEEE International Technology Management Conference*, ICE 2010, 7477025.

[18] R. Söderberg, L. Lindkvist and S. Dahlström, Computer-aided robustness analysis for compliant assemblies, *Journal of Engineering Design*, 2006, 17:5, pp. 411-428.

[19] T. Hasenkamp, M. Arvidsson and I. Gremyr, A review of practices for robust design methodology, *Journal of Engineering Design*, 2009, 20:6, pp. 645-657.

[20] R. Söderberg, L. Lindkvist, K. Wärmefjord, J.S. Carlson, Virtual Geometry Assurance Process and Toolbox, *Procedia CIRP*, 2016, vol. 43, pp. 3-12.

[21] A. Lanzotti, Robust design of car packaging in virtual environment, *Int J Interact Des Manuf*, 2008, 2:39–46.

[22] A.-J. Fougères and E. Ostrosi, Intelligent agents for feature modelling in computer aided design, *Journal of Computational Design and Engineering*, 2018, 5(1), pp. 19-40 .

[23] E. Ostrosi, A.-J. Fougères, Intelligent virtual manufacturing cell formation in cloud-based design and manufacturing, *Engineering Applications of Artificial Intelligence*, 2018, Vol. 76, pp. 80-95.

[24] E. Ostrosi, J. Stjepandić, S. Fukuda and M. Kurth, Modularity: New trends for product platform strategy support in concurrent engineering, *Advances in Transdisciplinary Engineering*, 2014, 1, pp. 414-423.

[25] J. Yang, E. Kim, M. Hur, S. Cho, M. Han, I. Seo, Knowledge extraction and visualization of digital design process, *Expert Systems with Applications*, Vol. 92, 2018, pp. 206–215.

[26] A. De Marco, M. Di Stasio, P. Della Vecchia, V. Trifari, F. Nicolosi, Automatic modeling of aircraft external geometries for preliminary design workflows, *Aerospace Science and Technology*, Vol. 98, 2020, 105667.