Chapter 12
Major Technology 6: Digital Mock-Up—DMU

Executive Summary

This chapter deals with the following topics:

- Basics and advanced techniques of Digital Mock-Up
- Providing insight into how engineers benefit from using Digital Mock-Up (DMU) technologies
- Describing functioning, benefits, and limitations of DMU technologies in practice.

Quick Reader Orientation and Motivation

The intention of this chapter is:

- to give an overview of DMU technology in Virtual Product Creation as driver and enablers for Digital Transformation in engineering
- to present DMU technology as part of Virtual Product Creation from a practitioner's point of view to analyze the need and usefulness for day-to-day industrial work practice
- to give instructions on how to use DMU technology
- to explain models, frameworks, and mathematical representations that help to grasp the internal working modes of DMU technology.

A *Digital Mock-Up* (DMU) is a *digital collection of 3D models* that represents a comprehensive physical entity *with the help of a structured digital representation.* Usually, two different types of comprehensive physical entities are subject for such digital representation, *products* like e.g. machines, cars, aircrafts, trains or ships and *factory or production* line environments. In addition, a range of digital functionalities is offered by DMUs in order to investigate the digital models and their interplay. DMUs do also play another integration role: they are used where complex products or factories are developed and represented in heterogeneous 3D CAD environments like in automotive industry, aircraft design or plant manufacturing. Hence, DMUs represent (neutral) digital integration environments to avoid tedious CAD-to-CAD translation work for packaging and layout investigations, please compare Table 12.1.

R. Stark, *Virtual Product Creation in Industry*,
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Table 12.1 Application areas of hardware/physical and digital mock-ups [1]

	Engineering and manufacturing supportability	Training	Marketing
Primarily used	DMU for the product itself (airplane, ship, car…) but also for all its production means (factories, transportation equipment…) and verification of servicing procedures	HMU e.g. Space Shuttle Training Mock-up, International Space Station facilities, Fuselage/Cabin Mock-ups for workers being assigned to a new assembly line	HMU e.g. to provide customers a “touch and feel” impression, e.g. with fully functioning Cabin Interior—the “Sales Mock-up”; (scaled) Mock-ups for exhibitions
Secondarily used	HMU to validate particular risk areas, to cover certification relevant items, prove required functions (system tests) that are not yet reliably possible in a digital environment; examples: Design-, Production-, Engineering Mock-ups;	DMU supporting faster and better learning e.g. for Space Mission preparation; growing importance as computer performance and computer graphics advance (e.g. Virtual Reality)	DMU growing importance for external communication especially when coupled with virtual reality techniques, increased reactivity on customer need and requirements

However, even with modern computer power, traditional physical or hardware mockups (PMU or HMU)[1] still have their usage in product development [1].

Especially, when human product interaction comes into play, physical features like haptic and weight become important. This is the reason why Digital Mock-Ups are potentially not sufficient to represent a full engineering prove out environment for critical engineering investigations such as fitting clearance for manual assembly, service and dismantling tasks. Figure 12.1 shows the typical three types of representations (the final physical product and the physical mock-up resp. Digital Mock-Up during its development) in present engineering practice.

For distributed product development, a DMU can be used as a reference model, in which every new designed part or assembly can be directly implemented. This allows then for an easy check of the entire product assembly against other adjacent 3D models (e.g. space analysis) across multiple locations. This is not possible with physical mock-ups since they can only physically exist at one location and therefore cannot be virtually compiled to one representation over network and database connection as it is the case with Digital Mock-Ups.

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[1] Hardware mock-ups (HMU) or physical mock-ups (PMU) are distinguished between the following types in aerospace and aviation industry [1]: Design Mock-ups, Sales Mock-ups, Production Mock-ups and Engineering Mock-ups (EMU). The latter represent the most “sophisticated ones” with functionalities usually evaluated using so-called “(System) Test Benches” or “Iron Birds”.

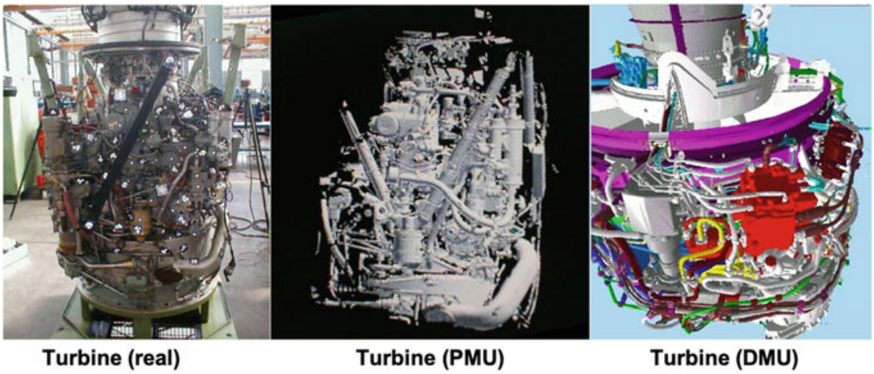

Turbine (real)
Turbine (PMU)
Turbine (DMU)

Fig. 12.1 Real aero engine, its physical and digital mock-up

12.1 Engineering Understanding of DMU

A Digital Mock-Up is a virtual representation of the entire product in all its variants, options and versions. It can be used throughout the product life cycle (if maintained consistently even after production starts!) and it supports validation, communication and decision-making processes. It is, therefore, a specific digital representation of a virtual prototype, which in turn is part of the virtual product.

Figure 12.2 illustrates different types of Digital Mock-Ups (DMU) of complex products and explains the core elements of a Digital Mock-Up. Hence, a Digital-Mock-Up (DMU) is defined and characterized as follows:

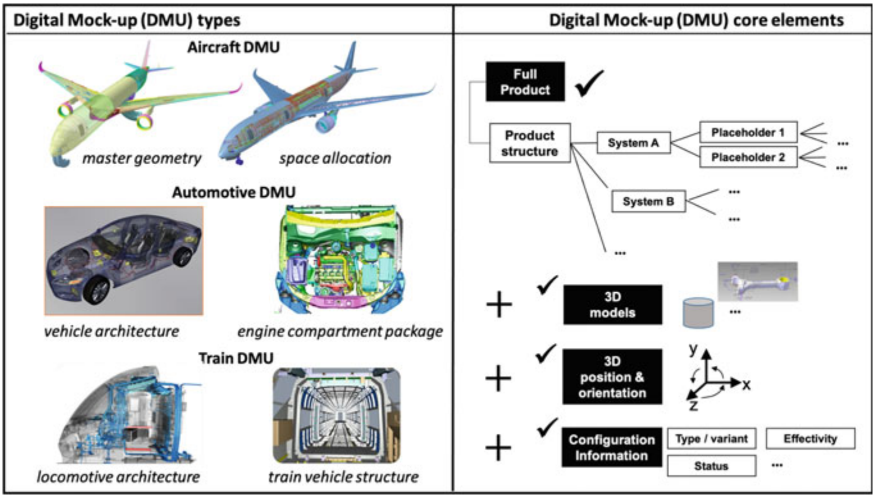


Fig. 12.2 Digital mock-up types and core elements

A Digital Mock-Up is a virtual representation of an entire product model of a (complex) product or other technical systems (e.g. production line, factory or service station). A Digital Mock-Up represents positioned and oriented 3D geometric models in a reference coordination system and offers configurations such as product type, variant, effective dates and/or other engineering/business attributes (e.g. weight class, temperature zone, cost level etc.*). A Digital Mock-Up serves as analysis, validation, communication and decision platform throughout the product/manufacturing engineering phase and—if possible—throughout the entire product lifecycle.*

Since the birth of the digital concept and environment DMU in the second half of the 90ties of last century substantial industrial experiences and further research developments have happened. Advanced engineering departments enrich the classical DMU by overlays of CAE analysis results (colored result file representations of FEA analysis, motion files of rigid motion simulations etc.) and transform the DMU into virtual prototypes in order to support the next level up to a fully virtual product. If elements such as logic functions, cross-domain interactions and behavioral modeling are getting added also the terms “Functional Mock-up (FMU)” or “Functional Digital Mock-Up” are increasingly used (compare [2] and [3]).

The DMU provides the geometric description, e.g., of an entire vehicle; the virtual prototype adds further data to the DMU so that functional and behavioral simulations get supported. The virtual product contains all information that is needed for the entire product lifecycle in different business sectors ([4], p. 9). A DMU consists of a (digital) product description and the collection of 3D models of all relevant parts in their correct spatial position. In particular, a DMU is used to detect collisions between parts and to simulate the assembly process [5], both in static and in dynamic situations.

For dynamic motion analysis, it is necessary to add motion behavior to the DMU by associating DMU components to motion files, which have been calculated before in Multi Body Simulation (MBS) software packages. The motion paths of DMU components are then driven by animated motion sequences in 3D space referenced to appropriate relative or absolute coordinate systems.

DMU structures and models are also leveraged in later phases of the product lifecycle than product development and manufacturing engineering: e.g. during review and analysis of problems and solution proposals in the mid of life activities such as ongoing production, product marketing and offering, during product use and as part of product enhancement activities.

12.1.1 Why Does an Engineer Use DMU Instead of CAD?

A DMU is used to perform investigations on assemblies of high complexity and with many components. Principally, it is possible to build these mock-ups from CAD models directly. However, CAD models usually contain data intensive, accurate and parametric geometrical information sets, which include a rich mix of meta data and supportive data structures. Oftentimes, such detailed information sets are not required for typical visual reviews, inspection work, clearance and collision analyses or kinematic simulations.

If approximated geometric data is used to an accuracy level of 0.5 mm with an overall product dimensional level of around 5 m, it is possible to reduce the size of the 3D geometric representation to only 30% of the original size. If precise data is then integrated for measuring purposes as part of the DMU representation the size is doubled again to an absolute level of around 60% of the original CAD file size. If then compression file technology is applied it can be reduced to the 30% of the original CAD file size again.

The reduction of 3D file size and clever applications of a range of algorithms for dynamic loading of visual data according to interactive viewing intentions supports swift and interactive working within DMU tool environments. CAD systems (either 3D or 2D) provide functionalities to construct and modify geometry of technical product models or drawings of mechanic and electronic parts. In cases where only a limited number of parts (max. up to 40 full 3D CAD models simultaneously) are in direct working interaction CAD models are o.k. to work with as long as the graphic and CPU (central processing unit) power of the computer hardware is good enough. For example, it is possible to support a scenario where a supplier who delivers bolts to an OEM, has to ensure the digital validation of the appropriate attachment situation. Here, a single CAD model for every bolt type carries all necessary information and the associated design/assembly situation for attach the right components via such bolts in appropriate design context can be supported well in a CAD environment.

In complex situations, however, where packaging, behavioral, assembly in context or other studies must be undertaken, a higher number of different 3D models need to be linked together in order to ensure speedy interaction without delays in human machine working modes. Here, the 3D CAD models are transformed into "lighter" DMU 3D representations (see explanation above concerning the geometric accuracy) to serve as basis for realistic visualization and simulation of the entire product or associated processes. These studies are, therefore, conducted with *Digital Mock-Up* (DMU) techniques using reduced data sets (i.e. lowered meta data richness and geometric accuracy) [6]. In order to handle these tasks, also non-relevant meta data information of the original CAD parts are deleted prior to the conversion into neutral 3D DMU file formats for the sake of speed.

A CAD design component may represent the left and the right tire of a vehicle, i.e. the same CAD file represents two instances of the same 3D CAD model. Digital Mock-Ups representations, however, create the visualization of the entire product in three dimensions and require, therefore, two separate entities of the instances in order to visualize the right and the left side position of the tire in vehicle position correctly.

Similarly, representations based on part records may use a single part number for an entire end-item assembly (like a full suspension subframe), that in fact consists of dozens of parts. In such cases, DMUs require unique identification of every entity. In addition, the whole configuration of the 3D DMU representations has to be able to resolve interferences, packaging and other design integration issues on an individual configuration level as well as on the combined cross configuration level.

12.1.2 *What Does DMU Do for an Engineer?*

Conceptual designers as well as System, Component and Manufacturing Engineers use Digital Mock-Ups to explore alternate product options, implications of various packaging scenarios and other information sets (like manufacturing process alternatives or ergonomic issues and consequences) across multiple configurations (see Fig. 12.3).

The Digital Mock-Up is used for packaging studies and engineering investigations throughout the product creation process. The DMU can also be leveraged for simulations such as package investigations, kinematics calculations or thermal simulations as well as simulations to plan the production process [9]. For example, modifying the air conditioning unit of a passenger car can affect the positioning and functioning of the steering devices. Similar system dependencies become apparent by studying the true 3D package positions in a front-wheel-drive engine compartment (compare Fig. 12.4):

- The transversal engine location drives the battery location
- The battery drives the brake booster location
- The brake booster drives the brake pedal location
- The steering column and the brake booster must not cross to allow column ride-down
- The steering column needs to be on the LHS (Left Hand Side) of the brake pedal
- The steering column cannot be further outboard due to the steering rack travel
- The brake pedal might end up too far inboard which causes trouble to be too near to the gas pedal and/or to limit the space for the inner compartment console.

Such a 3D based system integration and packaging analysis, however, does not work automatically and still needs substantial (automotive) system knowledge as well as the availability of a robust and reliable 3D representation of all technical systems in interplay of this vehicle zone in correct absolute and relative position. A specialist DMU or Packaging Engineer for engine compartment investigations leverages a full DMU with all core elements (product structure, 3D models, product position, product configuration), as outlined in Fig. 12.2. They have to conduct the

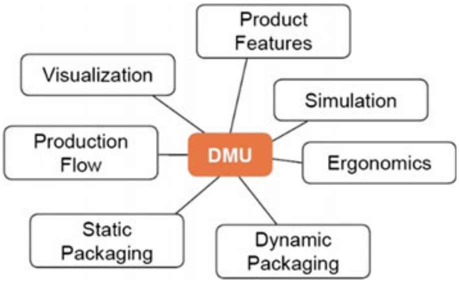


Fig. 12.3 DMU as central point for further applications

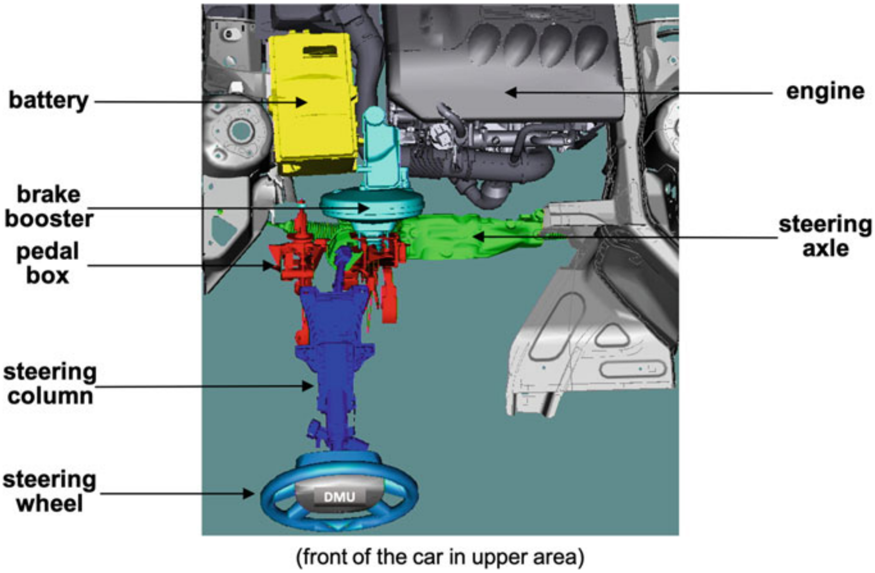


Fig. 12.4 DMU to investigate the mechanical package system dependencies between engine—battery—brake booster—steering column—pedal box positions

following methodological analysis steps in order to assess the situation as outlined above and shown in Fig. 12.4:

1. Determine the exact zone area of interest (usually done in xyz coordinate space or relative to a major sub-system). As it is shown in Fig. 12.5 (compare also the good match between the Digital and the Physical Mock-Up, which nowadays

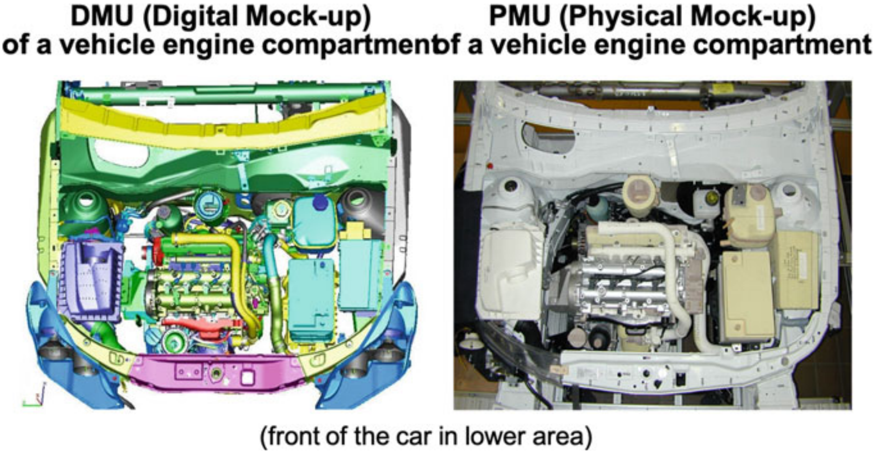


Fig. 12.5 DMU and PMU of an engine compartment of a passenger car

is no longer needed in most of the cases) the engine compartment zone can be limited by the car cross beam resp. dashboard panel (upper area) and the front grille opening (lower area). Such an engine compartment zone accounts for approximately 800–1000 individual parts, combined in different types of assemblies, incl. fasteners).

2. Perform an expert search for the systems of interest in the product structure, select a suitable component or assembly of such systems and conduct a proximity search in order to only show the possible sub-set of relevant components, assemblies and sub-systems for the specific system package analysis. Following this step, the number of different parts can usually be reduced by half or two thirds.
3. Down select those components and assemblies that follow the functional and package relations as shown in Fig. 12.4. For this step also significant technical knowledge is necessary by the DMU and Package Engineering since today's DMUs do not yet inherit functional and behavioral knowledge graphs. As result, the DMU or Package Engineer still has to work interactively with approx. 150 visual representations of different parts on screen, which explains why a lightweight representation of the geometry is necessary.

In any of such analysis cases, DMUs can help to assess effects of component movements and deformations or altered tolerances of components with respect to the entire product [7], e.g. with integrated static and dynamic analysis tools. However, any further detail analysis goal does trigger specific functional and behavioral models in outside simulations software packages (FEA, GD&T etc.) before those results are integrable into specific analytical type of DMUs.

12.2 The Role of a DMU in Product Development

DMUs start getting used for design and compatibility reviews at early phases of product development, long time before part records are released for production. In the old days of digital engineering development, up to the mid 90ties of last millennium, CAD models where composed in major CAD layouts every 4–8 weeks and afterwards, colored layout drawings where used to discuss the state of development progress. In contrast to these times, the appearance of Digital Mock-Ups drastically changed the advancements of digital engineering of major products such as aircrafts, cars, trains and big machineries. The constant building and delivery of DMUs every week or even every day became only possible due to the following three major advancements:

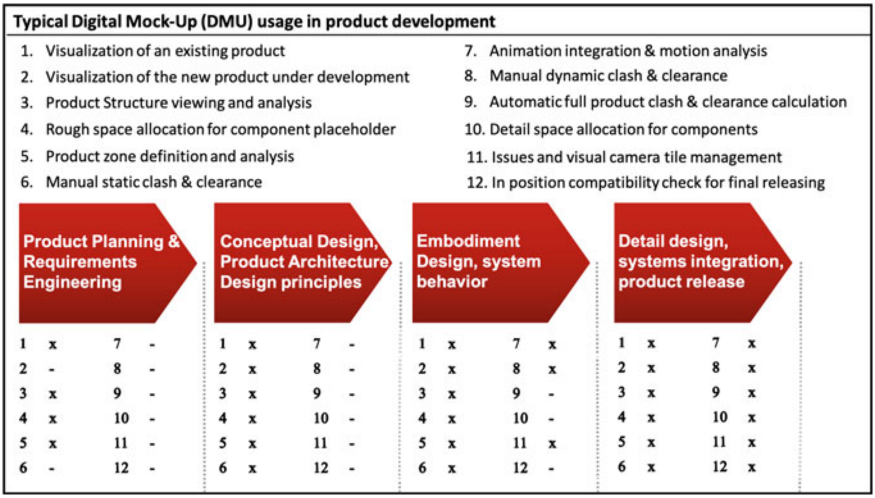
- Refinement of CAD assembly modeling in absolute product coordinate systems as part of the new digital modeling capability of Virtual Product Creation
- Set-up of solid publication processes from CAD to a companywide PDM environment as part of the new digital engineering process set-ups of Virtual Product Creation: unlike the traditional Team Data Management environments which only

provided data exchange insights for teams up to 20 or max 30 designers and engineers, the PDM environments provided data access and integration for thousands of designers and engineers

- Significant progress in IT technologies for Virtual Product Creation in order to:
- establish companywide intranet networks,
  - enable multi-lever IT server set-ups to constantly convert geometric and meta data formats into DMU type representations,
  - interrogate product and data structures via multi-branching structure traversal algorithms and
  - deliver rich and light weighed IT client interfaces to dynamically load and collaborate with data rich DMU representations of multiple Giga Bytes sizes.

With these new digital engineering capabilities of Virtual Product Creation DMU pioneering companies such as Boing, Ford, GM and Airbus started to set-up step-by-step a new regime of DMU based digital engineering methods to scale up Virtual Product Creation within their companies but also with outside partners and suppliers.

Figure 12.6 provides an overview on typical DMU usage pattern across the major phases of product development as they have been established since the end of last millennium. Quickly it became clear that the availability of DMUs are not only of advantage for CAD Designers and CAE Analysts. Manufacturing Process Planers, Engineering Managers, Buyers, Service Engineers and other product life cycle related personnel started to appreciate in the first decade of the 2000s the "easy to understand and consume" availability of DMU based design data nicely arranged in correct product position and step-by-step also in the most important product variant configurations. Obviously, it was difficult in every company to establish robust DMU creation



Typical Digital Mock-Up (DMU) usage in product development

1. Visualization of an existing product
2. Visualization of the new product under development
3. Product Structure viewing and analysis
4. Rough space allocation for component placeholder
5. Product zone definition and analysis
6. Manual static clash & clearance
7. Animation integration & motion analysis
8. Manual dynamic clash & clearance
9. Automatic full product clash & clearance calculation
10. Detail space allocation for components
11. Issues and visual camera tile management
12. In position compatibility check for final releasing

Product Planning & Requirements Engineering				Conceptual Design, Product Architecture Design principles				Embodiment Design, system behavior				Detail design, systems integration, product release			
1	x	7	-	1	x	7	-	1	x	7	x	1	x	7	x
2	-	8	-	2	x	8	-	2	x	8	x	2	x	8	x
3	x	9	-	3	x	9	-	3	x	9	-	3	x	9	x
4	x	10	-	4	x	10	-	4	x	10	-	4	x	10	x
5	x	11	-	5	x	11	-	5	x	11	x	5	x	11	x
6	-	12	-	6	x	12	-	6	x	12	-	6	x	12	x

Fig. 12.6 Typical DMU usage types in different product development phases (each major usage type marked with an x at the usage instance)

processes as well as best fitting digital engineering process set-ups and associated digital skills. It was necessary to build up specific departments and business roles within the organizations to ensure scalable and active DMU based digital engineering processes. Consequently, DMUs may undergo a formal creation and release process as described in the next sub-chapter.

12.3 Usage of Different DMU Types

In order to understand the DMU creation process it is critical to determine the scope of usage as outlined in Fig. 12.6. E.g., static and dynamic DMUs may be distinguished and more advanced versions of dynamic DMUs called Functional DMUs are under development and in first deployments. All of them have their specific purposes and will be discussed in the following sub chapters. DMUs are created within various phases of the development process in alignment with the availability of CAD parts for mechanics or electronics, Functional DMUs are further enhanced by logic and software control features. It is essential that companies develop and release a CAD model progression plan with a schedule according to their virtual development process. Unfortunately, many companies are lacking such consistent model progression plan due to:

- missing ownership in individual departments or by classical engineering staff members
- missing understanding and awareness of urgency in Management
- unsorted digital policy rules within and across companies in order to steer digital engineering progression with suppliers and partners
- unavailability of robust process to track, review, reconcile & align matched delivery points in order to guarantee meaningful technical system development and compatibility
- unclear methods and easy-to-use IT tools for ongoing reporting and issues resolution.

12.3.1 Static Digital Mock-Up

In a static DMU, the digital representations of components and assemblies are non-movable and rigid. Static DMUs are used for collision detection, assembly and packaging studies as well as for complex design layout studies. These static DMUs are mainly related to mechanical design applications and often require mature state of the geometrical parts or at least representations that are easy to be interpreted by model consumers and reviewers. Therefore, the overall complexity of the represented 3D parts and the amount of data to handle are both very high. Large amounts of data can only be handled with the help of powerful computer technologies and dedicated data reduction software.

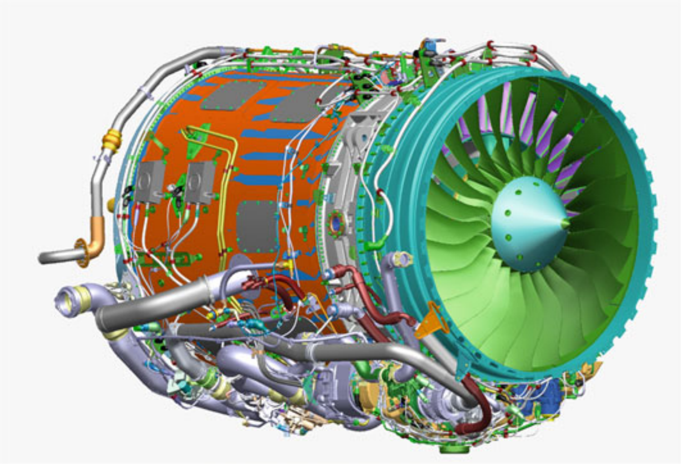


Fig. 12.7 DMU of an entire aircraft engine. Courtesy of Rolls-Royce Germany

The Digital Mock-Up of an aero engine (see Fig. 12.7) contains thousands of digital instances of visualization files, which are reduced in size from the original CAD master file with the help of data tessellation algorithms (i.e. data conversion operations which transform CAD models into triangulated approximations to reduce file size). Those data conversion operations are executed either at the CAD client side, that means at the CAD Designer's computer prior to the PDM upload or as part of the central data service of the overall PDM server regime (central server-side tessellation).

12.3.2 Dynamic Digital Mock-Up

The dynamic DMU is an enhanced version of a static DMU. It holds kinematic and dynamic elements and it is used for a variety of applications such as kinematic simulations, eigenmode analyses or for even more sophisticated simulations and investigations e.g. elastic or plastic deformations or behavior of hoses and cables. With a static DMU it is possible to ensure that parts and components of a product will not collide, meaning not occupying the same space while a dynamic DMU additionally allows for checking whether a specific part can really be assembled. For kinematic simulations one addresses information about degrees of freedom or motion capabilities to parts or components. This allows for virtual test of the functionality or for clearance and collision analyses.

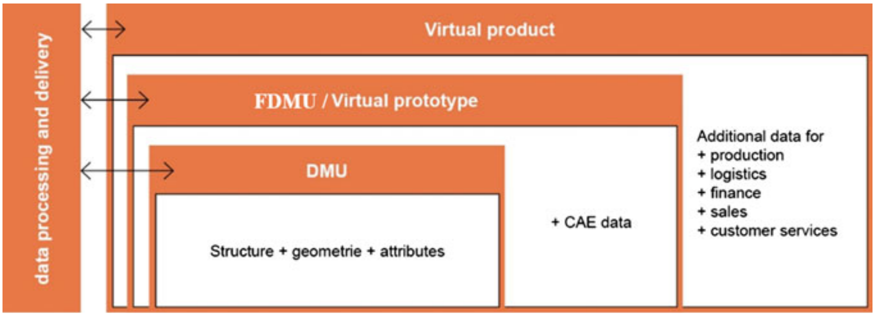


Fig. 12.8 Evolution from DMU to FDMU/virtual prototype and to (entire) virtual product

12.3.3 Functional Digital Mock-Up ("Functional Mock-Up")

Including more and more functions to products and considering larger and larger systems add also complexity to its digital representation. Functional Digital Mock-Up's (FDMU) driving the DMU concept further. In addition to the geometrical aspects of a DMU, a *FMDU* allows for simulation of the functional behaviors of such assemblies. *FDMUs* may couple control algorithms to CAD systems thereby allowing for a simultaneous functional testing of both together.

Let us understand the evolutionary positioning of the *FDMU* in the hierarchy of levels from DMU up the entire *Virtual Product* as outlined in Fig. 12.8: the Functional Digital Mock-Up (FDMU) belongs to the *Virtual Prototype level* and represents a DMU that is enriched with different types of CAE data (model characteristics, simulated behavior, etc.).

In order to achieve this evolution the concept of enrichment requires the incorporation of specific CAE models of mechanical components that are represented by visualization files of CAD models in current and correct position and configuration as part of the DMU, but also the integration of electric/electronic and software control model representations (compare Fig. 12.9).

A Functional Digital Mock-Up, therefore, adds the *functioning of the system under investigation* to the pure static geometrical aspects a conventional DMU. The Functional Digital Mock-Up (FDMU) is an extension of the well-established concept of a Digital Mock-Up. This approach constitutes a combination of traditional DMU with functional resp. behavioral simulation capabilities. Consequently, geometrical properties and functional aspects have to be considered simultaneously within a unique framework. This way, geometrical analysis/verification of a mechatronic system as well as functional/behavioral checkup of static, dynamic and logic functionality becomes possible. This combination constitutes an important step concerning the holistic validation and verification of mechatronic and cyber-physical systems (incl. the sharply growing cross product and technical system interactions).

FDMUs are intended to enable functional representations and analysis of a real technical system. As for all simulations, it is possible to use input data or boundary

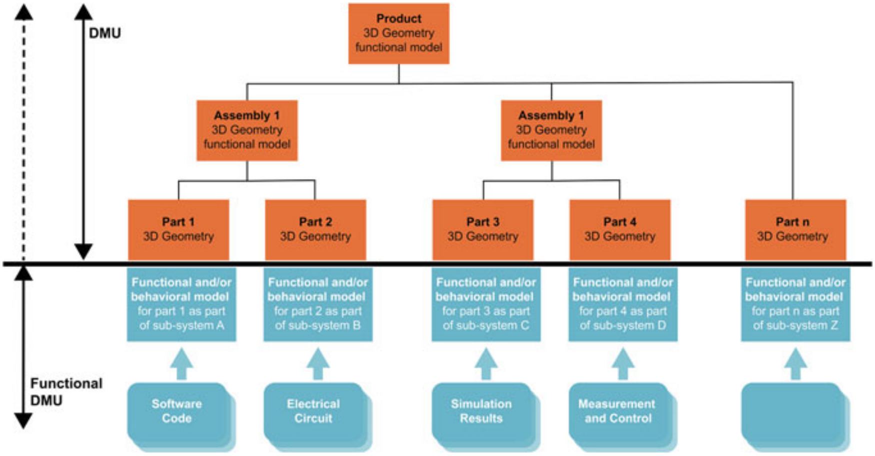


Fig. 12.9 FDMU and DMU

conditions obtained from real-life to conduct the simulations. In this sense, the FDMU takes over the role of the physical test object, as indicated in Fig. 12.10: although the full *Virtual Product* comprises additional information sets and characteristics (as shown already in Fig. 12.8).

The FMU/DMU has to align itself with the specific system analysis needs of the full *Virtual Product* in order to ensure that the three underlying FDMU elements model build-up, incorporated simulation models and virtual experiment assumptions are well aligned to each other.

An interesting property of the FDMU is the possible interaction between a visualization tool and numerical simulation in both directions. Hence, not only the simulation results can be presented e.g. within a VR-3D scene but the user can also actively influence a present simulation using the visualization environment.

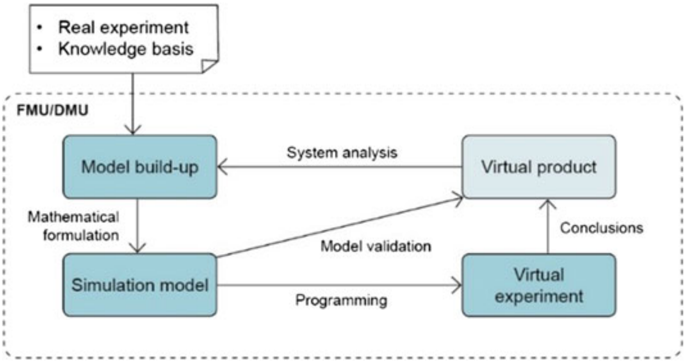


Fig. 12.10 Simulation set-up using FMU/DMU

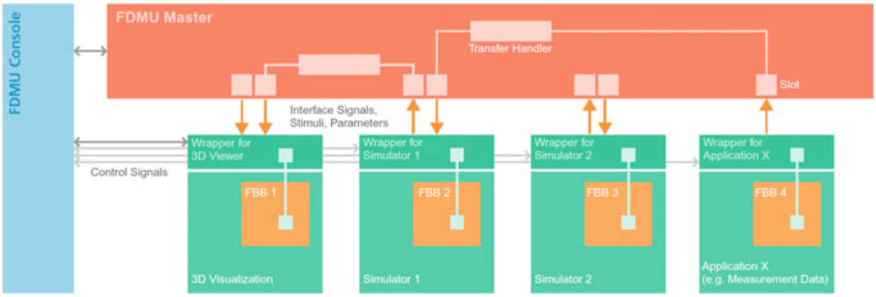


Fig. 12.11 FDMU principle based on a master simulator backbone according to [3]

Communication between visualization and simulation is carried out by a Master Simulator, as researched, developed and demonstrated within the Fraunhofer project "*functionalDMU*" between 2008 and 2011. This project has demonstrated that a FDMU allows for the functional interaction of a geometrical DMU with mechanics, electronics and soft- or firmware. Figure 12.11 shows the principle of organizing the individual functional simulation building blocks under the overall regime of the FDMU master (compare [2] and [3]).

Within the FDMU approach, the concept of a so-called Functional Building Block (FBB) is proposed by Enge-Rosenblatt et al. (compare [2]):

An FBB is an envelope summarizing geometric information (CAD models), behavioral models (e.g. described by differential–algebraic equations), and communication interfaces into one basic data module. Geometric information and behavioral information have to be created within their particular modeling tools. These models remain in their associated data files. Pointers to these files as well as all interface information and the mapping between geometrical data and the interface quantities of the behavioral model are collected within the FBB using the modeling language SysML for a unique description. Within every FBB, a simulator tool is also defined, which is capable to simulate the FBB's behavioral part.

A complete FDMU Simulation Model (FSM) consists of one or more FBB. Every input of an FBB must have an appropriate output belonging to another FBB. Furthermore, outputs can be propagated to the visualization to show simulation results using e.g. a geometric 3D model or some kind of plot versus time.

Obviously, there exist different kinds of technical realization options for Functional Building Blocks (FBB). Figure 12.12 shows a realization based on *Modelica*,[2] which is an acausal, object oriented technical notation language to describe physical models. *Modelica* uses mathematical algebraic and/or differential equations to describe the (inner) physical conditions and relations and offers interface connectors to couple the individual physical characteristics to other objects (or FBBs).

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[2] Modelica is standardized, maintained and further developed by the Modelica Association. Please see details under: https://www.modelica.org/.

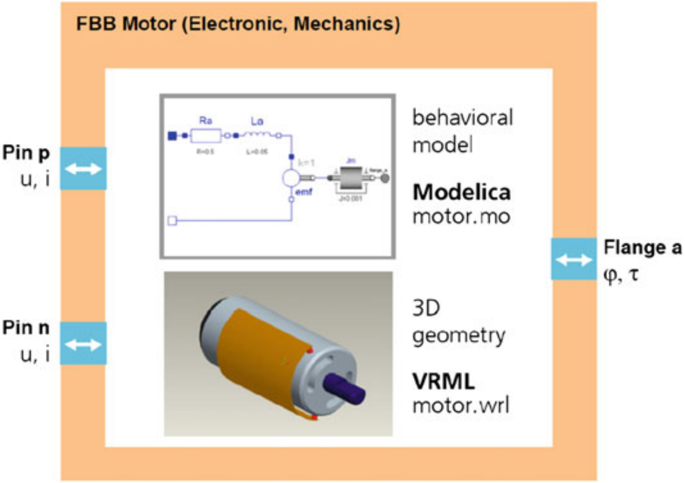

Fig. 12.12 Functional building block (FBB) example of an electric motor [2]

An alternative is a *causal* technical notation that directly uses so-called à-priori causalities of precedent objects with respect to the time-dependent influence on subsequent ones and that is mainly based on algebraic mathematical relations. The MATLAB[3] solution suite is, for instance, based on such a signal based causal notation with a wide range of other mathematical options to integrate technical-physical object behaviors.

A third alternative is represented by the system modeling language SysML which is maintained, explained and further developed by the *Object Management Group* (OMG)[4] and by *SysML.Org*.[5] The disadvantage of SysML, however, is that it cannot directly describe simulation models and, therefore, needs additional resources to realize the FDMU targets.

A fourth alternative is provided by direct couplings of encapsulated CAE simulation models by using the interface standard *Functional Mock-up Interface (fmi)*,[6] compare details in [7]: the Functional Mock-up Interface (FMI) is a free standard that defines a container and an interface to exchange dynamic models using a combination of XML files, binaries and C code zipped into a single file. It is supported by 100+ tools and maintained as a Modelica Association Project on GitHub.

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[3] For more information please refer to: https://www.mathworks.com/products/matlab.html.

[4] For more information please refer to: https://www.omg.org/.

[5] For more information please refer to: https://sysml.org/.

[6] For more information please refer to: https://fmi-standard.org/.

12.4 DMU Set-Up and Model Building

Setting up a DMU starts with collecting geometrical, configurational, behavioral and other information and attributes from CAD, CAE and PLM systems, respectively. Using best practices and proven guidelines, the DMU is generated from those building blocks. Figure 12.13 shows the overall process of building up a DMU model and of providing it for DMU based analysis work. The "design" of the DMU, i.e. the DMU model build requires a solid information base of all core elements that are candidates to be incorporated into a DMU (compare Fig. 12.2). This can only be guaranteed consistently if the following rules and conditions can be met within the overall Virtual Product Creation environment of a company as already outlined in sub-chapter *The Role of a DMU in Product Development.*

To generate a DMU automatically, the designer has to assign the 3D CAD model to a node in the PDM/PLM product structure and has to position it in every relevant car configuration. Positioning can be done either in absolute coordinates or in relative coordinates describing the position with respect to another part.

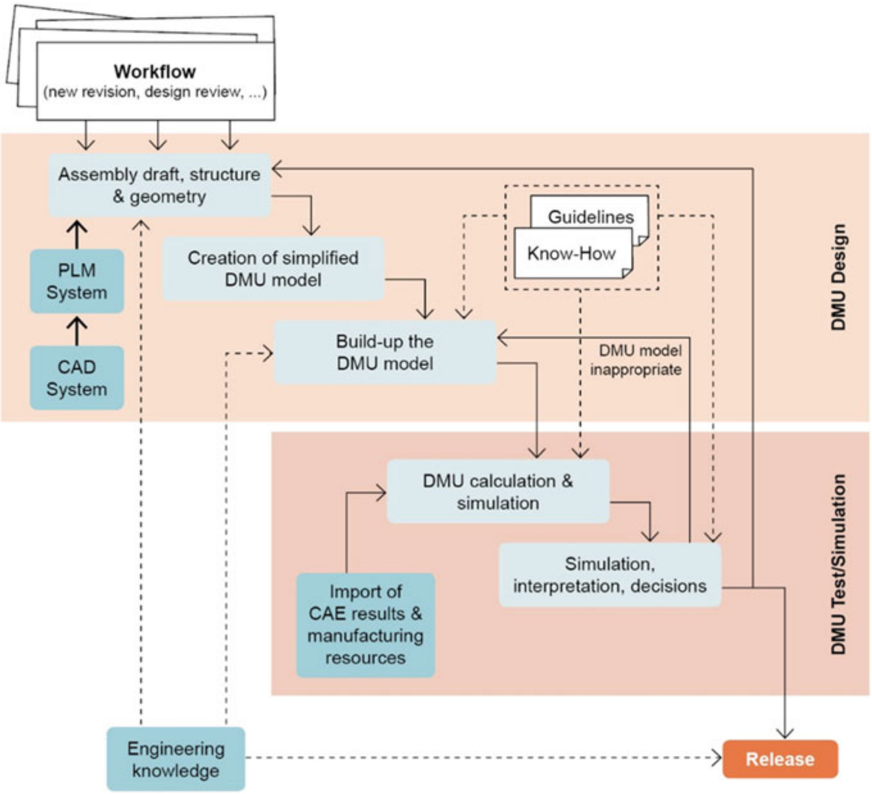


Fig. 12.13 DMU creation and use process

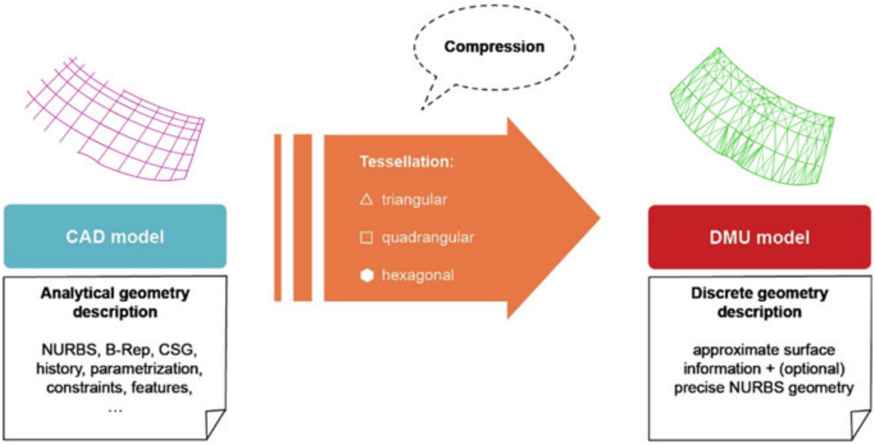


Fig. 12.14 Conversion of geometry from CAD model to DMU model

Based on a DMU model test and simulations such as geometrical layout or packaging clearance and clash analysis can be performed. For higher order simulations, the DMU model serves as basis. Depending on the aim of the DMU type (see sub-chapter before) the DMU model may be revised and enriched accordingly. Eventually, the DMU is released and can be used as single-source of truth for subsequent studies.

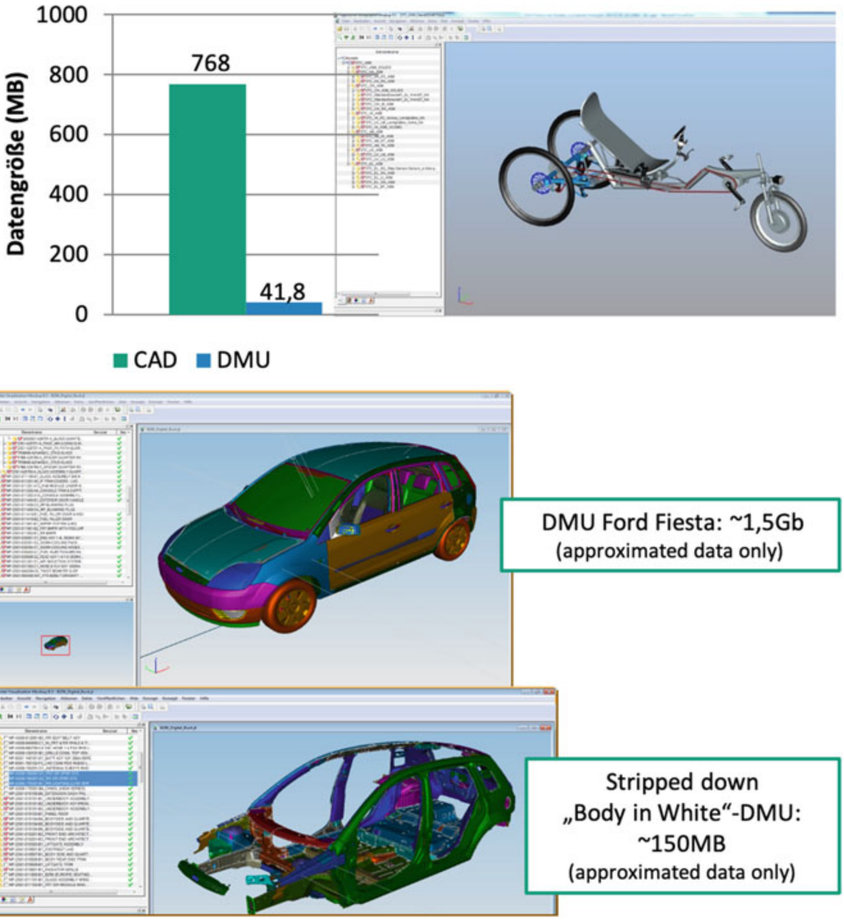
One of the core model build steps is the conversion of the exact (analytical and/or numeric) mathematical description of geometric entities such as surfaces and volumes into approximated ones. As shown in Fig. 12.14, the tessellation process converts the geometry descriptions of CAD models into approximated ones by using triangular (most common), quadrangular or hexagonal surface patches. In case of adding the original exact geometry representations from CAD to those approximated geometry representations in DMU compression technology is used to keep the file size small (compare explanations in sub-chapter "*Why does an engineer use DMU instead of CAD?*").

DMU models require only a reduced set of information compared to CAD part models. In principle, mainly the surface representation of the initial CAD parts is required to construct a sufficient geometry model in DMU. This information can be further reduced by simplification the surface modeling by a suited approximation, also called *facet representation*: it approximated the initial complex surface by more but simpler connected planes.

A process called tessellation, which means the approximation of any given surface by a set of geometrically simpler elements, realizes such approximation. These planes are polygon-shaped elements, where triangles are often used, as they are the simplest form of polygons. The process of approximating any surface by triangles is called *triangulation* (compare Fig. 12.14). For such purpose, various algorithms exist such as Delaunay algorithm or Watson algorithm [8].

Compared to the initial object, its tessellated surface model has significantly smaller data size. The DMU of the Smart Tripelec, shown in Fig. 12.15, has only 5.5% of the data size as the original CAD model. Another practical implementation offers different type of reduced and pre-configures partial DMU models which have been derived from a full product DMU. The lower illustrations of Fig. 12.15 show this effect. As starting point a full *multi variant vehicle DMU* based on ~9000–10.000 different visualization models in approx. 50.000–60.000 position instances would account for approx. 5 GByte of size (with an approximation accuracy of ±0.5 mm). Reduced vehicle DMUs (reduced by systems and variants) are offered like

- a *partial vehicle DMU* model with engine shrink wrap files only, without interior components, with limited underbody powertrain and electrical components



DMU Ford Fiesta: ~1,5Gb
(approximated data only)

Stripped down
„Body in White"-DMU:
~150MB
(approximated data only)

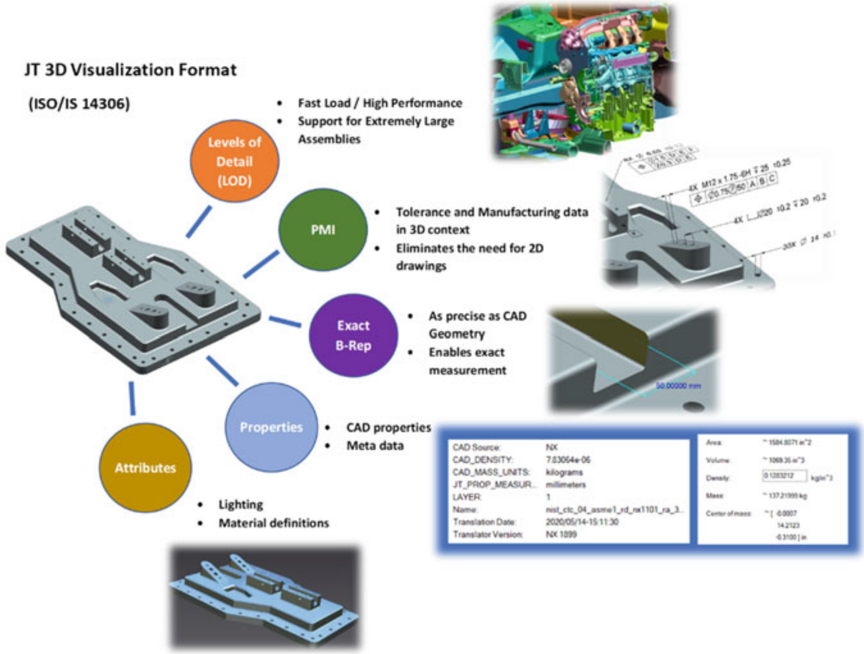
Fig. 12.15 File size of DMU models (CAD versus DMU) and partial vehicle DMUs, all based on JT (approximated data only without underlying exact NURBS representations) with a file size of ~1.5 GByte and

- a reduced *Body-in-White* sub-*DMU model that* only accounts of a file size of 150 MByes (with ~500 part instances).

However, discretizing the initial object and replacing it by its tessellated derivative means that this deduced object has lost the information about history, relationships to its neighbors, parameterization, constraints and other features of the initial object. Accordingly, the positioning of the components is not included in the discretized geometry description and must be specified separately. The geometry models from different 3D CAD systems are transferred to the DMU. Thereby, the surfaces described according to exact mathematical rules are replaced by surface meshes from flat surfaces in order to accelerate the visualization of the models in the DMU system.

The transferred models from the various 3D CAD systems are integrated into the DMU models. Examples for often used DMU-data formats are

- *JT* (Jupiter Tessellation), originally a proprietary standard from Siemens, meanwhile ISO standardized, compare Fig. 12.16



CAD Source: NX
CAD_DENSITY: 7.83064e-06
CAD_MASS_UNITS: kilograms
JT_PROP_MEASUR... millimeters
LAYER: 1
Name: nist_ctc_04_asme1_rd_nx1101_ra_3...
Translation Date: 2020/05/14-15:11:30
Translator Version: NX 1899

Area: ~ 1584.8071 in^2
Volume: ~ 1069.35 in^3
Density: 0.1283212 kg/in^3
Mass: ~ 137.21999 kg
Center of mass: ~ [-0.0007 14.2123 -0.3100] in

Fig. 12.16 Elements and capabilities of the 3D visualization format JT (courtesy support by Siemens Digital Industry Software)

- *3D XML*, proprietory format from Dassault Système, successor of the popular original Dassault Système DMU format *CGR* (Convergence Graphical Representation)

- *VRML* (Virtual Reality Modeling Language), ISO standard, meanwhile superseded by
- *X3D (Extensible 3D Graphics)*, ISO standard.

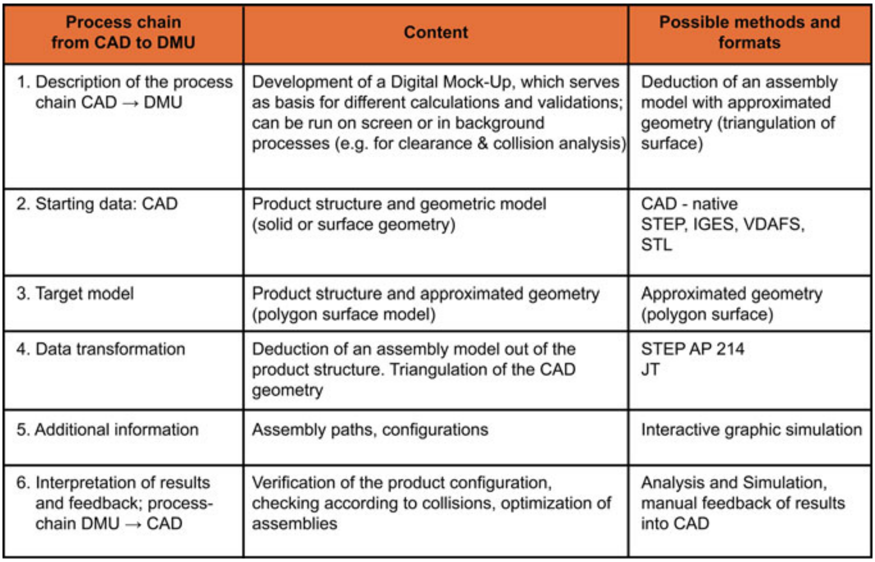
Originally the 3D visualization format JT (Jupiter Tessellation) was specified 1998 in a close collaboration between Hewlett-Packard and Engineering Animation, Inc. (EAI) and was developed based on the "Direct Model Toolkit". After having purchased EAI by UGS (1999) and after a later acquisition of UGS by Siemens AG (2007) JT nowadays belongs to Siemens Digital Industries Software.

JT is meanwhile an openly published data format as it has been accepted by ISO as an International Standard for 3D visualization. It is widely used for communication, visualization, digital mockup and a variety of other purposes at a majority of the world's leading manufacturing companies. In addition to visualization, many JT adopters use JT as a process format for workflows such as data exchange, supplier collaboration, and long-term data retention. As described in Fig. 12.16, JT supports characteristics such as approximated and exact mathematical (NURBS) description of geometric entities, level of detail (flexible mode of geometry visualization accuracy), PMI (Product and Manufacturing Information, i.e. support of engineering attribute data linked to geometrical entities) as well as other CAD properties, attributes and meta data.

For the positioning of parts and assemblies an absolute coordinate system is to be used, which all participants must comply with from the start. The product structure (optimally represented in the PDM/PLM systems), which must be defined and communicated at the beginning of the product development, is depicted in the reference model. The access of different areas to the DMU data can be regulated by the use of PDM systems [6].

However, the use of DMU is associated with a certain effort for the organization and usage. Furthermore, DMU geometries cannot be returned to the 3D CAD system because their structure must be changed when converting to the DMU system. The collision checks and measurements based on DMU analyzes also depend on the quality of the used geometry data. The overall creation of a DMU model, which is also called *DMU model build*, and its offering for DMU analysis work consists of six principal steps that are outlined in Fig. 12.17.

The overall DMU model build and the associated engineering support are owned by special DMU departments, which are meanwhile part of the engineering organizations. Such departments are not owner of the CAx data models and they are also not in charge of the underlying IT infrastructure (this is owned by the IT departments) which is needed to ensure robust DMU model build generation. The DMU departments, however, are the corresponding experts in order to build, verify, judge and analyze DMU models with respect to:



Process chain from CAD to DMU	Content	Possible methods and formats
1. Description of the process chain CAD → DMU	Development of a Digital Mock-Up, which serves as basis for different calculations and validations; can be run on screen or in background processes (e.g. for clearance & collision analysis)	Deduction of an assembly model with approximated geometry (triangulation of surface)
2. Starting data: CAD	Product structure and geometric model (solid or surface geometry)	CAD - native STEP, IGES, VDAFS, STL
3. Target model	Product structure and approximated geometry (polygon surface model)	Approximated geometry (polygon surface)
4. Data transformation	Deduction of an assembly model out of the product structure. Triangulation of the CAD geometry	STEP AP 214 JT
5. Additional information	Assembly paths, configurations	Interactive graphic simulation
6. Interpretation of results and feedback; process-chain DMU → CAD	Verification of the product configuration, checking according to collisions, optimization of assemblies	Analysis and Simulation, manual feedback of results into CAD

Fig. 12.17 Detailed steps of the overall process to create and use DMU models

- Setting scope and content of DMU configurations
- Orchestrating all IT services to perform the underlying data base interrogations, model conversion and model linking operations
- Enriching specific attributes and analysis results
- Keeping close contact to the CAD model authors in case of tessellation and or position/orientation errors.

- Providing hands-on navigation, analysis and documentation support in interactive design reviews incl. on-the-fly issues management
- Conducting and controlling off-line and automated clearance and collision analysis including the associated result management.

12.5 DMU Based Engineering Analysis Work

The DMU model build as described in the sub-chapter before must be aligned with the analysis and simulations tasks that belong to the identified DMU engineering investigation portfolio. Figure 12.6 introduced already an overview of typical DMU usage types in different product development phases. This sub-chapter will provide more insight into the immediate preparation of the appropriate DMU for such investigations and provides examples how the DMU based engineering analysis works.

To construct a DMU, it is necessary to have the *engineering bill of materials* and—which is even of more important during the development process—the *reliably configured product structure* of the product in question. Firstly, a DMU can be instrumental to analyze whether all required part geometries have been provided or which parts are missing just by visual representation of all linked visualization models (components, parts, assemblies) linked to the respective product structure nodes.

As in many other industries, the automobile industry, e.g., develops a number of different car variants of every model (left- and right-hand drive, automatic and manual transmission, different engines, and different customer-specific equipment) and so forth. Here, packaging is used to define the most critical configurations in terms of special constraints and requirements. These configurations then will be used to check the fitting of all parts with respect to each other. Clearly, a trade-off has to me made between the effort for these procedures and the number of variants to analyze. This trade-off is often made by experience and time constraints.

Figure 12.18 shows how the winglet sub-system of the overall aircraft wing system gets configured in the product structure which is available in a PDM System (in this case the PDM System Teamcenter Engineering of Siemens).

Usually, it is the task of a system and/or design engineer who owns this sub-system (winglet sub-system in this case), of a specific product modeler or of a BOM specialist to ensure that all components that are handled *as end-item assemblies* in the final assembly plant get variant coded with the correct company internal expression (feature code) language at the right level of the product structure. This task needs specific knowledge about:

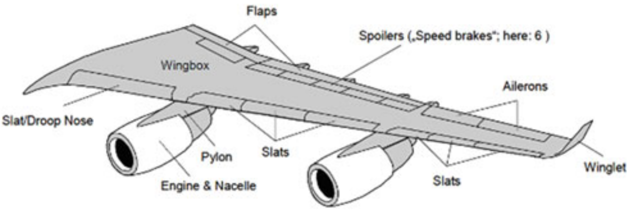
- the generic product architecture of the aircraft OEM as shown in the upper part a (compare details in [1])
- the design models of the sub-system of interest (in this case the winglet sub-system) as shown in the moddle part b and
- the correct coding expressions as part of the company specific expression (feature code) language.

As of today, there do not exist any variant coding standards within industry sectors or cross-company consortiums, which makes it difficult to align the variant coding for the product configurations. Even the type of variant expressions (see Fig. 12.18 part c) do differ significantly: there might exist rules, family expressions or even numerical value assignments.

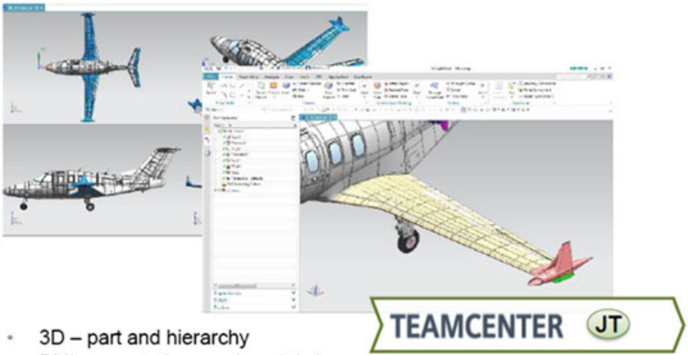
An aircraft DMU may contain 150,000 to 1,000,000 instances of visualization models depending on type (business jet, commercial aircraft or military jet or transporter), size (length, width, resp. single/double aisle), equipment levels and variant/configuration richness. Typically, such aircraft DMUs are used to represent different kind of development architectures through the virtual product creation process.

In the early development phases, the *Master Geometry DMU (MGD)* is created which contains all outer surface models of the fuselage, the wings, the empennage, power plant, and landing gear as well as the major aircraft axis. The MGD mainly serves as master to support basic airflow investigations with the help of Computational Fluid Dynamics (CFD) analysis, which constitutes a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that

a: Generic wing architecture (according to Dolezal)



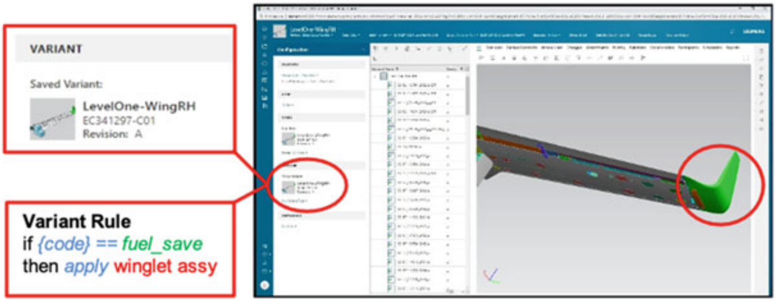
b: Creation of aircraft & wing configurations with digital models (JT) in PDM



- 3D – part and hierarchy
- PMI – annotations and model views
  - Formal annotation
  - Part and assembly level PMI
  - Organize information into model views and section views
- Author for multiple configurations

Views and PMI responds to configuration (effectivity) of design

c: Applying variant rules in Teamcenter (PDM) – coding/conditions for the winglet



Variant Rule
if {code} == fuel_save
then apply winglet assy

Fig. 12.18 Target oriented DMU model build preparation with the example of a configured wing system of an aircraft

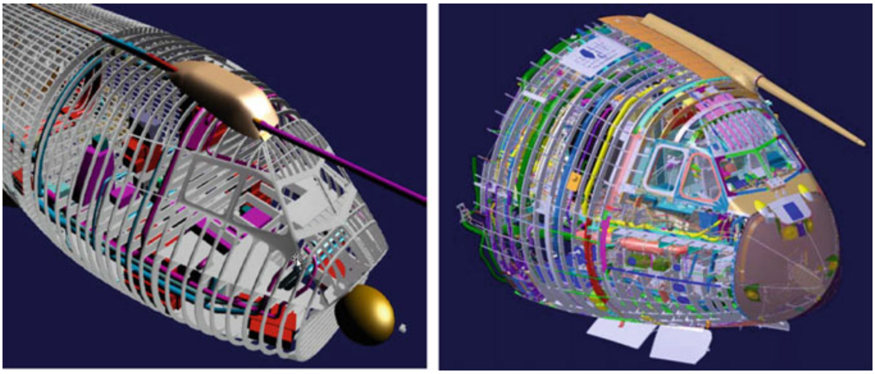


Fig. 12.19 Space allocation mock-up (left) and definition mock-up (right) of the nose fuselage section of the airbus A400M military transport aircraft based on Dassault Système CATIA CGR visualization files [1]

involve fluid flows. The second DMU often used in aircraft industry is called *Global Architecture Mock-up* (GAM): it is the master of the system architecture and support system installation engineering by representing package space and influence zones for fuel, electrics, hydraulics, air conditioning, flight controls etc. by simple cuboids, cylinders and flexibles. The third DMU type is called *Space Allocation Mock-up* (SAM) and represents major components in their allocated zones. The fourth type and most detailed DMU in aviation industry is called *Definition Mock-up (Definition DMU)* and contains all components throughout the final aircraft definition phase.

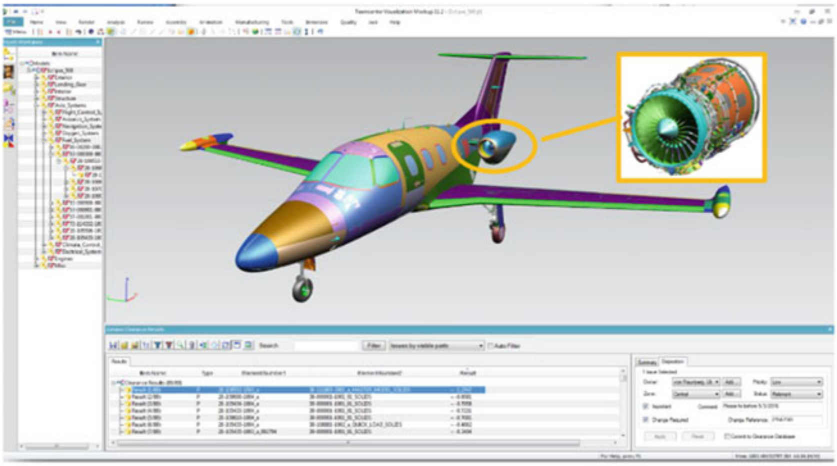
Figure 12.19 shows the difference between the *Space Allocation Mock-up (SAM)* and the *Definition Mock-up (Definition DMU)*. According to [1], those illustrations show two snapshots of aircraft development with a time span of about five years: while the *SAM* (left side) shows rough geometry of major structural elements and first space volume “claims” by systems and equipment the *Definition DMU* (right side) represent a densely packed nose section with all sorts of structures, systems and equipment fully detailed ready to be released for production.

If a consistent variant coded product exist within the PDM product structure it is then possible to traverse the product structure according to configuration sets that have been defined for the overall product. Figure 12.20 shows the situation of such a configured product—a full aircraft in this example—in the upper part a.

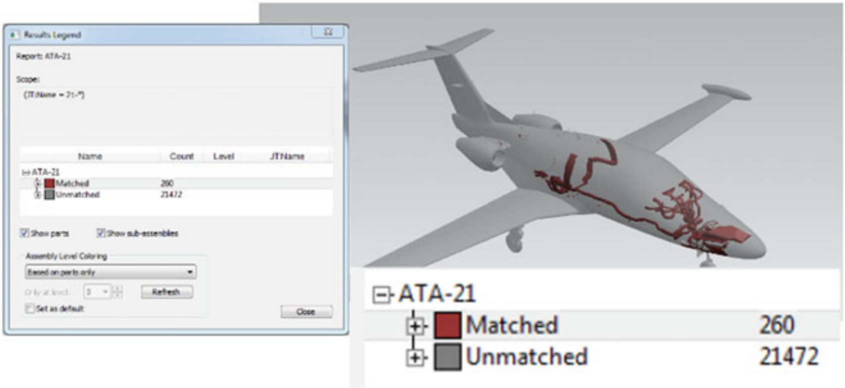
For such fully configures aircraft the aero engine systems usually are only represented in a „light “ shrink wrap mode, i.e. only the outer shape and attachment points are fully represented in the propulsion DMU model. All internal combustion and other technical system representations might be suppressed before providing it as supplied system to the full aircraft DMU.

In order to support the engineering progression of a product development program the DMU analysis plays a vital role: althrouhg designers and engineers might have received an official *space allocation* (i.e. a firmly claimed and “contractually” assigned virtual 3D x/y/z coordinate system space volume) for their own technical

a: Configured DMU representation of an aircraft within Teamcenter (PDM)



b: Clash & clearance calculation result summary for a selected technical system



Results Legend

Report: ATA-21

Scope:

(JT.Name = 21-*)

Name	Count	Level	JT.Name
⊟ ATA-21			
⊞ 🟥 Matched	260		
⊞ ▨ Unmatched	21472		

☑ Show parts ☑ Show sub-assemblies

Assembly Level Coloring: Based on parts only

☐ Set as default

c : Interactive fuselage zone analysis with clipping function for issues resolution

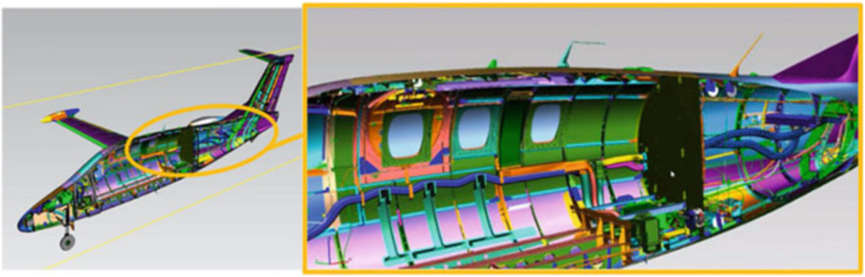


Fig. 12.20 Different types of engineering analysis based on a configured DMU

system components as part of the overall engineering steering process or mutually agreed one as part of the collaboration work amongst the neighbor system owners and the progam leadership team, there exist a high chance of mutually violating or distubring space violations.

In order to detect and manage those and to prevent system interacting noise distrubance the clash and clearance analysis process has been introduced as part of the overall DMU analysis activities. As starting point, it is executed based on static DMUs. As a second step, after having reached process maturity for the clash and clearance of the static DMU, also enriched dynamic DMU instances are added to the analysis. There exist different working modes within companies how such clash & clearance studies are conducted:

1. Automated calculation in a specific database (see results in Fig. 12.20, part b)
2. Interactive analysis of a DMU engineer or analyst (see Fig. 12.20, part c).

In order to be able to conduct automatic calculations within a DMU clash and clearance database, the following preparations must be done, both methodologically and technologically. Only very few companies in the world have meanwhile achieved this high maturity level of robustly executing such *automated* clash and clearance without disturbance and/or troublesome discussions around the daily, weekly etc. delivered results files with the respective system or design owners. Please note the pre-requisites for achieving such maturity level:

- Each configured DMU model will be additionally registered in an additional database that manages the used geometric space consumption of a component, assembly or system measured within a grid of volumetric elements called *voxels*. A voxel data base entry of a geometric entity, therefore, represents a value on a regular volumetric grid in three-dimensional space.
- Rules need to be defined together by the DMU analyst and the system/design engineers and owners with respect to:
  - Defining *clearance rules* with meaningful target values to guarantee sound technical system performance; e.g. within automotive package engineering a general clearance rule exists. This rule prescribes that a static clearance should not fall below a value of 15 mm between different components, which should not interact with each other. If such value is, lower a specific engineering analysis need to be conducted. For technical systems with specific dynamic interactions or possible disturbing error modes, the identifiable technical requirements need to be included into such specific clearance rules.
  - Defining *clash exclusion rules* in order to sort out all unintended clashes between components that cause clashes in their modelled shape due to standard CAD design modeling practices. This allows in many cases to reduce design modeling efforts of not showing the exact final shape of a components (e.g. in case of flexible or conformable material) or to only show the “as manufactured” but not the “as installed” design situation (this does include situations where rubber sealing and other interface parts are not shown in compressed form).

  - Allowing for specific *"non buildable worst case engineering configuration rules"* in order to accommodate for product variant spanning, invariable design situations or protection (often platform based engineering needs to protect for future, upcoming design situations which are not yet represented by appropriate 3D representations).

- Customized and tailored clash and clearance report generation for specific zones, product systems and system/design engineers and owners in order to meaningfully reduce the high number of first run reported clash and clearance issues from thousands (for a DMU consisting of 60.000–100.000 model instances) down to dozens or to a maximum of low hundreds. Since this requires substantial technical system development know-how, there exist a great potential of AI support for that task in the future!

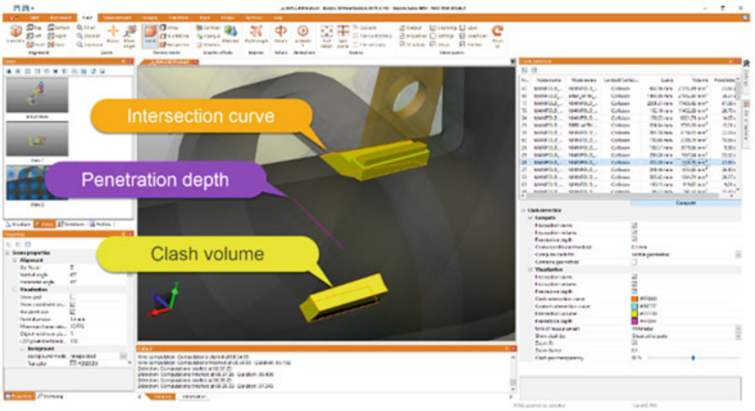
It becomes obvious, that, still today, the majority of the clash and clearance analysis needs to be conducted interactively by DMU and system/design engineers by using 3D analysis methods in combination with inherit design and engineering knowledge of individuals or within an engineering team. For such interactive analysis, the following approach is being taken:

- The DMU resp. design/system engineer selects the relevant configuration from the list of offered DMU variants, manually selects the relevant DMU parts from the DMU product structure or uses different kind of search algorithms within the DMU software in order to finally determine the intended *collection of DMU parts for the analysis*, please note, e.g., the following three ones:
  - Neighbor search
  - Proximity search (all parts in the nearness of a bounding box with a certain size around the selected components)
  - Attribute search (selecting all components that carry a certain engineering or variant attribute such as released, in work, in configuration etc.)

- Having arranged the analysis collection of parts, now the interactive clash and clearance function of the DMU software can be activated; such algorithms works internally as follows:
  - For each of the DMU part the bounding box representation is used in order to detect which of the bounding boxed do interfere to each other (based on the target value of clash, i.e. less then ~0 mm distance, or the clearance value of interest). If a positive case is detected all facets of the approximated representation of the individual DMU parts are cross-analyzed to each other in order to determine where exactly between the parts the clash or clearance situation exist and the shortest distance is measured, represented with a line vector and stored.
  - After all analysis calculations are done within seconds or minutes (depending on the size of the collection of DMU parts for the analysis) a report is created which can be interactively reviewed and studied.

- Finally, it is decisive how the results are presented back to the DMU resp. design/system engineer in order to trigger a direct and smooth analysis interpretation and potential resolution steps. As shown in Fig. 12.21 there exist a couple of different visual aid opportunities to increase the immediate understanding of the engineering interpretation of the results:
  - Highlighted colored explanations of the clash volume, the penetration path and the overall intersection curve of the involved components and/or assemblies (see Fig. 12.21, part a)
  - Color-coding for the clearance zones between the involved components and/or assemblies (see Fig. 12.21, part b).

a: Presentation of a clash result within the DMU application 3DViewStation



b: Presentation of a clearance investigation within the DMU application 3DViewStation

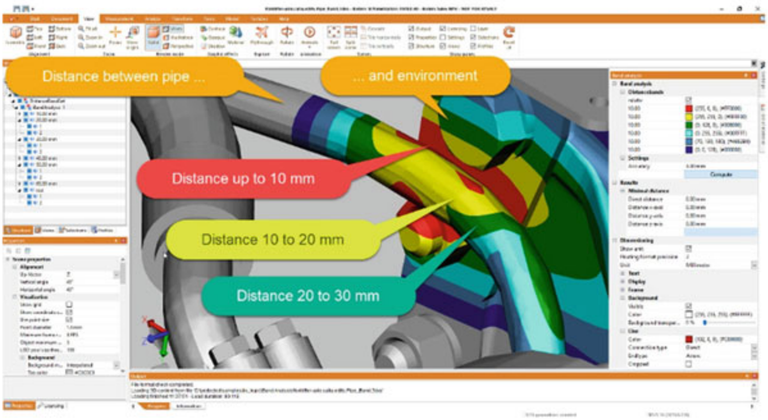


Fig. 12.21 Clash and clearance result presentation in the 3DViewStation of KISTERS

3D DMU models are also used for a range of other typical engineering investigations in order to judge the overall product system characteristics, behaviors and design opportunities. As shown in Fig. 12.22, the DMU engineers or users get trained to interactively use a set of sequenced DMU methods in order to drill down to the design and engineering point of interest.

Applying overall product system knowledge of the entire DMU model ((a) the DMU engineer or user selects the appropriate viewing angle and plane (b) in order to further applying down select methods such as part (de-) selection (c) and clipping plane application (d) in order to reach the free view on internal key characteristics of the product.

The power of Digital Mock-Up has meanwhile been transferred from aerospace/aviation and automotive industry also to other industries such as maritime and to new application fields such as city navigation and development.

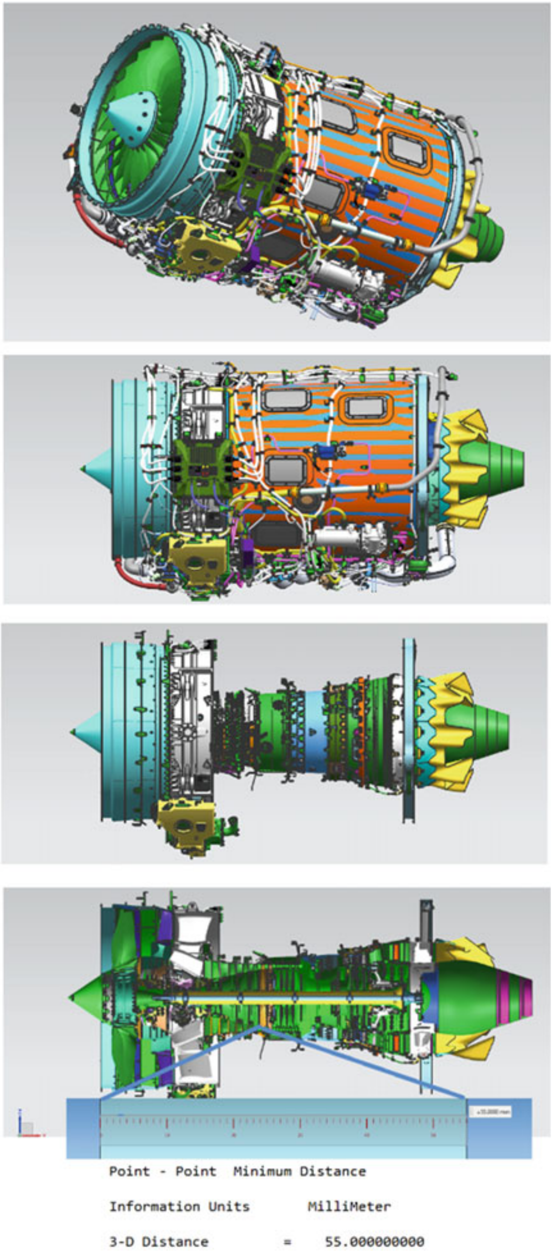
As shown in Fig. 12.23, the number of elements and instances shown in such DMUs extends those of automotive DMUs by a factor of 10–20. In order to allow for smooth interaction within such environments Dassault Système has developed a service as part of the 3DEXPERINCE platform in order to dynamically configure, visualize and analyze large sets of DMU model instances. As part of the data representation schema all DMU objects within 3DEXPERIENCE are indexed (i.e. even the individual facets of the 3D models) in order to shown one or several facets at a time, given the user scenario (system engineer, layout engineer, manufacturing engineer, design engineer etc.). As an example, 3D faceted representation plus the semantic representation such as functional tolerances plus the links between objects can be displayed at once, for a manufacturing engineering role. As a designer role, the exact geometric representation can be dynamically added for such geometry to be modified. The semantic indexing technology deployed for such a scenario allows for extremely fast working sessions setup.

The DMUs in 3DEXPERIENCE support different kinds of views from sources such as 3D CAD, 3D laser scans, panoramic pictures, piping and instrumentation diagram (P&ID) and systems or functional diagrams, among others. The overarching data standard for such capabilities is called 3DXML, which exists in two types:

- 3DXML for authoring (design and modeling)
- 3DXML for experience (viewing, simulation results, animations…).

The '3D visualization' part of 3DXML is based on a derivative of the CGR (Convergence Graphical Representation) technology. In summary, Digital Mock-Ups (DMUs) are powerful environments for engineers, designers, planners and managers in order to provide consistent virtual prototyping capabilities to support the following types of investigations as part of the following three classes of DMUs:

1. Technical system, assembly and component interactions as part of a *Product DMU*
2. Machinery, tools and fixtures, handling and logistics as well as plant infrastructure interactions as part of a *Factory DMU* (compare Chap. 15)



a: Loading a DMU with around 27000 part instances

b: Selecting a viewing plane for further engineering investigation of the DMU model

c: (De-) select parts for an engineering detail investigation (applying zone, component and system knowledge)

d: Choose a clipping plane to cut away external material in order to measure, analyze and assess internal system dimensions, tolerances and functional characteristics

```
Point - Point  Minimum Distance

Information Units       MilliMeter

3-D Distance         =    55.000000000
```

Fig. 12.22 Interactive DMU aero engine investigation using a series of 3D DMU methods

a: DMU of a cruise ship with approx. 10 million instances in 3DEXPERIENCE

b: DMU of a city: 200 000 buildings, 1 million trees, 500 000 urban furniture, and 3000 km roads in 3DEXPERIENCE

Fig. 12.23 Mega size DMUs in the 3DEXPERIENCE platform of Dassault Système

3. Building, technical building infrastructure (water, electricity, data networks, heating etc.), roads, squares, energy infrastructure, traffic systems (rail, road, aviation etc.) interactions as part of *Real World* (City, Agglomeration areas etc.) *DMUs.*

The International Organization for Standardization (ISO) has released in 2019 the world's first international standards for BIM (Building Information Modeling), the ISO 19650-1 and ISO 19650–2, which become pivotal for the set-up and exchange across companies and organisations of the DMUs of class 2 and 3 (see listing above). The full name for the standards is *"Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—Information management using building information modelling,"* and the organization has already released Part 1: Concepts and principles and Part 2: Delivery phase of the assets. The ISO plans to release a Part 3 (on the operational phase of assets) and a Part 5 (security-minded BIM, digital built environments, and smart asset management) within the following years (compare [10]).

References

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