GEOMETRY APPLICATION EVOLUTION - FROM RESEARCH TO INDUSTRIAL APPLICATIONS OVER TWO DECADES

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ABSTRACT

Digitalisation is making significant inroads into society at the same time as the general commercial trend is to able to personalise the product one acquires. The field of digital product representation, and the techniques for adopting a particular product in accordance with the customer's expectations, have become very important corporate assets. From a company's perspective these assets can be leveraged both for internal efficiency and also for different types of external customer interactions. In this article, the standpoint is that product geometry forms the foundation for digital product representation. It is from this perspective that the geometrical ecosystem comes into focus. Geometry creation and geometry consumption, in combination with geometrical configuration management, are high-value areas that must be mastered. A research-based 20-year industrial perspective building up such capabilities serves as an example. The article concludes with a forward-looking perspective on potential areas for continued exploration on this journey.

Keywords: Computer Aided Design (CAD), Concurrent Engineering (CE), Visualisation, Integrated product development

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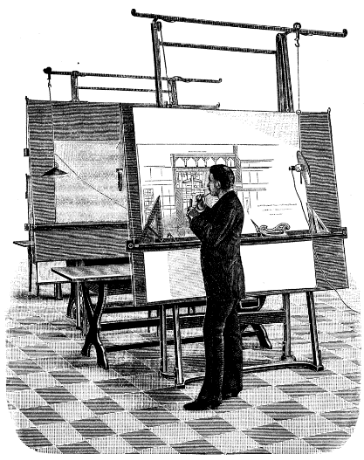
1 INTRODUCTION

Society is currently in the midst of a digitalisation phase so the existence of systemised approaches to provide representative digital product representations is a necessity. Already back in about 2000 it became evident that there was considerable potential in leveraging on the advances made with the introduction of the latest generations of Computer Aided Design (CAD) systems to provide these digital product representations. Industrial success stories (such as Whithers 2020; Hudi and Spies 1999) are good examples from that era. In this paper, a contemporary doctoral research project completed in 2005 (Fuxin 2005) presented an approach whereby the focus was on establishing prerequisites for creating, maintaining and collaborating on geometry-based product information (GBPI). The key findings were:

- The importance of supporting different users' geometry requirements; geometry consumption
- Best practises in the way of working, and how to interact and collaborate; the process
- Systemised positioning principles to optimise geometry documentation; geometry creation
- Geometrical configuration management and mechanisms to create relevant product views
- How to work with geometry in preconceptual stages of engineering design

Are the research project results, conclusions and recommendations still valid today, 20 years after the project's initiation? What has evolved over these years that should be reviewed and potentially complement the research area? What are the challenges ahead?

2 GEOMETRY CREATION



The evolution that has led to the current automotive design engineer landscape has lasted for roughly 80 years (Cohn 2010, Piegl 1994). Over the past 20 years things have settled in the area of computer aided design, and nowadays 3D CAD is more or less taken for granted, for instance for the classic domain of mechanical design engineering. There are a number of more immature design engineering areas that still show considerable potential for improvement, such as pneumatic design and electric routing. Over the past 20 years a number of different industries have been challenged with such problems (Curran 2020).

For industries working with extensive product offerings, the challenge is to efficiently incorporate the strengths of 3D CAD capability to support parameterised, and associative, product definitions and then leverage on this definition utilising configuration management to derive different product representations (Fuxin 2005, Hirz, Harrich & Rossbacher 2011). The potential for utilising a parametrised approach has been further investigated and described in academic publications (such as Bodein, Rose & Caillaud 2013, Wencke and Sachse 2009).

Having a 20-year perspective on this area, it is frustrating to realise how much is taken for granted. There is no difference between 2000 and 2020; it is still the design engineer who creates and maintains the geometry-based product information. The number of man-hours spent on governing this information from its initial creation stage, through the refinement of its definition to its final outcome, still represents immense efficiency potential. The potential from parametrised and associative definitions enables associative positioning information (API), which in turn has capabilities that make it possible to ease the documentation burden, and also characteristics that open up for alterations of geometrical topology definitions, so-called generative approaches.

Geometry-based product information holds both the geometrical definition and also the appurtenant information, such as product data management (PDM) related information; efficiency, applicability and other types of information. Especially when working in pilot studies, but also at the start of larger product projects, there are plenty of product platform definitions that are not yet defined and that make it impossible to define the appurtenant product information. This obstacle is managed by relying on capabilities that reside within the geometrical models and their definition. The formalisation levels are put aside and the focus of support is instead on flexibility and creativity. Once the necessary initial activities of product platform definition have reached such a level of maturity that it becomes possible

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to formally define and document this "upper structure", this can be settled. Accordingly, 3D CAD is also an enabler for supporting work in early stages that must be acknowledged and leveraged.
The area of geometry creation cannot be sufficiently emphasised. The geometry-based product information created is a precondition for a majority of all downstream geometry consumption over the entire product life cycle. This downstream utilisation is true reuse and exemplifies how it is possible to leverage on the design engineer's efforts. The key is to maintain a systemised setup with stringent definitions and continuous educational efforts to keep all contributors at the same level in the task of being geometry creators.

3 GEOMETRY CONSUMPTION

Native CAD formats, that is to say the original format of the geometry models, become very large. With the attendant mathematical definitions of all the relevant geometrical entities, full definition history and meta data, the native formats quickly grow in size so larger CAD assemblies have a tendency to consume large amounts of computer memory. In addition, performance is impacted. Furthermore, modern CAD applications support very complicated geometry definitions and operations – many man-hours are required to get to know all these capabilities, and regular utilisation of the CAD applications becomes a necessity. For the design engineer community, the strengths of CAD applications easily compensate for the many drawbacks and some of these drawbacks can be overcome for instance by utilising visualisation tools.
If a company has decided to rely on more than one CAD application, CAD conversion technique is necessary between different CAD applications. Many of the large CAD vendors (PTC 2020, 3DS 2020, Siemens software 2020) support a business environment with multiple CAD systems, known as a multiCAD environment. CAD data interchange, that is to say conversion, takes place by relying on different intermediate formats known as neutral formats. Two of the most acknowledged neutral formats are IGES (Nagel, Braithwaite and Kennicott 1980) and STEP (Schenck and Wilson 1994). The STEP standard is newer that IGES and the establishment of the STEP standard was an international joint venture between industry and academia that evolved over many years. This area is undergoing constant change since evolution takes place both in underlying mathematical definitions and in application upgrades.
For a huge majority of the consumers of geometry, all details such as design intent (Papalambros 2010) that are encapsulated in the geometry models are of no relevance for their intended use. This implies that one of the major drawbacks of huge native CAD file sizes can be overcome by migration into a visualisation format. The migration technique is often referred to as conversion (Krause, Stiel and Lüddemann 1997 or CAD data exchange 2020, Rappoport 2003). This is where extraction of the required information takes place and the outcome is a visualisation format that is reduced by up to 95% in file size; the term 'lightweight formats' is sometimes used. The conversion ratio is dependent on the requirements on the information that is extracted and the complexity of the geometrical definition. This implies that it is possible on a normal business laptop to view/consume a complete product, see Figure 1. Accordingly visualisation tools are an enabler for mass consumption but are also a prerequisite for collaboration.

Figure 1. Viewing of a complete product in a visualisation tool.

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Different categories of geometry users have responsibilities and assignments that require access to different portions of the GBPI (Fuxin and Edlund 2001). At the same time, the area of visualisation tools, that is to say the tools that consume the relevant portion of the native CAD geometry files, has evolved immensely over the past 20 years. There are several frequently recurring terms that are used when describing these tools; among them digital mockups (Hudi and Spies 1999, Digital mockup 2020), Virtual Reality (Ottosson 2010) and Augmented Reality (Mourtzis, Zogopoulos and Vlachou 2018). Accordingly there exist a large number of commercially available applications and each one has added its own twist on how to visualise and consume geometry. Visualisation applications are in general much more easy to use because they do not support any functionality for definition or alteration of geometry.

There are a couple insights that it is important to emphasise concerning conversion. First of all, conversion is not an exact science, it's about information mapping between different information models that store a mathematical definition of geometry. Thus, approximations and mitigations are a central part of conversion. This in turn can potentially lead to poor geometry quality. For obvious reasons the scale of conversion-induced problems escalates with the depth of the structures that need to be converted. Conversion performance is another bottleneck; all conversion is time-consuming and the risk of latency must be taken into account. This really boils down to strategic decisions: how many CAD systems and visualisation tools make up the optimal mix for a particular company?

Consumption and collaboration are made possible by having convenient access to the geometry models. Nowadays the most common practice is to store the sought geometry models in one, or several, databases. For large automotive OEMs the old-fashioned way of relying on disc storage is far too inefficient. Concurrent engineering, collaboration, globally distributed teams – they all require systemised solutions for the native CAD files stored; the geometry information needs to be versioned and converted into appropriate visualisation formats.

4 GEOMETRY CONFIGURATION

In order to physically produce the truck shown in Figure 1, the physical bill of material (PBOM) must be collected based on the product specification – its configuration. The actual content of the PBOM is governed by a product definition logic (PDL) that makes it possible to define the unique requirements of a specific customer and accordingly extract the relevant PBOM from a decided product standard offering from which the customer can choose. The PDL is the kernel of the PDM system. The PDL is defined, managed and stored in the PDM system and accordingly this is the logic that makes it possible to manage variety. Furthermore, this is also the logic that determines the rule base for how to divide the total standard offering into different ranges and segments and to classify different product platforms. Hence, the PDL is the true soul of the products produced and it is by having in-depth knowledge of how to define and leverage on this logic that a company can excel; it is therefore essential to master common architecture and shared technologies. The PDM system described is in-house developed, a common setup in industry (Nomaguchi, et al. 2017). Earlier studies describe the importance of setting up systemised approaches on documentation and configuration systems (Shafiee, et al. 2017).

It is possible to equate the PDL with DNA. Product development guides the activities where customer requirements are transferred into technical solutions that must be able to be differentiated. The technical documentation drives the definition of the PDL. On the journey of developing new technical solutions, the manufacturability of these solutions must continuously be assessed to ensure that it is possible to efficiently put the technical solutions together into products – the assembly of the PBOM (Inkermann, D. et al 2019). Another very important stakeholder is the aftermarket/service organisation that has to maintain the products sold, and to disassemble and assemble the PBOM. The customer interface, the sales organisation, is yet another stakeholder that must be involved. The challenge on the sales side is to transfer the technical solutions into customer-oriented packages that can be priced and that meet different customer expectations regarding product differentiation. The PDL is a red thread that goes through all stakeholders – it is the common architecture.

The two previous paragraphs target the PBOM and therefore primarily later phases of the product development process (Fuxin 2001b). In the classical sense, the PBOM does not specify any position. The digital bill of material (DBOM) is put it place to overcome a number of challenges that the PBOM should not be forced to handle, such as position of articles and early phases. This implies that dual product structures are required to implement such a way of working. The PBOM composes articles

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that are utilised to assemble the product; the DBOM composes geometrical building blocks (GBB) that geometrically represent the product and its representation in different phases of development (Fuxin 2003). There are two types of GBBs: static and generative. The two product structures, the PBOM and the DBOM, share the same PDL but are decoupled when it comes to how they are aggregated and with regard to whether positional aspects are in focus when documenting applicability. This decoupling has its pros and cons; in earlier phases of product development only the DBOM is in focus and it is also possible to rely on separate state classifications. The drawback is synchronisation of two decoupled product structures.

By combining the capabilities of the DBOM with the opportunities of parameterised and associative geometry models of 3D CAD applications, and leveraging these assets with the CAD database strengths in terms of providing accessibility, versioning, global geometry data distribution and conversion to relevant visualisation formats, a foundation is put into place to support geometry configuration. The integration of these different systems is realised by a data warehouse approach where the necessary data is collected and systemised to provide the geometry configurator with the proper preconditions. Within the data warehouse solution an operational framework has been developed that features a queue system for collecting and despatching user requests to a globally distributed server cluster, a batch environment to support the creation of project populations for instance, and a maintenance environment for efficient monitoring of the setup. Furthermore, two independent solutions have been developed to support users located outside the company.

There are two different types of positioning techniques that should be highlighted: associative positioning information (API), and discrete positioning information (DPI). Both techniques rely on the same configuration information. API builds on core CAD technology to create the requested configuration and accordingly operates on the native CAD files (a CAD database connection is required). The result is a CAD assembly that can be fully parametrised and associative and thus support “true relative positioning”; in other words, if 15 GBBs are positioned against a coordinate system, all GBBs will follow a positioning change of the coordinate system when working with the final configuration in a CAD session. Since API operates on native CAD files, it is possible to support generative approaches, for example in very complicated areas where the possible solution space (the number of feasible GBBs that could be created) may span anything from a couple of thousand combinations up to a couple of billion combinations; the GBBs are generated on the fly based for instance on computational input. Two good examples where generative solutions are utilised are the front-axle area and the frames, see Figure 2. If an API-created configuration is to be made available in a visualisation tool, conversion is required.

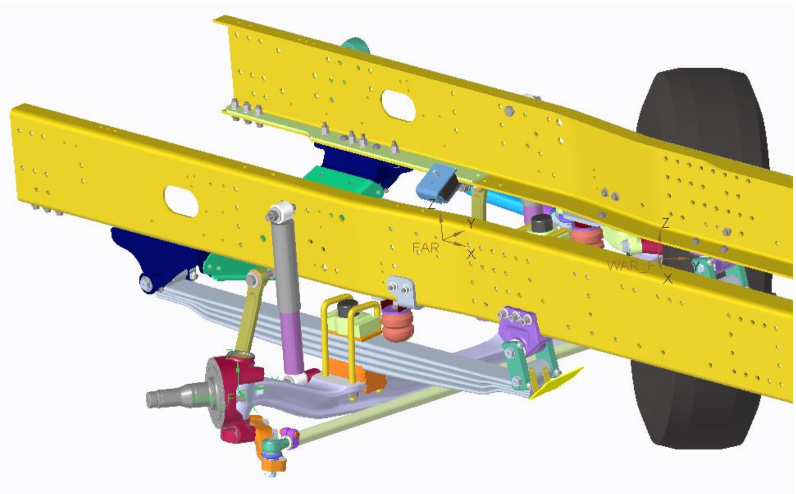

Figure 2. Two areas with generative geometry creation.

The DPI technique instead relies on the transformation matrix of the positioning mechanism being extracted into positioning tables when each GBB is checked into the database. This means that when configuration takes place, the positioning can be resolved directly in the database and the configuration performance becomes very fast compared to the API technique. When API configurations are converted

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into visualisation format, they are converted from API to DPI and accordingly become static. The strength of the DPI technique is three-fold:

1. Very good performance where the output is most suitable for visualisation tools
2. Since there no database interaction is required, very large assemblies can be created
3. Since there is no parametrised and associative information, the resulting assemblies can basically be repositioned in virtually any imaginable way

The most important disadvantage of DPI is its inability to support parametrised and associative geometry models. For this reason it cannot support generative geometries and is therefore no so suitable for supporting 3D CAD users. The challenge therefore is to establish an intuitive business environment where API and DPI capabilities are available and where it is obvious which technique to utilise when.

The PDM system has been designed to manage variety. From the very beginning it supported the configuration of the PBOM. Over the past couple of decades it has been complemented with support for the DBOM. During the same period, CAD and visualisation domain capabilities improved and matured enormously. Geometry configuration has continuously evolved to take advantage of these enhancements. The outcome is a geometrical framework that can meet the requirements of geometric representation. The driver behind this setup is customer demand for transport solutions; the customers want products that optimise their transport mission. This in turn results in a combinatorial challenge that is far more complicated than the traditional automotive industry.

Figure 3. An example of challenging variety in the wheelbase area.

In Figure 3, a range within a segment for a particular platform is partially depicted. See the difference in fuel tank combinations and note the impact this will have for example on frame rails, space allocation and routing for each truck.

5 STATUS OF INDUSTRIALLY IMPLEMENTED RESEARCH RESULTS

The contemporary doctoral research project was completed in 2005 (Fuxin 2005a). That is just over 15 years ago. One way of evaluating the industrial impact is to assess the extent to which the research results have been implemented and leveraged. The industrial framework that was put in place is called Automatic Vehicle Packaging (AVP). AVP has been developed and implemented in a data warehouse system setup called Engineering Data Base (EDB). One metric that it is relevant to review is the number of configuration requests being put to AVP annually, see Figure 4. Over a period of 15 years, utilisation increased by a factor 150. Different colours represent different fields of application, such as product project batch vehicles, virtual manufacturing vehicles and external truck body builders. The application field of on-demand generation, that is to say a geometry consumer that requires a complete or partial portion of the product, is the area that increased the most.

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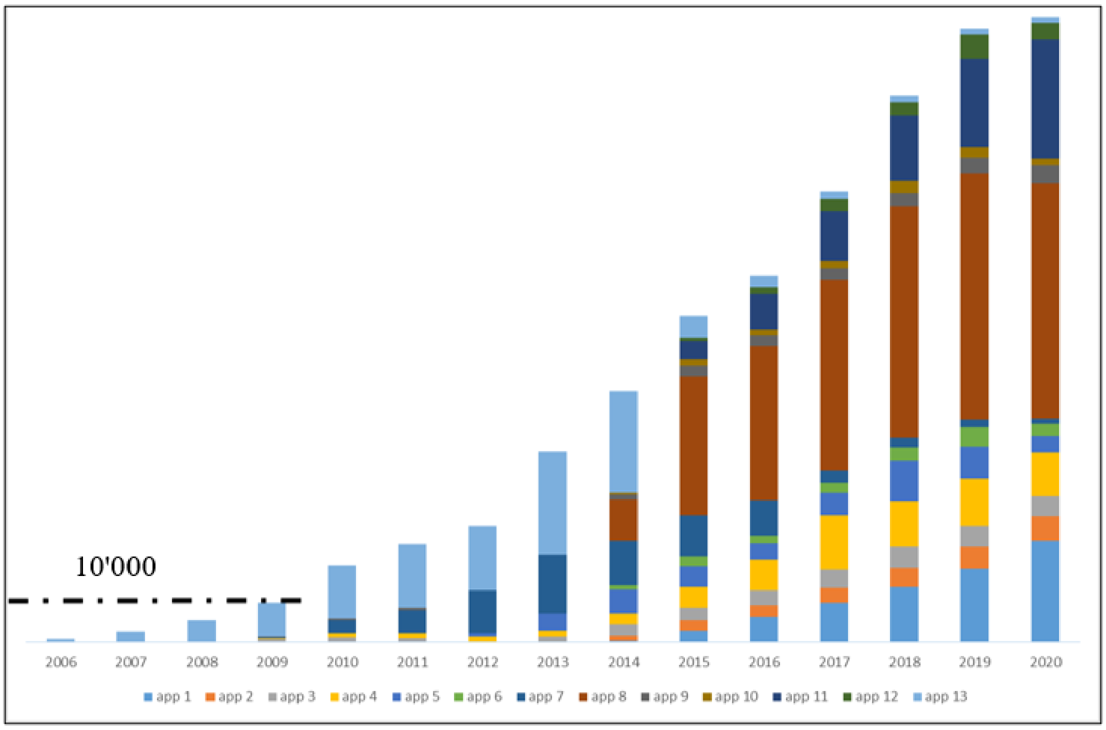

Figure 4. Examples of application of geometry configuration.

Another potential metric could be amount of reduction in product documentation. There are internal company metrics where measurements were carried out prior to, and after, changes to the documentation logic. In one of the areas where extensive analysis was undertaken, it turned out that it was possible to reduce the amount of product documentation by approximately 60%. In terms of engineering efficiency, this is a truly major improvement.

After gathering more than 20 years of experience in research, development and maintenance, many lessons and observations can be highlighted. A few significant areas will be briefly elaborated upon:

- Product and end customer focus: Income is generated by selling a product and supporting it during its life cycle with different types of services. In order to meet customer requirements, understanding of the customers' business and their utilisation of the product cannot be sufficiently emphasised. The same goes for the products' interaction with the environment and society. Depending on in which branch of a company an employee is located, it can be more or less easy to embrace these fundamentals and identify the individual contributions. However, it is necessary to establish such awareness to get a company's collected resources to work together towards the same goal.
- Organisation and staffing: Competence must be built over time and valued accordingly. It takes time to establish highly skilled employees knowledgeable in areas such as the product, business way of working, CAD/visualisation systems, PDM, and so on. It is time-consuming to empirically collect knowledge and build up highly skilled people, and to make them prosper and feel appreciated to keep them passionate. In a setup with the right people, trust is an enabler for a lean organisation; the need for massive control and follow-up can be kept to a minimum. Cultural values are another very important ingredient that is vital for lean efficient organisations.
- Holistic understanding: Larger organisations in particular have a tendency to become more silo based. Key performance indicators are normally not established cross functionally, it is not unusual for this to cause sub-optimisations and a blame-game between the silos. For example, technical solutions that excel but are inefficient to manufacture and/or maintain on the aftermarket, IT systems that architecturally and performance-wise are outstanding but do not meet the requirements of the business organisation, pricing that not is on a par with cost due to split responsibilities. Hence, it is a true challenge to find the optimal equilibrium between all areas, across all organisations.
- The processes: It takes time to gain acceptance for evaluations, decisions and coordination to be carried out as far as possible using only a digital foundation. All participating organisations do not necessarily possess equal preconditions for fulfilling their assignment on a digital basis.

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Trying to establish shorter iterations and alternative milestones has sometimes resulted in obstacles and bottlenecks; this is a positive thing because it indicates a potential for improvement. Another lesson is that one project seldom faces the same challenges as another one. The processes, the way of working, are constantly being challenged and adapted to become more efficient; there is such thing as one-size-fits-all – flexibility is key.

- A sustainable business environment: Over a period spanning more than 20 years the setup of the business environment has shifted in a number of different areas due to infrastructure changes, such as computer platforms, operating systems, upgrades and changes in various applications and databases. Accordingly the business environment is under constant change, one way or the other, and the importance of establishing a sound basis for taking aspects of infrastructure, architecture and standards into consideration becomes very important. The contradiction between commercial off-the-shelf systems and applications versus in-house developed counterparts is under constant debate. The potential of modularity in engineering design definitely has its given place when forming a sustainable business environment – a modular approach with well-defined information interfaces makes the replacement of applications and systems easier.

6 THE NEXT LOGICAL STEP

For many years, huge efforts have been invested in preconditions to manage and support variety. The outcome of these efforts is a product offering that is fantastic, perhaps even too fantastic. The number of possible product combinations has grown exponentially so the next logical step is to undertake research in an area known as Strategic Vehicle Combinations (SVS). It ought to be possible to master the solution space represented by all feasible product combinations, if one could pinpoint which information is required to sufficiently accurately describe the limited number of product combinations it would take to predict and simulate the entire solution space.

The described PDL, leveraged with the geometrical framework, constitutes a great starting point for supporting product representation and visualisation. However, the true research challenge is to identify which information is required, and must be gathered and systemised, to identify the SVS population.

One pragmatic starting point is to try to identify where we are currently and what we do know. We need to be rather humble, because even though we possess enormous amounts of data, facts, figures, and so on regarding what we do and how we perform, when starting to conduct more in-depth analytics on this information we also realise how much there still remains to find out when it comes to how things we thought we know actually correlate – quite simply, there are so many more discoveries to be made. Hence, leveraging on analytics and building up techniques and methods for how to conduct such investigations is the next logical step – a data-driven, learning organisation. It is also clear, already at this stage, that the current product offering must be documented, and understood, on an even deeper level to really be able to define a comprehensive SVS framework. It is also important to highlight that it is not only the product definition itself that must be enhanced, we must also conduct research into describing society and our customer requirements even better. Furthermore, the field of logging the already sold population of products is an enormous area where vast effort needs to be spent. For obvious reasons, the extraction of relevant logging information is a tremendously important input for the definition of SVS.

7 CONCLUSION

The research project results, conclusions and recommendations presented in 2005 have served as a foundation for the work that has continued in the industrial setting – the AVP framework. An organisation has gradually been built up that operates, maintains and further develops this AVP framework. The agility and seamless joint actions between the AVP team and the business organisation have proven to be a success story when evolving different areas. This success is manifested in AVP utilisation by the business organisation and the way product documentation efficiency, and quality, have improved over these years. The holistic enterprise perspective has been taken to new levels where organisations such as Virtual Manufacturing and Aftermarket nowadays benefit from utilising the AVP configuration framework at the same time as external parties are also leveraging from this setup. This article has been written as a testimony after driving the AVP framework as an AVP team member for 15 years. The knowledge and experience gathered has formed, and influenced, the article structure and pointers and discussions have been brought forward on topics that were not part of the original research project results and serve as an opportunity for continuous research in this vast research area. Examples of potential research complements include the following: refinement and detailing of the concepts of geometry creation versus geometry consumption, strategies for multiple CAD applications and visualisation applications, the extension of geometrical configuration setup harvesting from the strengths of both API and DPI techniques and further strengthening of the area of early phases. The challenges going forward have a strong bearing on how to evolve the current product offering while at the same time providing sustainable products to customers. The sustainability dimension is largely influenced by environmental aspects. Reducing the environmental footprint involves enhancements on classical combustion techniques, alternative fuels, alternative energy sources and electrical powertrains. For this reason, the challenges ahead include evolving techniques for assisting and supporting the engineering design community in identifying, differentiating and defining the future product offering.

The focus of this article is that the digitalisation era's product representations are derived from geometry models. The general trend in society is a push towards high individualisation/adaptation of products. Hence, geometric configuration management is key to generating these requested product representations. This dependency chain starts with the area of geometry creation and the CAD tools. It is in engineering design that the foundation of the geometry ecosystem is established and documented. It becomes apparent that CAD modelling systemisation is a very important ingredient. The CAD toolbox makes it possible utilise concepts such as parametrisation, associativity and different types of rule bases and relationships. This is therefore the cradle of product representation and an area that cannot be emphasised strongly enough.

Geometry consumption normally takes place through utilisation of some type of visualisation application. These applications possess a number of very attractive features: they are normally easy to use, they offer very fast retrieval, and rendering performance and the size of the geometry models is much more manageable, even on an ordinary laptop. The consequence is that these lightweight formats really are an enabler for collaboration. However, one should always bear in mind the origin of the geometry models and that conversion procedures are a necessity for this type of application. An unfortunate misconception, which has been encountered on several occasions, is when personnel with less insight give lower priority to geometry creation in favour of geometry consumption.

Efficient high diversity bill of material management requires a systemised PDM approach. It is the PDM PDL that is the foundation for product documentation and its impact on product documentation efficiency is indisputable. A DBOM approach, a complementing product structure for the classical PBOM, has proven to be a considerable strength. This approach makes it possible to further leverage on enabling 3D CAD capabilities, such as in the field of parametrisation and associative, and therefore contributes to documentation efficiency. The configuration setup benefits from these capabilities but it also implies that in order to support geometry consumption, the differences between API and DPI must be clearly understood and applied accordingly. The duality of API and DPI is an asset that contributes to geometrical ecosystem diversity, but it is the 3D CAD capabilities that are the key enabler for geometry creation and DBOM documentation efficiency.

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