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Bridging the Gap Between Product and Simulation Data Management

An Analysis of the Needs and Possibilities in Industrial Engineering

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Public Version

Due to the confidential nature of this thesis' content, parts of it have been censored to allow a publication. Where appropriate, the names of the interviewees and companies have been substituted with an identifier in Table 3.2. Other or more critical information has been censored. The interview notes and their summaries in the appendix have been wholly left out.

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1. Introduction

"Coming together is a beginning, staying together is a progress, and working together is success." Henry Ford

Virtual Engineering

A key working method in manufacturing engineering is developing and validating product requirements throughout the development process. While requirements for products become increasingly advanced, engineering solutions become increasingly complex. This called for the digitalisation of product modelling, which at the same time allowed for more precise geometry variation and in-advance calculation of manufacturing processes. This virtual modelling is known as Computer Aided Design (CAD). On a larger scale it is often referred to as Model Based Design (MBD). [see 2]

The increased complexity of engineering solutions leads to assessments being, at times, very expensive undertakings. To save time, material, and personnel, virtual testing has been continuously established since the late 20th century. E.g., previously whole prototypes had to be destroyed for crash testing, or separate test benches were needed for each structural or dynamic, solid or fluid test. Instead, verification, debugging, and optimisation for such cases can now be run in simulations. The various simulation types are subsumed as Computer Aided Engineering (CAE). [see 3, 2]

Standardisation

As manufacturing units become specialised and disjoint, data exchange among departments, companies, and engineers becomes increasingly difficult. The collected information, therefore, needs to be understandable and traceable throughout the Product Development (PD). Traceably carrying all relevant information during the development process is known as Data Continuity. Ideally, it establishes an unbroken so-called Digital Thread.

The Digital Thread usually needs to be kept across varying software landscapes. For the data to remain interpretable by different applications, data standards are necessary to allow for a smooth translation from one application to another. For this, well accepted standards exist on both CAD level (such as STEP) and CAE level (such as VMAP).

Problem Statement and Research Question

CAD and CAE - as well as many other functions in virtual product development - solve very different problems. Therefore, they have fundamentally different questions to the virtual representation of the product, known in later development stages as the digital twin. Accordingly, different numerical methods, software solutions, engineering workflows, and business units are involved. The connection between these is a main function of Product Lifecycle Management (PLM). (see Figure 1.1)

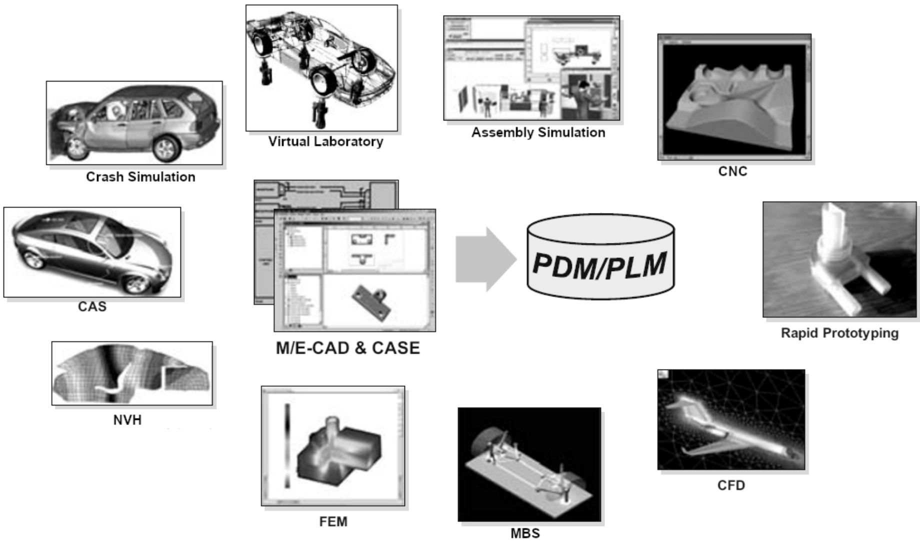

Figure 1.1: Examples for different product views in parts of PLM. As each solution fulfils very different functions, different data is required. (Translated from German) [2, p.49]

While standardisation efforts allow for smooth exchange of data within domains, they are currently not capable of establishing a complete digital consistency when data is transferred from CAD engineers to CAE engineers. Although some attempts for a connection exist [e.g., 4, 5, 6], they are currently not well established in industry. Therefore, workaround solutions and customised, self-written codes prevail in places, where appropriate standardisation might bring the two domains closer together, and slim down and speed up industrial workflows.

The aim of this thesis is to research the industrial situations in the parts of PLM which are concerned with the two domains - namely, Product Data Management (PDM) and Simulation Data Management (SDM) -, and derive directives for solutions to the found issues. This implies the research question of this thesis:

What are the needs and possibilities in the manufacturing industry for connections between CAD and CAE data in product development?

Thesis Strategy

To answer the research question, first the current situation in PDM and SDM is evaluated on the basis of existing literature and the standards STEP and VMAP are introduced. From this, an objective for the connection of CAD and CAE data is derived. This sets up an engineering requirements analysis in the form of interviews in an industry survey. The survey is based on theoretical literature for exploratory research as well as existing surveys in similar fields.

The results of the survey are used to update the perspective on the industrial situations and workflows. Lastly, development directions are derived from the findings to drive the improvements for the STEP and VMAP standards.

2. Current Technical Capabilities of Virtual Manufacturing Engineering

Summary: This chapter offers an overview of the situation of workflows, data management methods and data standards concerning design and simulation in PD for industrial manufacturing. It leads to a problem definition and objective for the subsequent engineering requirements analysis.

2.1 Industrial Manufacturing and the Digital Twin

Industrial manufacturing is a chain of product or service development steps, from idea generation to disposal. Using CAE in industrial workflows has led to a number of improvements. Product design generally follows the same rules, but a significant reduction in costs was possible by conducting tests virtually instead of repeatedly damaging products for destructive-testing purposes. The simulations serve to verify each process, to assess the manufacturability of the parts, to consider manufacturing effects and influences of structural performances and to optimize the workflow chain. [see 3]

An example for the product development process is displayed in Figure 2.2 in a so-called V-Model, including the validation connectivity, system detail level and disciplines.

Figure 2.1: PROSTEP AG's vision for a digital twin in shipbuilding. [1, p.9]

In MBD, a virtual product representation is created, also referred to as a digital twin [7, p. 64] (see Figure 2.1. This can be a very useful tool which allows to quickly produce results to judge the manufacturability and performance of a product. Within the next decade, digital twins are expected to be omnipresent in simulation-based engineering solutions, and will be a central part of the engineering work cultures, including a wide range of information from the whole of a product's life cycle. So, on one hand the digital twin plays a role within simulated workflows. On the other hand, simulation is only a part of the information contained in a digital twin. [see 8, 7, 3]

Modern PD involves multiple steps, all of which cannot be carried out by a single application. However, to complete the development cycle, all these functions must refer to the same data. This data is typically stored in PDM systems for design and management data. Simulation tools, on the other hand, involve complex numerical concepts and each tool specialises in carrying out only specific mathematical equations. Therefore, their data is managed in different systems called SDM. Bringing these - and many other data management systems - together is the main objective of PLM. [see 3, 2]

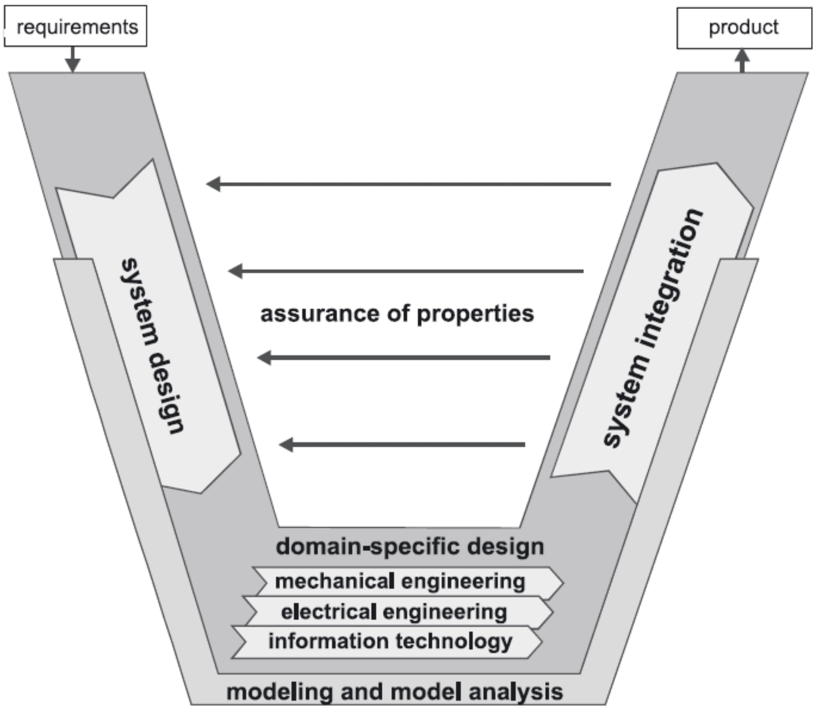

Figure 2.2: Schematic example for a V-Model in product development. During the development stages, the requirements are created left-to-right on levels of increasing detail (lower) and then verified on levels of decreasing detail (higher). During development, disciplines such as mechanical engineering, electrical engineering, and IT separate with the increasing level of detail and are later combined for higher-level verifications. [9]

2.2 Workflow Perspectives in PLM, PDM and SDM Environments

2.2.1 Product Lifecycle Management and Product Data Management

PDM systems arose in the 1980s as a common system for print and digital documents, in order to centrally organise design and management data. It is now a central IT solution in PD. Its key functions are:

- Traceability of all PD stages.
- Linking documents and data to each other in various ways.
- Process management, made up of
  - Work management, including version control,
  - Workflow management, being the most distinct component of PDM including graphic descriptions of workflows, and

– Work protocol management. [2, pp.32f]

In the User Interface (UI), typical PDM functions are the technical Bill Of Materials (BOM) and sensible grouping techniques [see also 2, ch.6.3] for fast tracking of data. Other functions can be workflow management, project management and archival. [2, ch.3]

The combination of well implemented data and process management allows for Configuration Management, which implies transparent and visible physical and functional features (i.e. configuration) of a product throughout its life cycle, including all past constructed and/or manufactured configurations [see also 10]. [2, ch.3]

Product Data Management (PDM). A system for the collection and management of CAD relevant and related data, including product and process models. It aims at producing unambiguous and reproducible configurations. [see 2, 7]

While PDM encompasses mainly the product planning and development, PLM widens the view to other aspects of a products' life cycle. It does not set the BOM as its central structure, but the requirements structure and the resulting configurations, see Figures 2.2 and 2.3. Key components of PLM are management functions, engineering collaboration, material sourcing (coupling with suppliers), PDM (coupling with PD), PD management (coupling with the digital factory) and customer needs management (coupling with the customers). Instead of offering "out of the box" solutions, most PLM solutions couple to existing IT systems and integrate them into a mutual framework. [see 2, ch.3]

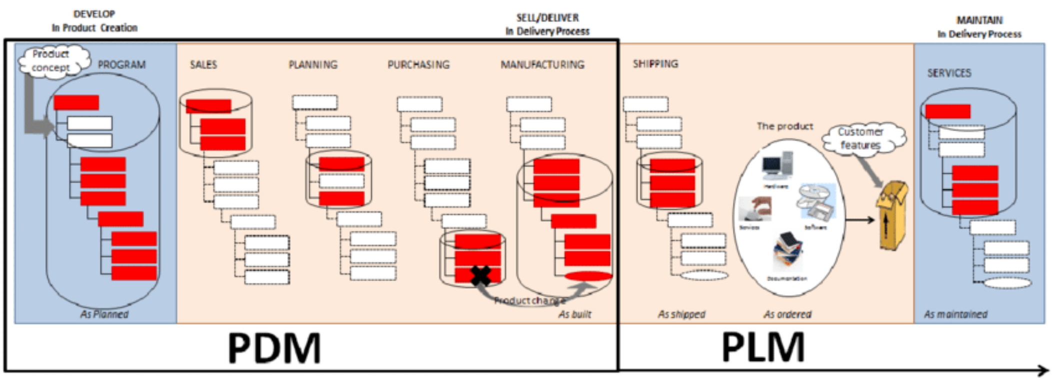

Figure 2.3: The subset of the PLM spectrum covered by PDM. The accessed product structures vary significantly during the different development stages. [11, Fig.3]

When defining and organising a data management environment, a key aspect is ensuring a Single Source of Truth (SSoT). For this, Master Data Management (MDM) systems are used to combine different data management systems. As such, PLM systems subsume all data management systems related to product data (e.g. mechanical or electronic PDM and SDM systems), as well as product-relevant management data (e.g. Enterprise Resource Planning (ERP) systems), and ideally in-use data like Internet of Things (IoT) (see Figures 2.3 and 2.4). Unlike classic PDM systems, modern PLM solutions do not necessarily store data themselves, but refer to data stored in other systems. [see 2, 12]

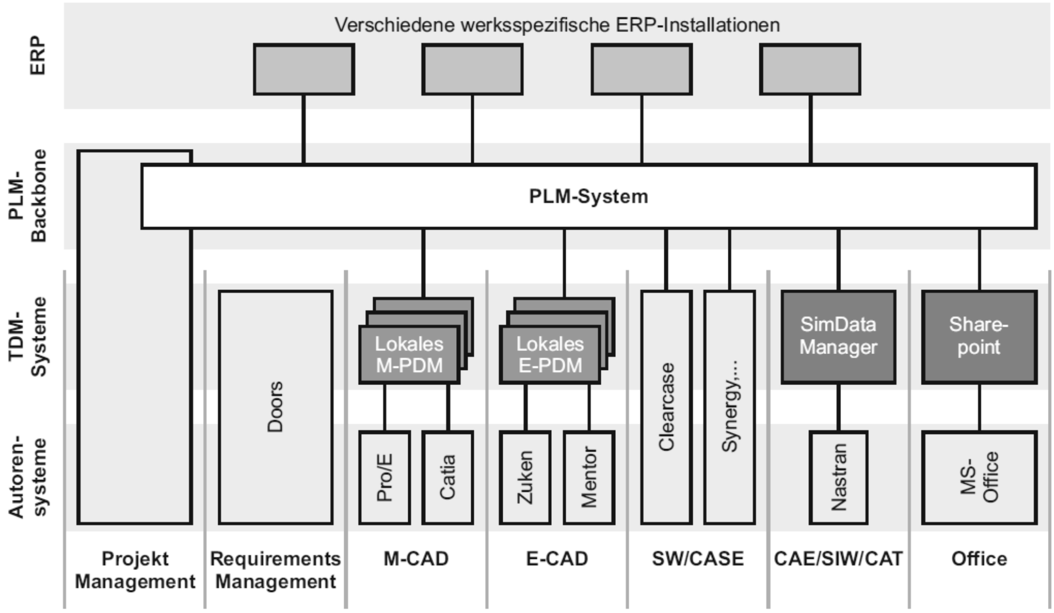

Figure 2.4: Hierarchy of subsystems related to a PLM system. The UI is defined by the authoring systems ("Autorensysteme"). Data is organised in Team Data Management (TDM) systems such as local PDM and SDM and exchanged and set in relation to the unit-specific ERP systems via the PLM system. [2, p.43]

Product Lifecycle Management (PLM). "A system for the collection, management and interpretation ('handling') of relevant information for the product, project or system to be managed." [8, p.28] It captures a holistic multi-level view of the whole product life cycle from cradle to grave, covering pre-development, marketing, management, production, and servicing. (see [2, 7], Figure 2.3)

Although it can be argued, that the ideal PLM is still not properly implemented anywhere (see subsection 4.2.2), most PDM solutions strive towards covering PLM, especially with regards to Requirement Traceability Management (RTM), and mostly contain information beyond product design. Therefore, the term PLM is used for both, unless an environment is specifically or exclusively concerned with CAD data or set in relation to a separate MDM.

2.2.2 Simulation Data Management

Parallel to basic PDM, SDM systems are usually used as independent management systems for companies or company units specialised in simulation services to organise their simulation-related data. It is sometimes integrated into existing PLM systems. This integration is still only a very small part of PLM, though. [see 2]

The key characteristics of SDM also mark the main differences to PDM and classic PDM-based PLM systems:

1. Simulation data is complex, large and agile. The results of crash simulations can be terabytes in size, dimensions of simulation results can be scalars up to tensors, and much of the data is temporary or only interpretable in the context of the

simulation parameters. Typically, adding few parameters can easily increase the file size by orders of magnitude.

2. Simulation data is distributed, some data remaining on the High Performance Cluster (HPC) units running the calculations, other on local clusters. The file size implies that intensive data transfer is not feasible.

3. The space-discretisation of CAE brings about, that visualisation and collaboration run in very different processes than CAD.

4. These processes must be tracked down to the 'how' and 'why', tracing simulation results to the input data and software application version. [see 7, 13]

Additional features of SDM systems can be ERP functionalities, storage management (such as compression and deletion rules), rights & roles for access, light weight visualisation, simulation automation, and integration or interfacing with CAE tools and other data management solutions. Depending on the degree of process management included in SDM, it is also referred to as Simulation Process and Data Management (SPDM). [see 7, 13]

Simulation Data Management (SDM). "A specific technology developed to capture and manage complete, granular simulation datasets comprising any flexible, evolving structure of simulation and process data for Process Systems Engineers (PSEs). SDM captures the data arising from simulation processes, enables the Digital Thread of the simulation to be displayed as a Graph [7, p.65] and acts as a digital notebook for the analyst. SDM can be deployed in order to assure quality & traceability, capture Intellectual Property [sic!], enable the working of global simulation teams, accelerate processes and build a Knowledge Database." [7, p. 66]
Simulation Process and Data Management (SPDM). "An SDM Solution extended by the integration of simulation process management in order to enable automation of repetitive tasks by simulation engineers." [7, p. 67]

SPDM and SDM are used interchangeably in practice and usually SDM systems today include process management. Therefore, the term SDM will be used collectively.

2.2.3 Data Exchange Between Design and Simulation

For any simulation workflow, a virtual representation of the simulated object is required. This is provided as a CAD model in most PD workflow scenarios. The model can either be exported from the PLM, from the CAD application, or transferred internally within the PLM. However, the latter is currently not the regular case, as data is stored in many different ways (see section 2.4). Instead, the models are transferred using either native or standardised formats. [see 2, 7]

A schematic workflow figure for simulations within PD is given in Figure 2.5.

Usually, the communication back from simulation to CAD uses 3rd level results. 1st level would be the output-deck, 2nd level the converted raw numbers in diagrams, animations, heat maps, etc., 3rd level are reports and assessments such as whether the requirements were met. Nowadays, some CAD tools even have pre-defined simulations for testing inside their environments. (see B.6)

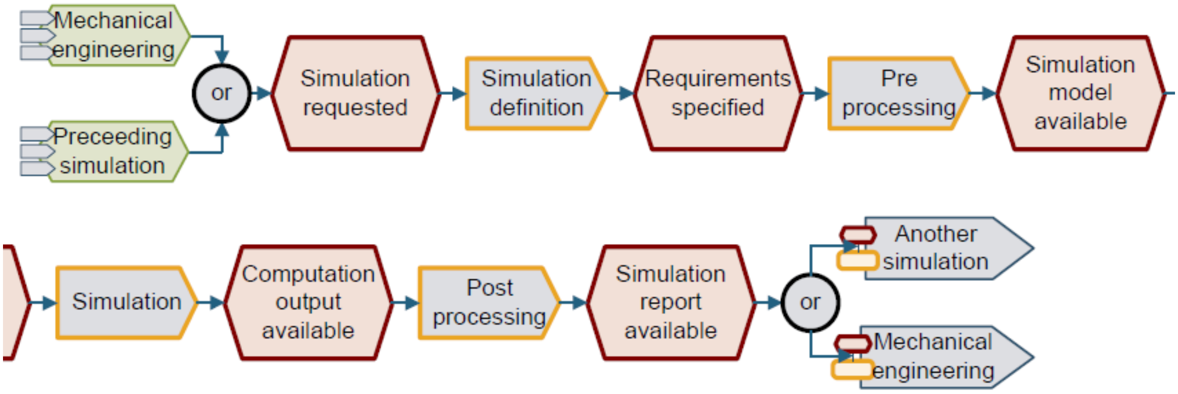

Figure 2.5: A typical simulation workflow within product development. Green represents a function or process, red an event, and orange the exchanged information or data. [5, annex B1]

Typically, 1st and 2nd level results stay within the simulation domain. They are differentiated between working steps (running a simulation to get an idea of how it works and discarding the results right away) and milestone simulations (proving that a part matches the requirements, the data of which is kept for a much longer time). For the final release of a part, most PD workflows demand a proof that the part met the requirements, which is most obvious in the aerospace industry, when assessing plane crashes for design failures or external causes. (see B.6)

2.3 Data Standards in Design and Simulation

Unless a single software vendor provides all these tools and hence uses a universal data format, it is almost impossible to share data among the various functions without a standard format. Promising standards for better Data Continuity in CAD and CAE are ISO 10303, "Standard for the Exchange of Product model data" (STEP) and VMAP respectively. These are very briefly described. Other prominently used formats to exchange 3D simulation results are Jupiter Tesselation (JT) and Visualization Toolkit (VTK). However, the data exchange using these is not as popular, so they are not looked at in depth. (see B.8, B.17, B.7, B.13)

2.3.1 STEP - "Standard for the Exchange of Product Data"

STEP is an international standard specified in ISO 10303. It defines a computer-interpretable representation of product information to allow the exchange and long term archival of product data. It aims at allowing the software-independent description of product data throughout the products life cycle. [14]

Within the standard various parts exist to describe both programming environments and data models. In the center of the STEP architecture lie the domain models (Application Protocols (APs)), which can be represented as Application Reference Modules (ARMs) in the EXPRESS language, or in Systems Modelling Language (SysML), which can be translated to XML Schema Definition (XSD) or Extensible Markup Language

(XML) schemas. Domain models are mapped to and from conceptual models, which are referenced by Application Activity Models (AAMs). ARMs are mapped to the more extensive Application Interpreted Model (AIM), which finally define the way data is described in the physical files. (see Figure 2.6)

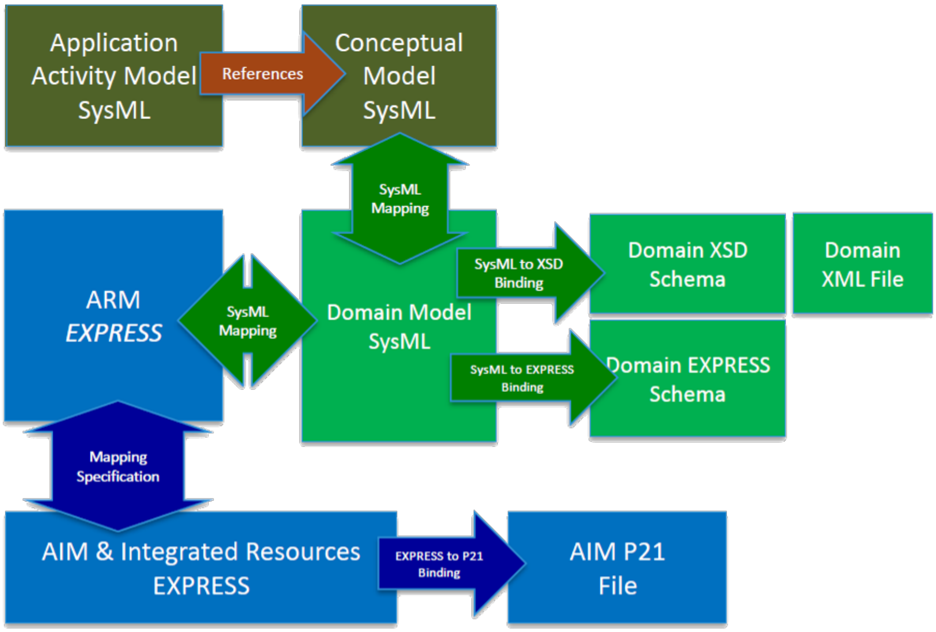

Figure 2.6: STEP architecture connecting the SysML and EXPRESS representations of data models and the representation of data in a Part21-file. [15, p.12]

Data Model of STEP

The data model description is divided into Application Modules (AMs) and APs. Each AM captures a very small range of information and is valid for its scope within the whole architecture of STEP. The AMs are thus used and combined for different domains by APs, which are specific for certain application or industrial fields. They may add information to their AMs, but more often than not the additional information needed is captured in new AMs. An AP may also include a whole other AP including its AMs and their relations, as seen for AP209. Two specific APs fall in the domain of this thesis:

1. **AP242:** ISO 10303-242:2020 Industrial automation systems and integration — Product data representation and exchange — Part 242: Application protocol: Managed model-based 3D engineering (AP242) is widely accepted as a standard for storing and exchanging CAD data. This domain was previously covered by ISO 10303-203:2011 Industrial automation systems and integration — Product data representation and exchange — Part 203: Application protocol: Configuration controlled 3D design of mechanical parts and assemblies (AP203) and ISO 10303-214:2010 Industrial automation systems and integration — Product data representation and exchange — Part 214: Application protocol: Core data for automotive mechanical design processes (AP214). When AP242 succeeded

these in 2014, they were withdrawn in conclusion. AP242 includes definitions for preliminary development, concept development, product engineering, evaluation, production planning, tool design, tool manufacturing and quality control. Since the second edition, it includes the electrical design domain as an addition to the previous PDM, 3D shape definitions, 3D Product and Manufacturing Information (PMI), 2D draughting, 3D kinematics, 3D assembly constraints, 3D composite design and process planning (see Figure 2.7). [16]

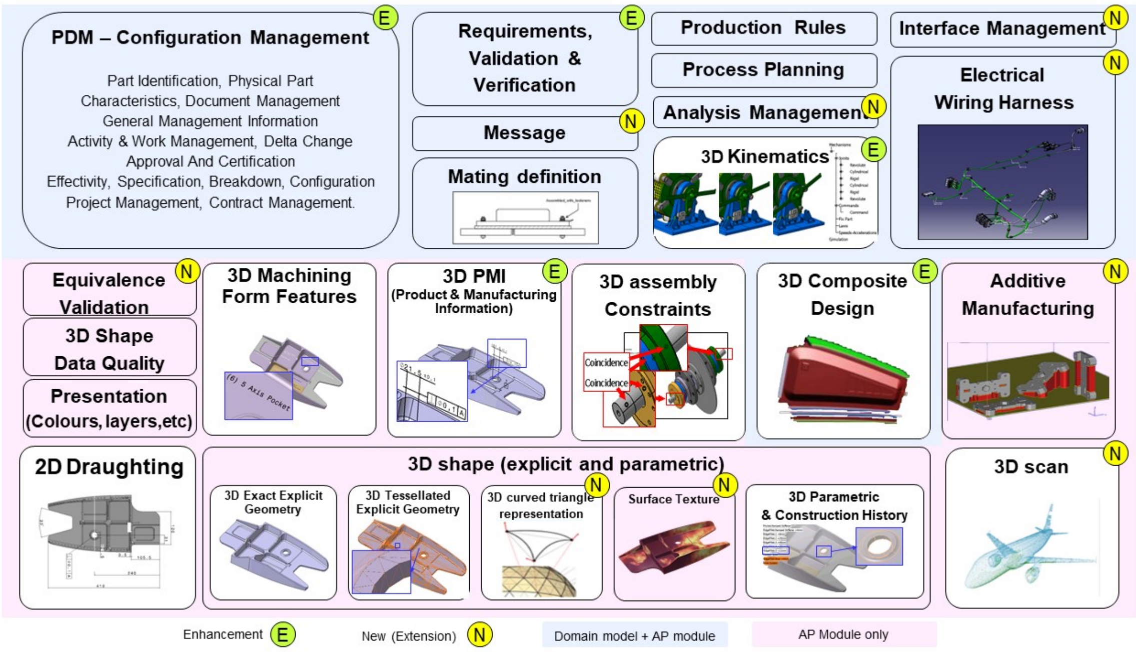

Figure 2.7: The scope of STEP AP242 edition 2. [17]

2. **AP209:** ISO 10303-209:2014 Industrial automation systems and integration — Product data representation and exchange — Part 209: Application protocol: Multidisciplinary analysis and design (AP209) supplements AP242 with CAE information such as element shape, material properties, boundary conditions and results to cover the domains of composite and metallic structural analysis. It is concerned with the iterative design and analysis stages of a product life cycle. The disciplines covered by AP 209 have been broadened to Structured Finite Elements Method (FEM), Computational Fluid Dynamics (CFD) and Kinematic Analysis in the 2nd Edition. [4]

Programming Environment and Data Storage in STEP

The data models are described in ARMs. The language for both the machine-interpretable and the graphical representation, called EXPRESS-G, are defined in ISO 10303-11 Industrial automation systems and integration — Product data representation and exchange — Part 11: Description methods: The EXPRESS language reference manual (EXPRESS). The EXPRESS files are called 'Part11'-files, and stored with the ending '.exp'. The examples of the data model structure in the following figures are found in a physical file given below in Figure 2.12. [18]

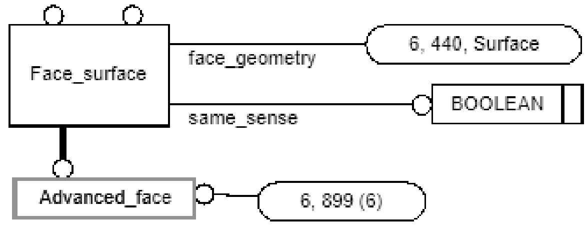

Figure 2.8: Definition of the type `Face_surface` according to AP242, represented in the graphical EXPRESS language, EXPRESS-G. [19] Its entities connect to a `Surface` entity via a `face_geometry` attribute - and so do those of its subtype `Advanced_face`.

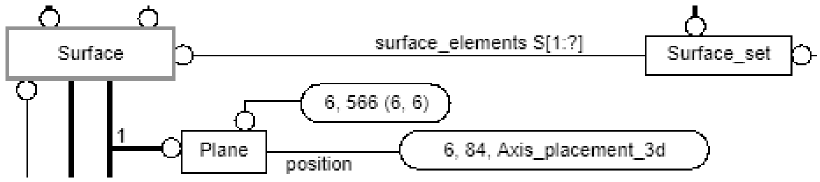

Figure 2.9: Definition of the type `Surface` according to AP242, represented in the graphical EXPRESS language, EXPRESS-G. [19] The subtype `Plane` is connected to an entity of `Axis_placement_3d` via a `position` attribute.

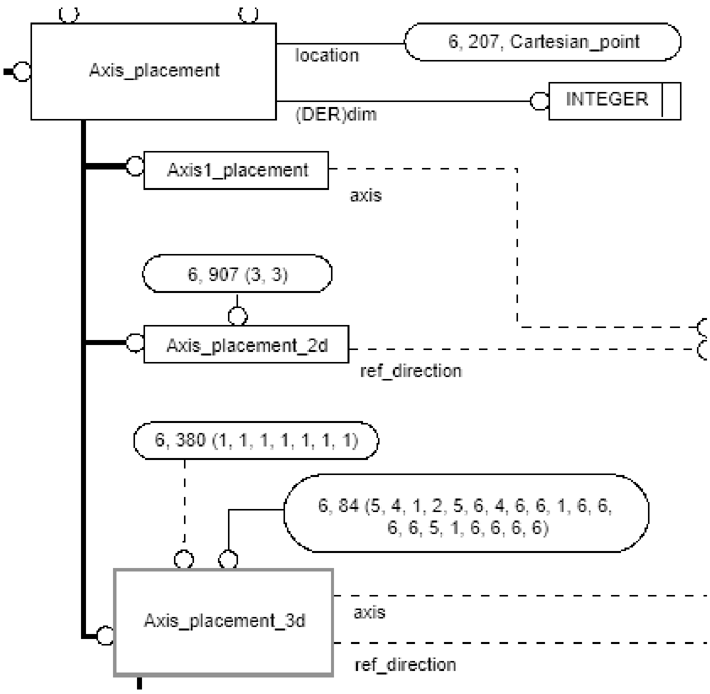

Figure 2.10: Definition of the type `Axis_placement_3d` according to AP242, represented in the graphical EXPRESS language, EXPRESS-G. [19] As a subtype of `Axis_placement`, it requires a `Cartesian_point` as a `location` attribute.

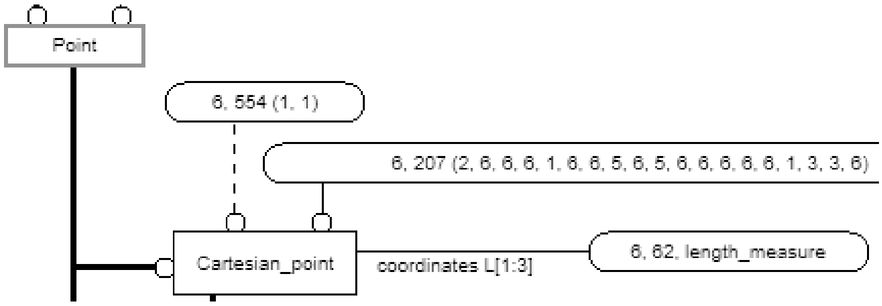

Figure 2.11: Definition of the type `Point` according to AP242, represented in the graphical EXPRESS language, EXPRESS-G. [19] Depending on the type of `Cartesian_point`, coordinates can be defined in Cartesian, cylindrical, polar or spherical measures. These have different types of the `measure_value`, which is a `Value_with_unit`. A generic `Cartesian_point` entity requires a list of three `length_measure` entities as `coordinates` attributes.

Data for a product entity is written in a file according to ISO 10303-21 Industrial automation systems and integration — Product data representation and exchange — Part 21: Implementation methods: Clear text encoding of the exchange structure (Part21-file). Data in Part21-files is stored according to the data model they refer to (i.e. AP209), but is otherwise unsorted. This means that not all information is stored on the level of a data entry, but only the information individual for the entry. Other information is stored in the super type entries. For example, the coordinates of the location of an Axis_placement will be stored in a Cartesian_point entry.

When reading or importing a Part21-file, a (possibly random) seed is chosen from which the connected information is found by opening the references to other IDs, as illustrated in Figure 2.12. When storing data, many different sensible structures are possible, depending on the implementation. This means that data can be structured very differently and still be unambiguous. However, for large data such as simulation data, processing and storage can be resource consuming. [20]

An alternative to Part21-files is ISO 10303-28 Industrial automation systems and integration — Product data representation and exchange — Part 28: Implementation methods: XML representations of EXPRESS schemas and data, using XML schemas (STEP-XML) [22]. This approach is similar to that of large software vendors, who use their proprietary XML formats, such as PLM-XML in SIEMENS Teamcenter and 3D-XML from Dassault Systèmes (see B.6)

As both Part21-files and STEP-XMLs are clear text representations, the file sizes can be compressed using ZIP algorithms as an accepted industry standard, allowing for up to 80 % compression [20]. Even with the reduced file size, processing simulation data does not perform well for the clear text formats. While CAD models can be some hundred megabytes in size, simulation data easily reaches scales of terabytes, wherein data processing for clear text formats is very costly. (see B.6)

An alternative solution to file size reduction is the Hierarchical Data Format (HDF5) binding in ISO 10303-26 Industrial automation systems — Product data representation and exchange — Part 26: Implementation methods: Binary representation of EXPRESS-driven data (STEP-HDF) [23]. However, this is not used by the STEP implementers. As [redacted]

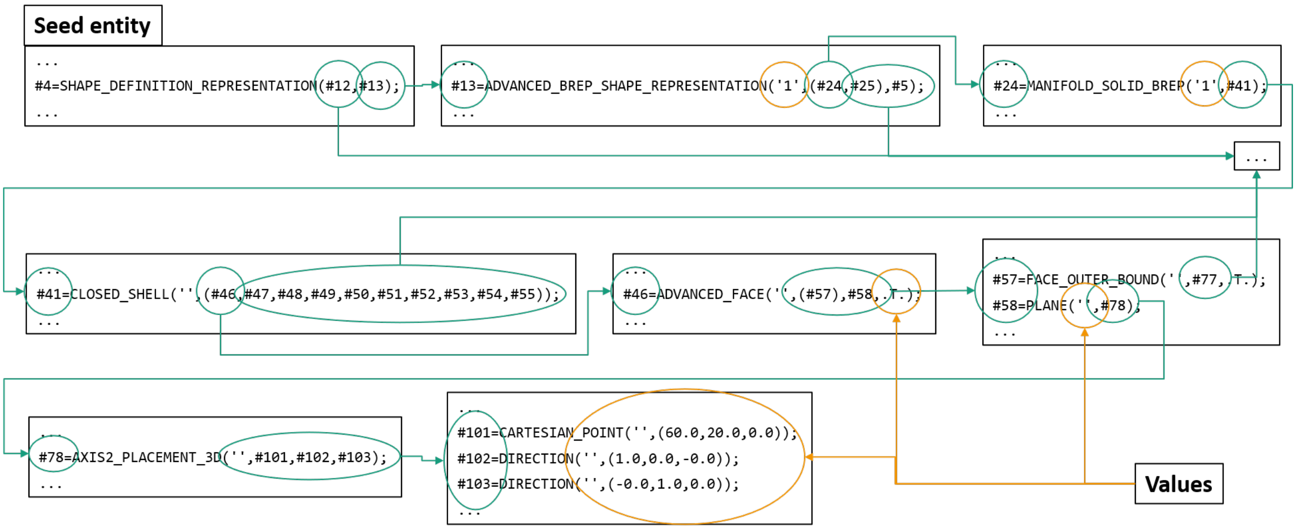

Figure 2.12: Excerpt from a Part21-file created by Abaqus according to AP214 [21], which is now replaced by AP242. The cross-references are marked in green, the orange arrows point to entries representing values. See Appendix D for the complete file and the picture of the represented geometry. The EXPRESS-G representation of the ARM definitions for `ADVANCED_FACE`, `PLANE`, `AXIS_PLACEMENT_3D` and `CARTESIAN_POINT` can be followed in Figures 2.8 through 2.11. (This figure is an own creation and also used in [8].)

put it in the interview: "That has just basically to do with the underlying data structure. So, HDF5 is a strictly hierarchical format, so it has a tree structure, whereas the data structures of AP209 have a much higher degree of interrelations. It's more a network, or to stay in the picture it's not as much of a tree, it's more a shrubbery, and that just doesn't fit well together." (B.6, 41:00-41:30)

An example for this 'shrubbery' structure, meaning many references going across the file, is given in Figure 2.12.

Drivers and Implementation of STEP

Further developments of STEP are primarily driven by sectors in which long term archiving of development assessments is a main objective. This involves mostly aviation sector, organised in the Long-term Archiving and Retrieval (LOTAR) project by ProSTEP iViP e.V.

Recommended practices for AP209 and AP242 are published by two implementor forums, which aim at improving the quality of existing data exchange and developing recommended practices:

1. The PDM Implementor Forum (PDM-IF) focusses on the XML representation of AP242. It is organised by ProSTEP iViP e.V. and AFNeT in France since 1999. It intents to increase the PDM interoperability between companies, to test it on a common platform, and to lower implementation efforts of STEP PDM standards.

2. The CAx Implementor Forum is organised by ProSTEP iViP e.V., PDES, Inc. in the USA and AFNeT in France since 1999. It focuses on the domains of both APs with two test rounds and meetings each year. Its additional aims are minimising development times for new functionalities and harmonising the exchange of CAD data across to other disciplines. [see 24, 25, 17]

2.3.2 VMAP - Virtual Material Modelling in Manufacturing

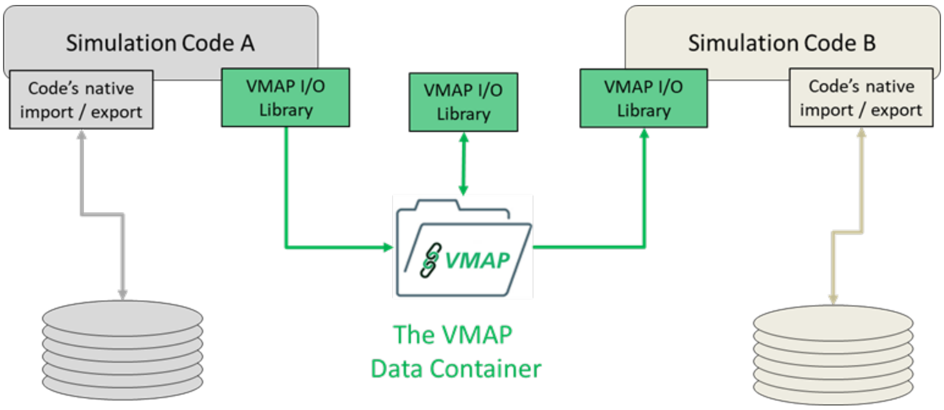

Figure 2.13: The VMAP concept for connecting two differenct simulations through a common data container. The I/O libraries can be maintained independently. Each simulation code can still import from and export to a data base in their native format, but translations between the codes are done via VMAP. [3]

"VMAP is a vendor-neutral standard for CAE data storage to enhance interoperability in virtual engineering workflows." [3, p.15] The VMAP Project was initiated in 2017 within ITEA, the Eureka R&D&I Cluster programme for software innovation. [see 3]

The developers identified that data transfer between simulation tools becomes a problem within CAE simulation chains, as the Input / Output (I/O) libraries of the simulation tools are not always compatible, especially when tools from different software vendors are used. This is usually inevitable, as applications as much as engineers need to be very specialised in the CAE domain. Before VMAP, simulation tools used their native formats, which would need to be translated by scripts developed by simulation engineers. Instead of having to write a code for each software interface, VMAP offers a central I/O library which only needs to be programmed once for each simulation tool as a hub-and-spoke schema. Figure 2.13 displays the general concept of the VMAP standard for two simulation codes. [see 3]

Data Model of VMAP

CAE data in VMAP files is stored in four main groups which were found to form the essence of simulation data:

1. Geometry and discretisation,
2. result and state variables,

3. coordinate and unit systems, and
4. material models.

The data model is described in the VMAP Standard Specifications and implemented and tested by the VMAP Standards Community e.V. (VMAP-SC). [see 26, 27].

While most of the data model is intended to be as generic and open as possible, some commonly used definitions have been included. These are twenty-five generic element types including points and user-defined types, more than ninety integration types like Simpson, Gauss, Trapezoidal, Lobatto, user-defined types and combined integration types, and over fifty properties for results and materials. Other definitions are dimensions like scalar, vector and tensors, basic coordinate systems and scale factors for the SI unit system. [26]

Data Storage in VMAP

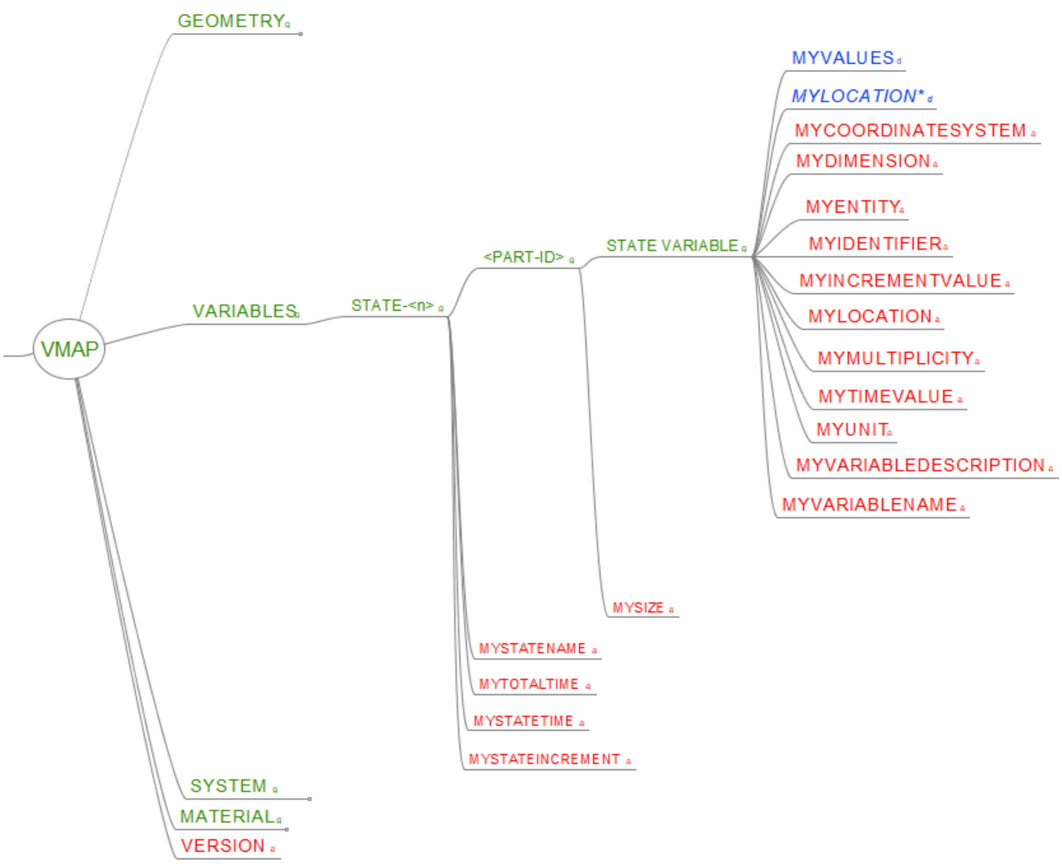

Figure 2.14: General data structure of a VMAP file, demonstrated for the VARIABLES group. The other groups GEOMETRY, SYSTEM and MATERIAL each contain similar structures. Within the groups, subgroups (green), attributes (red), and datasets (blue) can be stored. Multiple instances of the STATE-<n> and <PART-ID> groups can be stored.

VMAP files are stored in the binary HDF5 format. It is built in a directory-like structure. As HDF5 is an open source format, its C++ libraries and the HDF

Viewer can be accessed by developers of VMAP implementations. Additionally, if an application supports HDF5 files inherently, it can be viewed with internal viewing tools. A VMAP storage structure as displayed by HDFView can be found in Figure 2.15. Next to the pre-defined structure, additional data can be stored in tables within the files. [see 26, 3]

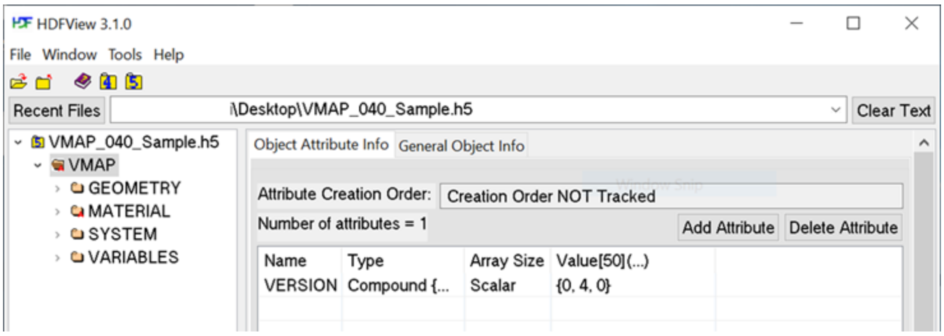

Figure 2.15: Sample HDF5 file format showing the VMAP Storage Structure displayed in HDFView. [3]

Within the HDF5 structure, data is sorted into groups, attributes and datasets. Attributes provide details and metadata for groups and datasets. Datasets contain large quantity information such as points, elements, or parts.

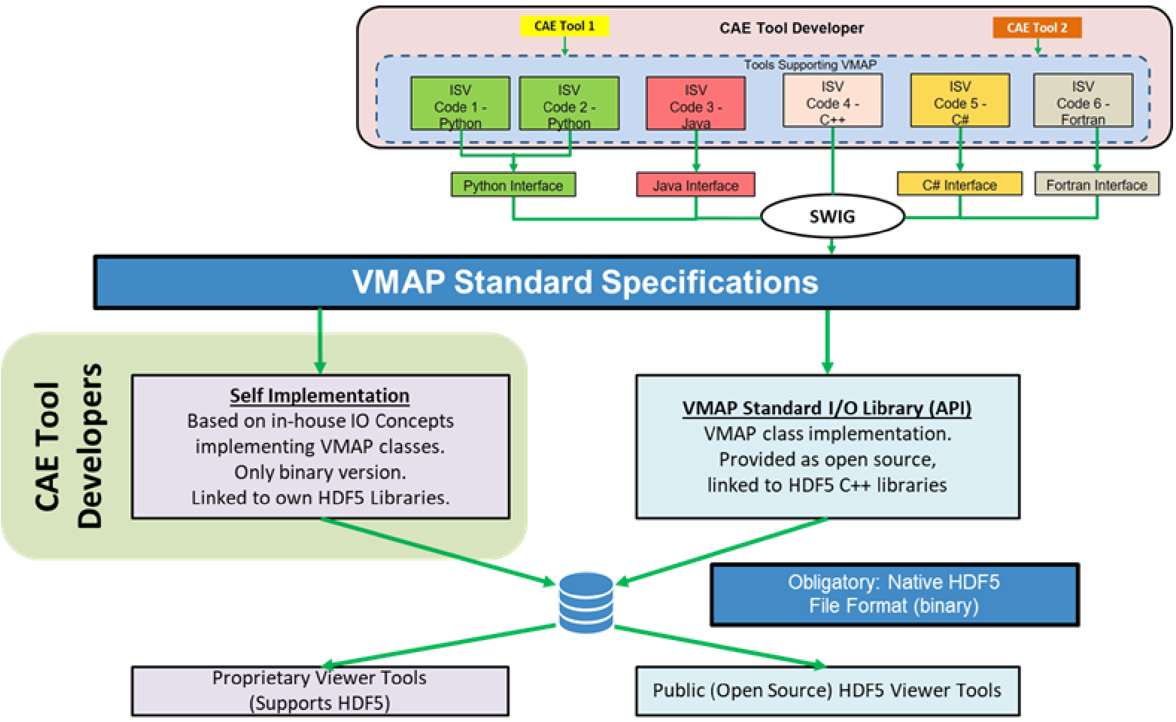

Figure 2.16: VMAP implementation architecture. The connection of the two tools can be implemented in different basic programming languages and connected to the C++ code using SWIG. This, together with the Standard I/O library (i.e. the VMAP API), allows for reading and writing in data containers by proprietary and open-source viewing and importing tools. [3]

Implementation of VMAP

Translations to and from native software formats are written in C++ in the VMAP Standard I/O Library, or VMAP Application Programming Interface (API). This includes a set order for consecutively reading and writing system data, mesh, element and integration types and lastly variables, in the respective groups. Programming languages other than C++, like Python or Java, can be connected to the original C++ implementation using Simplified Wrapper & Interface Generator (SWIG). Alternatively, CAE tool developers can build their own implementation based on the VMAP Standard Specifications [26]. (see Figure 2.16)

2.4 Problem Definition and Objective

2.4.1 Missing Links Between The Data Domains

"Bridging the gap is a challenge and has been a challenge for the past 20 years at least." (B.6, 19:30)

Although approaches like Unified Simulation Modelling Language (SMILE), VMAP and STEP already offer improved engineering workflows, the standardised link between PLM and SDM data bases is still missing on two major levels:

1. A common version-control system connecting CAD and CAE models on a data management level. AP209 does not offer the desired capabilities for CAE applications, while AP242 and VMAP do not share a common version definition. Table 2.1 shows an overview of the two data models.

2. Integrating the simulation results back into the CAD model. On a numerical level, CAD and CAE data are stored in fundamentally different ways. This causes a sharp divide in workflows between the data used by CAD and CAE engineers, and can cause transmission errors when designs need to be updated on either side. Connecting the geometries in both models would mean an immense improvement of workflow performance and costs.

Table 2.1: Comparison of the data models of VMAP and STEP. While AP209 covers a wide range of information types, VMAP allows for more accurate simulation definitions.

	AP242	AP209	VMAP
PLM relevant information	X	X	
CAD model	X	X	
Defining Part ID and description	X	X	X

Continued on next page

Table 2.1, continued from previous page.

	AP242	AP209	VMAP
Multiple production stages per product entity	X	X	X
Element-based mesh		X	X
Element-level results		X	X
Element-level material properties		X	X
Element geometries		Multiple pre-defined / custom	Multiple pre-defined / custom
Element shape functions		Linear / quadratic / cubic	Multiple pre-defined / custom
Integration methods		Gauss / Simpson	Gauss / Simpson / Lobatto / custom

2.4.2 Bridging the Gap Between Product and Simulation Data Management

PROSTEP AG (PROSTEP) helps in implementing STEP-based PLM systems. The Multiphysics department at Fraunhofer-Institute for Algorithms and Scientific Computing SCAI (SCAI MP), as member of the VMAP project and now founding member of the VMAP-SC, is working on the advancement and further development of the VMAP standard. Building upon their experiences and consultation with their closest project partners, PROSTEP and SCAI MP have developed the idea of an adapter between the two standards to offer solutions to the problems defined above.

As this intent aims at driving standardisation, they are working on a proposal for the Wissens- und Technologietransfer durch Patente und Normen (WIPANO) funding project of the Bundesministerium für Wirtschaft und Energie (BMWi). Both partners now have brought together a group of industry players who may benefit from a connection between the CAD and CAE domain, to support this 'VMAP-STEP-project' and drive the development towards a usable application.

To propel the VMAP-STEP-project in a direction that meets the current needs of the industry, an analysis of the requirements in virtual engineering should be implemented. This thesis is part of this research.

3. Analysis of the Engineering Requirements for Data Continuity in Virtual Manufacturing

Summary: The requirements analysis for bridging the gap between product and simulation data management was conducted by two people in the form of *exploratory, problem-centred expert interviews* via MS Teams. The identified target groups were Original Equipment Manufacturers (OEMs), CAE software developers, and users and PLM/PDM/SDM software and standard developers. The resulting problem and use case definitions suggest a promising outlook for the proposed adapter solution.

3.1 Methodology of the Analysis

Market research is an important part of the early stages of PD. Its role is to explore new products and evaluate product concepts in customer-oriented development directions. In a "Technology Push" [28, p.34], the company-specific capabilities drive the product development, i.e., the high capabilities of the two standards. This thesis supplements the "Technology Push" by a "Market Pull" [28, p.34], as it regards the customers' demand through research. [see 28, ch.2]

Considering the degree of specialisation of the target-market for the VMAP-STEP-project, purely theory-driven literature - which is mostly found in the field of business administration, sociological research and market research on a much larger scale - does not propose a precise enough proceeding. Therefore, requirements engineering analyses from similar fields as this research were taken into consideration.

3.1.1 Qualitative Analyses in Theory: Market Research

For idea generation, and for research in small and specialised markets, qualitative market research methods are indispensable despite their greater expenditure compared to some quantitative methods

Main tasks of qualitative market analyses are

- structuring a research field by identifying relevant factors and dimensions,
- developing qualitative prognoses where quantitative material is missing or inapplicable,
- root cause research for complex issues,
- idea generation, using creative faculties of the interviewee and
- screening for alternatives like ideas and concepts [29, pp. 357-360].

> ”**Qualitative studies** are non-standardised surveys in the context of exploratory studies on the basis of small samples.” [29, p. 357, translated from German] Exploratory studies are not necessarily purely exploratory, but are used for fields in which existing knowledge needs to be verified and deepened. [30]

Qualitative interviews try to lead an as open as possible conversation to allow the interviewees to set their own focus points and bring up new ideas. They can be subdivided as in-depth, focussed, and exploratory interviews.

In-depth interviews research unconscious and hard to capture motives and attitudes.

Focussed interviews on the other hand aim at analysing the reaction of the interviewee to a certain stimulus.

Exploratory interviews can serve both to identify relevant research dimensions and influence factors as well as prognoses as results of expert interviews. The interviewer takes the role of an interested listener and ensures that they receive an extensive collection of information. Exploratory interviews are loosely subdivided as narrative or problem-centred by the degree of directional influence employed by the interviewer, the latter involving more interviewer influence and being particularly useful for innovative products and service and therefore more suitable for this study. In English research, they are more commonly referred to as ’semi-structured’ interviews. For structuring the relatively new and small field of research for the VMAP-STEP-project, exploratory techniques should be preferred. [30],[29, pp. 358f]

The technical market research for the VMAP-STEP-project does not aim at implicit, emotional or socially sensitive information. Thus, a simple aggregation of explicit information is valid and a transcription is not necessary. [see 31]

The recommended sample size varies but can be set around fifteen hourly interviews to cover 80 % of relevant aspects [32, cited from [30]].

As the conclusions drawn from the interviews do not need to be representative of the whole target group, randomised sampling is not necessary. Instead, it is left up to the researchers to ensure a good coverage. For this, they can use methods such as the snowball effect to gather large samples. As the investigated market for this thesis consists of groups which are already connected to the VMAP and/or STEP standards, a larger sample size was found to be unnecessary. [see 30]

During the development of interview guidelines, some main points of interest should be covered [30, p. 471, translated from German]:

- Current situation of the interviewee
- What does not work properly?
- Solutions/Products
- Evaluation of added value of solutions
- Requirements
- Barriers to the adaptation
- Recommendations for the product
- Further fields of application / users
- Competition
- Trends
- Additional contact persons.

On a structural level, guidelines always take a place on the balance between opening the conversation as much as possible to allow for a ”discursive-dialogical procedure” [33,

p. 252, translated from German], and structuring the interview to help with the conversational flow. Especially to ensure satisfactory answers to all questions, a guideline can be used as a checklist. [see also 33, pp. 268ff.]

As a result of this research, the interviews can be characterised as an *exploratory, problem-centred (=semi-structured) expert interview.*

3.1.2 Qualitative Analyses in Practice: Requirements Engineering

To supplement the theoretical literature, the methods of a number of papers from the field of requirements analysis were considered. These also refer to standard works on qualitative methods such as Robson's *Real World Research* [34] [see 35, 36, 37]. Additionally, a practitioner's guideline was taken into account [38].

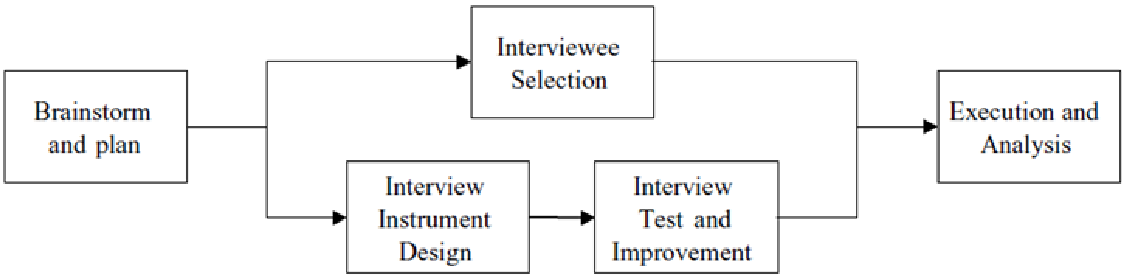

Figure 3.1: Sketch of the research procedure used in this thesis. (see section 3.4, [37])

The requirements analyses typically used simple procedures, as displayed in Figure 3.1. These used market-driven developments for smaller and rather new companies. The questionnaire was first validated with closer contacts, for example in the same university [see 36], before between seven and seventeen people from between five and fifteen different companies respectively were interviewed. [see 37, 35, 36]

The analyses were also rather simple. A structured questionnaire form filled by the interviewers helped to document the interviews. Results were aggregated by marking and discussing sections of the transcripts which appeared interesting. [see 37, 35, 34]

3.2 Central Questions of the Research Interviews

The interview guideline provided a prototype of question collection for the interviewers to follow. It was neither standardised nor mandatory to be filled in, but helped as a checklist. It evolves around four key questions:

1. *What are your typical applications [/ 'use cases'] involving CAE and CAD?*
   This question served to identify the general line of work which the interviewee deals with on a regular basis.

2. *Which simulation domains, tools and data formats do you use / support?*
   This question supplemented the first question by the technical level of the current situation. It was often partially covered before.

3. *Which difficulties are you facing on a Data Continuity / interoperability / digital thread level?*
   Here, key issues with the connection of the two domains on a data level were identified.

4. *Which interoperability features should a solution to these issues offer? What could be your benefits?*
   Lastly, directions for solutions were determined. This included current workarounds as well as ideas and wishes for solutions (which a VMAP-STEP-Adapter might offer).

The questions for the interview guideline were developed iteratively: Firstly, the general fields of interest and sub-ordered questions were identified by the author and the interview assistant. Secondly, these questions were reviewed to include missing information. Thirdly, after each interview we reviewed whether certain topics of interest were not covered and if the questions seemed appropriate. When changes were made it was made sure that new questionnaires would be downward-comparable. As an example, the last question was updated from "What additional interoperability features should a solution such as a platform-integration or a plug-in offer?" to "Which interoperability features should a solution to these issues offer?" to be more generic and less suggestive.

Another improvement was to transform the guideline further into a checklist, by opening the fields and only including the check points in one separate list. This update was also applied to the notes from previous interviews, so the formatting and the note structure had to be adapted (see the initial questionnaire format compared to the new one in Appendix B.4). The points to be checked were also adapted. For example, the point 'Results export' was added after the 5th interview, as it was a point which was often discussed.

When directing the interviews towards these more specific questions, it was constantly made sure to leave space for the interviewees to add their own opinion and direct the focus towards what they considered important.

These questions sufficed to guide the interview. Additionally, the information required from the product developers' point of view was noted in a more extensive questionnaire, to work as both checklist and documentation draft. These were initially differentiated for the three main groups of interest (OEMs, PLM/PDM/SDM software developers and CAD/CAE software developers). However, towards the end of the interview rounds, it was found that the questions and checklist were applicable for all three categories, though the results differed significantly (see chapter 4). The final guideline is given in Table 3.1. The initial guidelines for the separate target groups are found in Appendix A.

Table 3.1: Final questionnaire for the interviews, which was filled in during and after the interviews. Questions posed to the interviewees are printed bold.
Text in square brackets was not displayed in the presentation (see section A.2) and modified or explained if necessary. The bullet points are checked by the interviewers and asked specifically wherever necessary.

Topic/Question	Notes
Introduction	
What are your typical applications [/ 'use cases'] involving CAE and CAD?	
• application / industry • materials • engineering workflows (optimisation/ manufacturing/ . . .)	
[**I know you develop *(software)* / provide *(service)* ...**] **Could you tell me which simulation domains, tools and data formats you use / support?**	
• domain (FEM / CFD / meshfree / Multi-Body Simulation (MBS) / ...) • software tools (CAE and CAD) • standards / data formats (name + domain + stage in workflow) • simulation results export • data storage method and compression	
Which difficulties are you facing on a Data Continuity [/ **interoperability / digital thread**] **level?**	
• exporting results • version-control / change management • parametrisation for optimisation • traceability between CAD and CAE or within CAE	
Which interoperability features should a solution to these issues offer? What could be your benefits?	
• workflow concerned • tool format (platform integration/ plug-in/ external tool) • benefits	

3.3 Identifying Target Groups

Generally, three groups of interest were identified according to their domain:

1. Developers and users of CAE software tools. This turned out to be the largest target group, as SCAI MP had many contacts in this field.
2. OEMs. These were mostly found via the first group as they were connected via past and current projects.
3. Users and developers of PLM/PDM/SDM solutions. This group was smaller as the current market is not as big and the connections from the VMAP-STEP-project group are therefore not as varied.

The final list of interview partners is shown in Table 3.2. The domain classification were changed for the results aggregation, see chapter 4.

Table 3.2: List of interviews sorted by date. A small introduction is given for each interviewee. The domain PLM/PDM/SDM is abbreviated as data management (DM). **Admonition: The names of companies and institutions have been substituted with 'Company xx'. The names of interviewees have been substituted with 'Interviewee xx'.**

Company/ Institute/ University	Name	Date	Domain
Company 01	**Interviewee 01**	[redacted]	CAE
	Interviewee 01 works on crash simulations of automotive systems, [redacted]		
Company 02	**Interviewee 02**	[redacted]	CAE
	Interviewee 02 works at [redacted] on improving crash simulations using artificial intelligence. [redacted]		
Company 03	**Interviewee 03**	[redacted]	CAE
	Interviewee 03 provides CAE services in several simulation domains for external companies.		

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Table 3.2, continued from previous page.

Company/ Institute/ University	Name	Datum	Domain
Company 04	**Interviewee 04**	[redacted]	OEM
	Interviewee 04 works on internal research and development projects, particularly lifetime assessments for plastics.		
Company 05	**Interviewee 05**	[redacted]	CAE
	Interviewee 05 leads the research and development department, working on extrusion blow moulding simulations for optimisation workflows.		
Company 06	**Interviewee 06**	[redacted]	DM
	Interviewee 06 coordinates the development and implementation of [redacted] within their respective implementor forums.		
Company 07	**Interviewee 07**	[redacted]	CAE
	Interviewee 07 researches process and structure simulation of continuous and discontinuous fibre-reinforced plastics.		
Company 08	**Interviewee 08**	[redacted]	OEM
	Interviewee 08 implements the simulations process and data management on an information technology level for **Company 08**.		
Company 09	**Interviewee 09**	[redacted]	DM
	Interviewee 09 is responsible for software sales for several SDM software solutions and services for the automotive industry.		
Company 10	**Interviewee 10**	[redacted]	OEM
	Interviewee 10 is global coordinator of CAE processes at **Company 10**.		
Company 09	**Interviewee 11**	[redacted]	DM
	Interviewee 11 develops [redacted] modelling management system [redacted] and serves with integrating the automotive companies' CAE-processes.		

Continued on next page

Table 3.2, continued from previous page.

Company/ Institute/ University	Name	Datum	Domain
Company 06	**Interviewee 12**	[redacted]	CAD services
	Interviewee 12 provides specialised CAD services in product development.		
Company 11	**Interviewee 13**	[redacted]	OEM
	Interviewee 13 works on simulation automation in the FE domain.		
Company 12	**Interviewee 14**	[redacted]	DM
	Interviewee 14 develops and consults [redacted].		
Company 13	**Interviewee 15**	[redacted]	DM
	Interviewee 15 is a PLM consultant for [redacted].		
Company 14	**Interviewees 16**	[redacted]	CAE
	Interviewee 16.1 is a technical account manager for automotive customers. **Interviewee 16.2** is part of the mechanical team. **Interviewee 16.3** is an application engineer for geometry preparation support.		
Company 15	**Interviewee 17**	[redacted]	DM
	Interviewee 17 is a business analyst in IT, working on the implementation of MBSE.		

3.4 Implementation of the Research Interviews

Generally, four steps were followed for the interview framework:

1. Entering a contact and arranging the meeting,
2. conducting the interview,
3. keeping a follow-up contact and
4. evaluating and analysing the interview notes and recordings.

3.4.1 Establishing Contact to the Interviewees

As recommended by Kurz et al. [30, pp. 468f.], the first meetings were held with interviewees to whom a more personal contact pre-existed. The first contact was in most cases introduced via SCAI MP, some contacts were established via PROSTEP. Each e-mail followed a common script, adapting the language the interviewees were thought to be more comfortable in. The intent of this e-mail was to raise the interviewee's interest and to fix a date for the interview. Examples for these e-mails are given in Figure E.2 and Figure E.3.

Naturally, as the prior contact to the interviewees varied, there was no standardised contact e-mail. The main variations were the degree of formal language and whether there was an intermediary who established or suggested the contact. However, the included information remained the same. Addition as recommended by Kurz et al. [30], publicly available information about the interviewee and their field of work was researched before the interview .

3.4.2 Interviews

The interviews themselves were held in English. They were lead by the author, with an assistant to take notes and help out with professional expertise where necessary. A presentation accompanied the interview (see A.2).

The interviews contained four phases (according to the guideline in Table 3.1):

1. Introduction and general exploration, directing the conversation towards the topic of interest (see Figure E.1).
2. Specific exploration, deepening the understanding to allow interpretation and comprehension. And
3. Complementation, using questions targetted specifically at issues which have not come up yet. The latter two were covered continuously during the turn of the interviews.

Each interview started with a personal introduction using the webcams for the first few minutes of the meetings, before starting the recording. After, a generic introduction was used to introduce the interviewers, interviewees were asked to introduce themselves, and the important questions of confidentiality and the specific topic of interest were settled. (see Figure E.1)

3.4.3 Follow-Up

After the interview, an e-mail was sent to the interviewee to thank for the participation in the survey, to summarise the topics that were addressed and in some cases to give or refer to additional information that was asked for during the interview. Like the contact e-mail, the wording and text varied depending on the previous contact to the interviewee and on the content of the meeting. An example for this e-mail is given in Figure E.4.

3.4.4 Data Collection

As recommended in most literature [see 29, 33, 30] the interviews were recorded using the built-in function in MS Teams and stored on the MS Stream Cloud, with exclusive access to the interviewers. Each interviewee was informed about this in the first-contact e-mail, just prior to beginning recording and during the introduction as part of the recording, including the call to indicate sensitive and confidential knowledge as such (see Figure E.1).

The results were refined both top-down as well as bottom up:

Top-Down Results Refinement

After the 10th, 15th and final interview, preliminary results were collected, and connected to the interview notes. The updated key points were collected in a spreadsheet to allow for comparable results (see C). This does not allow for quantitative interpretation, but does enable an overview of the spectrum that was covered for the several points.

Bottom-Up Results Refinement

Firstly, The notes taken during the interview were compared by both interviewers and completed using the recordings. All notes were collected in one document per interview (see B). As transcription was not necessary and implicit behaviour by the interviewees not a matter of research, the notes were narrowed down to results of the interview, not capturing the questions asked by the interviewers or inquiries for better understanding. Instead, only the technical content of the interviews is documented to allow for a clearer overview of the findings. For a meta analysis of the interview method and quality, the recordings can be consulted.

Secondly, key findings were extracted from the interview notes and appended to them. This required some understanding of the fields of interest and needed to be repeated for the earlier interviews according to the acquired knowledge.

Thirdly, the top-down results were complemented with the key findings that were not yet mentioned after the last round. This added up to the final results in chapter 4.

3.5 Generic Findings

3.5.1 Response Behaviour To Interview Requests

The response times to interview requests were between one and five days for most contacts. Some interviewees asked to receive the interview questions beforehand. Most interviews could be arranged within one to three weeks after the first contact e-mail.

Out of thirty contacts, only one declined the interview entirely due to lack of time. One more contact asked to be sent the questions as this was easier than requesting decontrol for an interview. The results of these questions were unfortunately not received in time for the evaluation. Seven contacts did not respond to the interview request. Four more contacts agreed to an interview but could not find a time window.

3.5.2 Interview Implementation

Conducting the interviews online was found convenient for both interviewers and interviewees. It did not require expensive travel and thus made finding convenient time slots easier. Keeping the interview questions open instead of using a standardised questionnaire was received very well by the interviewees (see B.7, B.1, B.8). The recordings helped significantly for maintaining a full collection of notes. It was also checked again, whether significant subtext information implied working out full transcripts. This was not the case.

The assistance proved useful, as they contributed additional questions and were able to complement information about the VMAP project (see B.15, B.13, B.8).

Typically, the discussion about difficulties on a Data Continuity level took the longest time (10-15 minutes). The other parts of the interview guideline (introduction, typical applications, technical situation and solutions) took around 5 to 10 minutes each. Consequently, most meetings averaged at almost one hour, provided the interviewees had enough time. The meetings were still announced for 45 minutes, though, as this was expected to increase the acceptances. (see B)

3.5.3 Target Group Differentiation

The differentiation of OEMs, CAE relatives and PLM/PDM/SDM experts turned out to be obsolete. After discerning the main points of interest and transforming the guideline into a checklist, the questions could therefore be kept very generic for all three categories. These questions were individually specified and related to the interviewees background.

However, for very specialised departments like SDM (see B.8, B.9, B.10) a specific use case could not be defined. Instead, the first question was changed to "What kind of solution(s) do you provide?" after interview 9 with **Company 09**, and later to "What is are your typical applications / 'use cases' involving CAE and CAD?" (see A.2)

3.6 Limitations

3.6.1 Market Reach

The research focussed on talking to CAE engineers instead of focussing on CAE software vendors. This user-driven approach provided better insights, as the software vendors have very good solutions, but these are typically used by very large companies and not by Small and Medium Enterprisess (SMEs) (see B.16, B.5). The company sizes varied from small research institutes such as **Company 02** to medium sized enterprises like **Company 11** to large companies such as **Company 08**.

The connection of the interviewees to data also varied, some were working on data storage optimisation (B.2), some on the numerical processes (B.5) and others on process management (B.10) and standardisation (B.6).

Over all, the amount of seventeen interviews allowed for about 80 % coverage of the researched market [32]. It included a bias towards CAE engineers being the largest group (eight contacts), which came down to SCAI MP being more closely related to this domain. This also lead to SDM being the second largest group (five contacts). Together, these two cover the main target market for the integration and standardisation of simulation into data management environments.

Insights into CAD and Model-Based Systems Engineering (MBSE) were only covered by one contact each (B.12, B.17). These had experiences from different fields, though, and thus provided deep insides into their domain. The same counts for the PLM standardisation and implementation (B.6, B.15). Additional interesting interview partners would be, for example, [redacted]

3.6.2 Time Planning

The original time schedule of the thesis had to be adapted, as the questionnaire development took longer than expected due to the extensive methodology research, and not all interviewees replied as soon as was hoped for (see Figure E.5). For a more business-oriented research, to speed up the development of an interview guideline, first meetings with contacts should start before the development of a final guideline.

3.6.3 Epistemological Discussion

The main obstacles of problem-centred interviews usually are clearly defining the domain, short training periods and few available experts, all of which were not the case in this study [30]. A general concern is the "inevitability of bias in any research" [39, p.311]. The interviewer bias was reduced to a minimum by involving different parties in the research development and encouraging the interviewees to contribute additional input. Generally, subjective bias effects should be minimal, as the research topic did not involve personal opinions or interests. [see 40, 37, 33]

According to [30], the interviewers fit the category of "interviewers with moderate previous knowledge" [30, p. 470, translated from German], having and gaining knowledge through research prior to the interviews and learning experiences during the interviews. As suggested by [30, p. 474], the 'clients' of the research, the professors and representatives of both SCAI MP and PROSTEP were included in development and implementation to raise the acceptance and understanding of the study.

On a technical level, it must be considered, that the research regarded an advanced field, which limits the universality of its findings. Additionally, a bias towards the CAE group could not be avoided. As this is the main target group, this does not imply an epistemological limitation, but does make sense for the product development in which the research is embedded.

4. Derived Workflow Perspectives in PLM, SDM, and CAE

Summary: This chapter is a collection of technical findings about different industry groups. The results are divided into general (i.e. applying to the majority of interviewees) technical situation and issues, and specific situations, issues, and goals for the three identified groups, as well as existing integration attempts that were mentioned during the interviews.

Identified Industry Groups

During the evaluation of the results, it became clear that the situations of the interviewees were not distinct from each other as expected (see subsection 3.5.3). Instead, three different groups were identified depending on the depth of their connection to numerical data. The new differentiation is shown in Figure 4.1. The new allocation for the interviews is found in the interview notes headers and the aggregated results tables (see Appendix B and C).

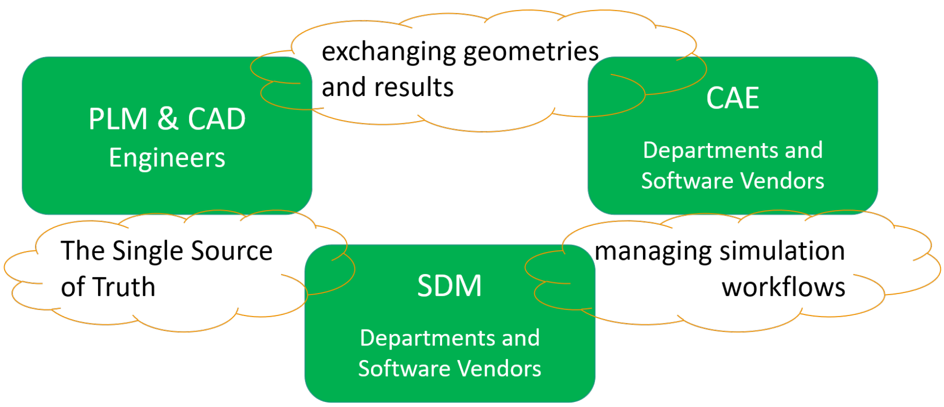

Figure 4.1: New industry distinction: The main differences are marked by the roles and interactions (clouds) in the product life cycle.

1. PLM developers and CAD engineers are concerned with the general PD process as well as the definition of an SSoT for data and change traceability. They mostly deal with simulation data while exporting geometries and exchanging results in the form of reports and assessments.

2. SDM departments and software vendors are concerned with managing the simulation chains and processes. They also try to seamlessly include the simulation data into the existing data management structures and thus complementing the SSoT.

3. CAE departments and service providers are concerned with the numerical modelling and calculation. As most of them do not have an external SDM service at hand, they manage their data themselves, which is a rather small part of their work. They are connected back to the PLM and CAD level during their workflows, when importing CAD models and exporting the related simulation results.

4.1 Common Issues Across Groups

Granularity of CAD versus CAE data

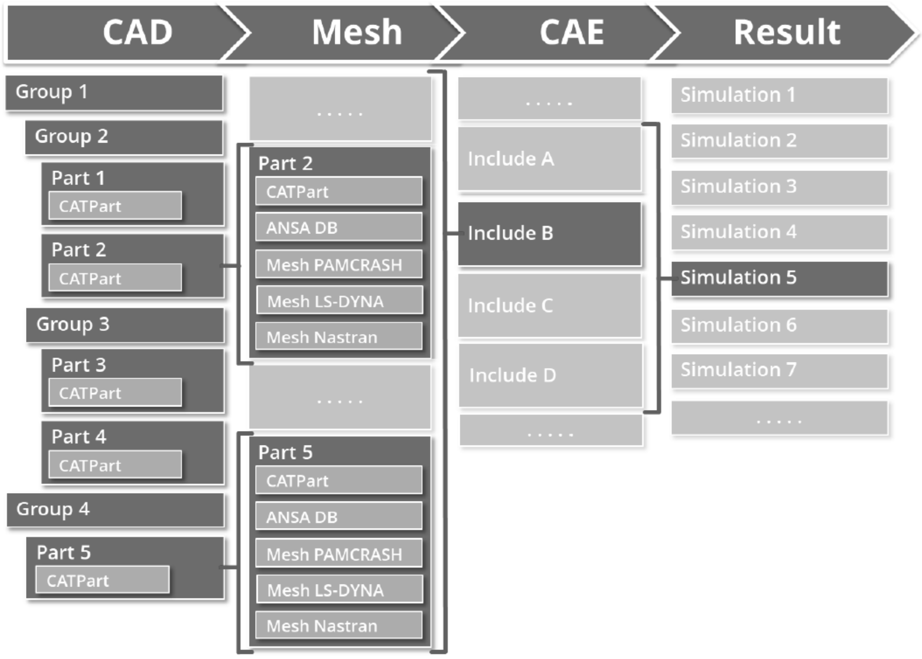

Figure 4.2: Granularity of CAD vs. CAE data. While CAD requires one entry for each sub-entity of a product, meshing, simulation groups, and simulation results in CAE use a variety of sets. [6]

An essential difference between CAD and CAE lies in the aspects of a product, which are required by the systems. The assembly-based CAD system subsumes parts according to the manufacturing and assembly processes. So, one entity will be available for each physical part. When meshing a part, the variety of tools already causes a variety of entries in the database. Additionally, simulations can create groups ('includes') in different structures, depending on the assumed physical connections. Lastly, each simulation can use various selections of these assemblies. [see 6]

Customisation

Since each simulation discipline, company, department, application, etc. use their own software tools (which are in turn often customised), modelling methods, management workflows, data formats, etc., a generic solution is not present. Instead, each software solution is either customised by the users or by their vendors.

Change Management

When design, material or boundary conditions are updated, in most cases a fixed workflow was not available to determine, which simulations have to be re-run, and an allow easily accessible comparative interpretation of the results. For instance, changing the thickness of a door panel will not change the aerodynamic simulation, but the side crash simulation. The question of Change Management is, how to propagate those changes. (see B.6)

For the CAE engineers, a clean Change Management would help even when they are set outside the regular development workflow, as they could readily update their CAE models instead of laboriously creating new ones for each update. (see B.1)

Version Control

When the design is tested in a simulation loop, the data is rarely automatically linked to the PLM versioning. This issue was reported by almost every interviewee except the software vendors, who do try to establish their own solutions for this, or do not see a demand for such a solution.

Material Data

Material data is typically not well harmonised: Either the PLM and SDM systems use different material databases (see B.11) or the databases differ between simulation solvers (e.g., PAM-CRASH, LS-DYNA, Abaqus; see B.9). This is also an identified problem from the VMAP project and was traced back to the extent of the material domain. (see B.7)

The standardised modelling becomes difficult even further when AI-driven intelligent data trimming methods are applied and mathematical models for material behaviour are altogether disregarded (see B.7). In practise, this means that material information may be defined on the CAD level, but needs to be redefined for the simulation (see B.12).

[redacted]

Market Viability

It became clear that SMEs and research institutes face different ranges of options on the software market than large companies. The latter has a wide variety of software solutions at their hand, as well as the readiness of the software vendors to provide well integrated solutions - not only within their own systems, but also across systems. The former on the other hand has to carefully choose their selection of software tools for interoperability, and often cannot find viable solutions which could be integrated into their workflows. This counts especially for SDM solutions, which are not popular among SMEs and research institutes as they are not affordable for them. (see B.5)

On the other hand, although these solutions are available to large companies, they often lack the ability to be tailored to the workflows of CAE engineers (B.10, 45:40).

Also large companies face the difficulty that their engineers would need to adapt their working culture to the data management system, which often enough they do not - although they use these expensive jack-of-all-trades solutions (see subsection 4.2.2).

Unidirectional Data Exchange

For CAE simulation iterations, the concerned CAD model is sent to CAE specialists. They verify it through certain tests and suggest changes to the CAD-developers, without sending back actual simulation results.

This leads to four key data transformations, where the Digital Thread is interrupted:

1. When creating the CAD model, design engineers often do not include information which is important for the CAE engineers, such as middle surfaces, shell thicknesses, or material information. Creating this data in the CAE model can be a laborious and tedious process.

2. The transfer of CAD data to CAE is incomplete in two ways:

   (a) It is only a reduced depiction of the model in the tool's native format, losing all parametrisation and, depending on the format, additional information such as material. The product geometry cannot be changed without importing it back into a CAD tool and manipulating it in such a way, that parametrisation can be implemented and used for optimisation iterations. Afterwards, the lengthy pre-processing usually needs to be run again. (see B.3, B.16)

   (b) The data is also often not suitable for the CAE import. The files can be erroneous, so that an export in a different format needs to be requested, or external departments are engaged to clean up the data.

3. When data is transmitted between pre-processor, solver, and post-processor software, the versioning, if it was created initially, is lost again.

4. When sending back the simulation results, only qualitative results are kept. These can at best be reconnected as a whole to a CAD version in the PLM system via a link, which usually needs to be done manually.

In a nutshell: "We can go forward from the customer, but we can't go back." (B.3, 24:10)

Different Terminology of PLM and CAE

For PLM, technical terms are mostly standardised, as exchange on this level has been ongoing for a long time. Therefore, glossaries exist with the ambition of being globally valid. [41] In contrast, CAE glossaries are typically restricted to a certain simulation domain or even a specific application. [42]

4.2 Group-Specific Results: PLM, CAD & MBSE Engineers

As the perspectives on data management in this group vary and only four interviews could be conducted, the results are largely separate between the PLM standardisation, the CAD, and the MBSE level. Over all, five basic issues could be identified for this group:

1. The data structures of CAD and CAE data, and the usage and development of PLM and SDM, are marked by substantial differences.
2. The footprint of CAE data by far exceeds the common PLM data.
3. Standardisation in simulation is difficult due to the diversity and agility of the disciplines.
4. The possibilities and actual usage of data management applications differ, as the working culture of cultivating the data and using the available functionalities is still missing. So, self-created Excel solutions still prevail.
5. Data and information about the data is not universally accessible and/or interpretable due to the deep separation between both disciplines and departments.

4.2.1 PLM Standardisation Issues

Three basic problems mark the SDM integration from a PLM standardisation point of view [redacted] (see B.6):

1. The semantic break between CAD and CAE modelling,
2. the very different file sizes and processing loads, and
3. the different development drivers and directions for SDM.

Semantic Break Between CAD and CAE Modelling

There is a semantic break in the product structures, where PLM uses one product structure and SDM needs to cover different product structures, which are each different from the design geometries and structures.

Product design on the one hand uses a manufacturing-centred assembly structure, including information such as weight, connections between parts, sources of parts, version-control of parts and assemblies, manufacturing of parts, tools for manufacturing or assembly of parts. They also agree on a Euclidean system, orthogonal right-handed axis system, shapes, etc. So, a standardised format is easier to come up with.

Simulation on the other hand uses different product structures for disciplines and applications - such as crash, aerodynamics, or fatigue, and external aerodynamics, internal aerodynamics, or combustion, respectively. Additionally, there are Electromagnetic, Noise, Vibration, Harshness (NVH), and MBS tests. Co-simulations (coupled simulations or simulation chains) again add to the variety. Simulation tools are therefore very specialised, and each uses its own formats. So, ”Because the underlying physical models are so different, it is much more difficult to come up with one standard format that would capture all of that.” (B.6, 16:10, see also B.15)

The level of detail can be lower on the simulation side, neglecting small parts such as bolts, small holes, etc., or require details only in certain parts of the model such as the frontal body of a car for frontal crash. In other cases, the CAE models will need more detail than the CAD models provide. For example they may need details about connection elements like rivets or bolts, where simple symbols would suffice for CAD, or electromagnetic properties such as currents and voltages. Simulation also has more data sources than simple CAD data, such as material data bases. ”So, it is definitely not the case that one is a subset of the other” (B.6, 22:45)

CAE Data Size

The data size for simulation data is very different from that of classic design data. A CAD file can be some hundred megabytes for complex models, while dynamic CAE results can easily have terabytes of data. This is where the ASCII formats for STEP, and other clear-text formats, reach their limits in terms of efficient data storage and processing.

The Different Etymology of SDM Systems

Aside of these data issues, it is important to understand that SDM emerged in different ways. Some companies worked front to back: Taking engineering models and clustering them into input-decks and then managing their simulations. Others worked the other way around: **Company 08** first had their SDM started by managing the results and post-processing, turning raw data into diagrams and movies, then into simulation reports and storing the resulting PDFs. From there they worked to the front via output-decks to input-decks and so on. Therefore, it is very difficult to build a common specification list for an SDM standard.

Simulation also develops continuously, which makes the integration a ”continuous challenge, because [...] when you’re trying to close the gap [between PLM and SDM], you’re shooting at a moving target.” (B.6, 49:50) A solution may need to be either generic to a point where customisation efforts exceed the standardisation improvements, or be agile to an extent which makes standardisation a continuously laborious undertaking.

In practice, the software landscapes in companies need to be balanced between ideal and realistic solutions. Ideally, an SSoT in a giant data base managed by one big software vendor - a ”one stop shopping” (B.6, 60:05) - would cause the least friction in data handling. However, as this would be very costly and mean vendor-locking, many companies decide for a multi-vendor solution. In this solution, there may be one SSoT per domain, PD (PLM), simulation (SDM), electrical data, software, etc. The question would be how to connect those hubs. For this situation, the standard they want to have is a ’hub and spoke’ approach. So, a standard which can connect to any domain and communicate all necessary information among them. This would mean that after tool upgrades, only the hub (such as a STEP-I/O integration) of this tool needs to be updated, instead of updating each I/O library from the updated tool to any other.

4.2.2 Data Management Implementation and Usage

The reality of PLM implementation and usage looks different from the solution-oriented point of view: While functionalities are offered in a great variety and performance by the software vendors, these are not always used to an extend that would allow a smooth integration:

"They get the system on a Monday morning and the management tells them, 'Here it is. Have fun. Be 25 % quicker than before.' And this is just not how it works." (B.12, 29:30)

A workflow for the usage of data management systems needs to be set up and replace the established workflows. At some companies, this even needs to be enforced on a regular basis, as the engineers often implement their own workflows in Excel (see B.15). "So, the initial idea of having a transparent PLM system is really nice and funny, but in real life everybody sets up an Excel sheet [. . .] It's a little bit sad." (B.12, 32:20)

For these issues, not the data formats or even software solutions need to change, but the industrial workflows need to include the tools and human resources at hand. Or the software solution needs to be flexible enough to be coupled with the individual engineers' solutions, as "No Excel means no engineering, and it's still one of the leading tools." (B.15, 17:15)

4.2.3 The Systems Engineering Perspective

The MBSE perspective does not relate directly to CAD and CAE data exchange, but is rather concerned with the general accessibility of data and information about the data. An application for an MBSE approach is the simulation automation with partial models. For this, holistic models are created in early stages of the development process, when not all models are available but need to be replaced with black boxes or placeholders. (see B.17, B.15)

This means, that data must be a) accessible and b) interpretable across departments and software systems. Ideally, the data should also be machine-interpretable.

For the accessibility, API solutions as well as rights & roles systems on a server basis suffice. The Functional Mock-up Interface (FMI) standard can be used well for the systems integration. For interpretability of the data, company-global standards for data storage are necessary. This in turn implies, that data in native formats must be created in such a way, that all relevant information can be translated to the global standard. Additionally, the question comes up, "How can I exchange this information with my external partner?" (B.17, 7:10). For this, well-establish industry-global standards are required.

Concerning CAE data, the integration does not go deep enough to be concerned with the numerical connection between CAD and CAE models, yet. It is already clear, however, that for a smooth MBSE integration meta-data about the simulation needs to be connected to the numerical data, to ensure repeatability.

4.3 Group-Specific Results: SDM Departments and Software Vendors

The situation of SDM implementation is largely shaped by the customers' demands. These are firstly file organisation, secondly process organisation, and only thirdly PLM integration (see B.14). Essentially, SDM solutions include software applications via APIs and scripts, and files of any format as objects, into a git-like repository. So, for the SDM implementation, knowledge of CAE numerical processes is usually not required, nor are the variety and cost of tools and data formats an issue, as the SDM developers are not directly affected.

Instead, the main focus lies on the management, concerning roles and rights, as well as UI handling. As such, the current SDM solutions on the market can be understood as SPDM systems.

CAE disciplines are difficult to harmonise as they use different models, workflows, discretisation and metadata storage, so changes cannot be updated automatically even within the SDM systems. Additionally, there is no general concept of a generic simulation workflow. Therefore, typically each CAE unit has a customised SDM system.

4.3.1 Technical Situation in SDM

Generally, SDM system developers face a high demand of customisation: Management structures, simulation processes, available software solutions, the solutions' changing interfaces, similar to PLM solutions, which are also customised for different companies.

CAD Tools and Formats

The most popular CAD tool in use is Dassault Systèmes CATIA. In one case, PTC Creo is also used (see B.10). For CAD file exchange the SDM uses the CATIA native format, Part21-files, or in one case each JT or Standard Triangulation/Tesselation Language (STL) – although STL is rarely used. Which format is used in the SDM depends on the compatibility of the pre-processors rather than the convenience of the format, as the CAD imports, like simulation files, are regarded as objects.

CAE Tools and Formats

Normally, simulation tools are integrated via scripts or by accessing the APIs, so SDM developers can integrate almost any CAE tool. This works very well for them, but it can be more difficult if the documentation is licensed (such as for Teamcenter) or poorly documented (see B.11).

SDM developers are not connected deeply with the numerical data but simply handle it as objects (see B.9). For CAE exchange, they use any format that the software tool is compatible with. Instead, they are concerned with managing the processes and resources connected to the CAE workflows. (see B.8, B.9, B.10)

CAE Results

Simulation results are mostly transported back to the design level as qualitative assessments and key results. They are typically created automatically on the HPC units. The exports can be changed by the users using markup languages (see B.11). The key results are collected in MS Power Point, MS Excel or PDFs , which all interviewees used in some way or another. They can also be compared to each other or to physical tests (see B.9). In one case, the standard ISO/TS 13499:2019 Road vehicles — Multimedia data exchange format for impact tests (ISO MME) is used for value exchange (see B.11). In another case, specific result values, 'classifications', can be exported into the PLM system (see B.14).

Simulation Automation

Automation is implemented in very different ways: Hochschule für Technik und Wirtschaft Berlin (HTW Berlin) automated the simulation run from the file input (geometry and parameters), including assembly, solving and post-processing ([redacted], see also [43]). **Company 09** integrated third party tools for optimisation in their SDM system (Optimus and LS-OPT, see B.9). **Company 10** developed their own code to allow CAD engineers to run standardised and automated modal analyses, which was previously done by their CAE engineers (see B.10). [redacted] offers various customised automated workflows (see B.14).

SDM Products

MSC SimManager is used by **Company 08**, which they call a "Simulation Lifecycle Management" (B.8, 27:55). **Company 10** developed their own git-like solution called [redacted]. It is exclusively based on open-source tools and itself an open-source code. It includes functionalities for task and resource planning. (see B.10). **Company 09** develops [redacted], also a git-like management tool, which is distributed as a desktop application. It is divided into three parts: [redacted] is used for simulation project management, [redacted] for the model setup and conducting simulations on HPCs and [redacted] for viewing and exporting simulation and test results (see B.9, B.11). [redacted] develops [redacted], covering a variety of SDM functionalities (see B.14).

PLM Systems

PLM is normally treated separately from SDM, except for [redacted]. Therefore, the PLM integration and versioning are also solved very differently:

[redacted] is integrated deeply into [redacted], so the simulation data is integrated via links. [redacted] (see B.14) [redacted]

At **Company 08**, such integration does not exist. However, on a management level, an awareness of inclusion of different departments to relevant meetings does seem to exist. As an example, multimedia system developers are included in meetings for the car body structure because they would need to know the cavity of the car for their simulations. (see B.11)

Change Management

For **Company 08**, changes outside of milestones need to be communicated manually, even among different simulation disciplines. (see B.8)

The **Company 09** users update their geometries every 3-4 months. Within their SDM environment, different disciplines have roles and rights and are informed about changes from other CAE departments. (see B.9)

[redacted] can implement change management as an [redacted], pushing information through [redacted]. It was not clear, though, how much this is used. (see B.14)

4.3.2 Technical Issues in SDM

Different from the CAE engineers, the integration of tools is not an issue for SDM departments and software vendors, as their functionalities only need to be accessed via the APIs. Therefore, well documented and unlicensed APIs are needed, which not every software vendor provides. (see B.11)

Harmonised simulation processes are a core issue: In large companies, the processes for carrying out simulations vary even across departments. At **Company 10**, they therefore developed global simulation standards for all CAE units (see B.10). **Company 08** tries to solve this issue by introducing standardised simulation definitions in [redacted].

Harmonised design processes could help the CAE model creation: **Company 10** introduced design rules to improve the conversion from CAD to CAE models (see B.10). Similarly, **Company 09** advises their customers to do so, for example, creating middle surfaces or defining sheet / shell thicknesses, which is a lot easier to do on a CAD than on a CAE level. (see B.11)

Open file standards are typically not an issue for SDM. Instead, this is up to their customers and the software developers. Only **Company 10** wants to move further into coupled and chain simulations and therefore looks for interoperable file standards, possibly in connection with the SCAI Mesh-based parallel Code Coupling Interface (MpCCI) mapper. (see B.10)

On a data model level, data granularity is a central aspect in two different ways: When integrating into PLM systems, the SDM needs to ensure a good traceability, meaning a data flow which is filtered and up-to-date. Filtered data means that updates of data contain exactly the necessary information for this department, which is difficult considering the very different data models (see section 4.1). Up-do-date means the link to the correct parts and versions must be strong, so the identifications need to be kept throughout file conversions (see B.9, B.14, B.11). This requires a compatible baseline management on the PLM side, ideally going further than only updating on milestones (see B.10, B.14).

Other mentioned issues are: The creation of crash models takes a long time, so automating this part could help with performance and quality of the simulation process (i.e., speed and consistency respectively, see B.8). Another issue is to integrate an interoperable task management, as this may in theory be implementable in STEP, but is not exportable to common project management tools such as MS Project (see B.10).

4.3.3 Main Goals & Expected Benefits in SDM

The main goals for SDM group are:

1. Process harmonisation. In order to not only manage the simulation data, but also simulation processes (i.e., becoming an SPDM system), the SDM developers need to define generic simulation workflows across departments and ideally disciplines and companies.
2. Workload reduction. A lot of tasks in SDM are still managed manually. Automating and better handling of ad-hoc data would improve this immensely.
3. Traceability. To be able to gain comparable and interpretable results, the identification and tracking of input data is vital.

4.4 Group-Specific Results: CAE Departments and Service Providers

Despite their diverse integration and fields of application, the CAE engineers group is the most uniform group with regards to their interoperability situation and needs. Most interviewed CAE engineers provide external or internal services for testing, improving and verifying the CAD definitions. They receive information about the design, run tests, and in some cases optimise the geometry or choose a suitable material. Their results are transmitted to the design engineers via reports, e-mails or discussions.

4.4.1 Technical Situation in CAE

CAD Import Into CAE

CAE engineers typically receive a geometry in a Part21-file. When the import does not work, they request other formats, mostly Initial Graphics Exchange Specification (IGES) or Parasolid. In situations in which their service is part of their customers' simulation chain, they could also import a meshed geometry.

Company 03 as a CAE service company also performs simulations based on drawings, descriptions or measurements, so they build their own geometries (see B.3). For some optimisation, CAE engineers can manually change the imported CAD geometries, which is laborious, though, because parametrisations such as extrusions need to be created again (see B.3, B.5, 5.2).

CAD Tools

The mentioned CAD tools are:

- ANSYS SpaceClaim
- Autodesk AutoCAD
- Dassault Systèmes CATIA
- Dassault Systèmes SOLIDWORKS
- PTC Creo
- SiemensNX

CATIA is the most common CAD tool, some use PTC Creo. **Company 04** has a variety of CAD tools (Creo, SiemensNX, CATIA, AutoCAD, SOLIDWORKS), but usually each engineer has their preferred tool (see B.4). PTC Creo allows simple simulations like structural and modal analyses to be run by CAD engineers. Later, simulations by CAE specialists are used for verification. (see B.12, B.13)

Simulation Tools

For their simulations, CAE engineers use a wide range of software tools. Additionally, many use self-developed solution. Once the engineers decided for a software line-up, as a rule, they "never change a running system" (B.1, 9:20), as this would be more costly than customising the tools their engineers got accustomed to already.

The mentioned simulation tools are:

- Pre-processing: Altair HyperMesh, Altair HyperWorks, BETA CAE Systems ANSA
- Structural: Abaqus CAE, Abaqus explicit, several ANSYS solutions, Creo integrated, LS-DYNA, ESI PAM-CRASH
- Moulding: Autodesk Moldflow, SigmaSoft, Accufoam B-Sim
- CFD: Altair AcuSolve, OpenFOAM (open-source), Siemens SimCenter STAR-CCM+
- Lifetime assessment: FEMFAT, nCode, pyLife (open-source)
- Coupling environments: MpCCI CouplingEnvironment
- Mapping: 4a engineering FibreMap, MSC e-Xstream Digimat, MpCCI Mapper
- Optimisation: Altair OptiStruct
- Post-Processing: HyperView, GNS Animator, ParaView (open-source), BETA CAE Systems mETA
- System modelling: MathWorks MATLAB and Simulink

Data Formats

As the exported results are mostly qualitative, the output decks are kept in the native format. Three standards are used for other cases, though:

1. **Company 01** use the SMILE format to store input decks including the geometry and parameter definitions (see also subsection 4.5.3). **Company 01 and 10** also use ISO MME for storing geometry-based results information. (see B.11, B.1)

2. **Companies 03, 04, 05 and 07** perform simulation chains of manufacturing workflows. For these, VMAP is used to transfer data between simulation tools.

3. To export results to external viewing tools and to store data efficiently, **Companies 07 and 11** use the VTK standard to store result data. This works particularly well for **Company 11**, as they select the parameters to be included in the VTK file. Therefore, they significantly reduce the file size (see section 4.5).

Company 07 is now switching to VMAP for some cases, in which VTK did not work. **Company 11** may also consider switching to VMAP, as they currently need a separate license to translate the Abaqus output decks to VTK, which could be done in the VMAP wrapper for Abaqus. (see B.7, B.13, [27])

Data Management

CAE service companies and research institutes largely work on a file-based system. They do not need a version control, as their service requests are largely separate from each other and only needed to be linked back to the simulation and/or test requests.

Data Compression

Saving data or improving data storage does not appear to be the largest issue, as the very large result files are be stored locally on the HPC or desktop. With one exception, none of the specialised CAE engineers are concerned with this, as they usually do not need to keep result files, but only the exported reports and the imported data. For storing the much larger crash result files on systems, however, a licensed tool called FEMZIP is implemented. This was developed by Numerical Data-Driven Prediction (Numerische Datenbasierte Vorhersage) department at Fraunhofer-Institute for Algorithms and Scientific Computing SCAI (SCAI NDV) and SIDACT to store the particularly large crash simulation results. A simple ZIP compression suffices for ASCII-formatted input and parameter files, as these are not as large and ZIP allows a high compression rate. Additionally, deletion rules can apply based on certain priorities according to the importance of the results, or after a set time.

Instead of data storage, data transfer plays a bigger role. Therefore, [redacted] tried storing and transferring only the differences between a baseline model and the transferred model ([redacted], see also [6]). For **Company 10**, this is already implemented in their intelligent SDM solution. **Company 10** also does not store simulation data created in its CAD-integrated simulation solution and backs up only vital output decks (see B.10).

Simulation Automation

Automated workflows rarely exist, as the performed simulations are usually not repeatable and cover very specialised domains. Some use their own solutions to run optimisation loops on a small selection of parameters, which is normally done mesh-based.

Company 14 provides a special solution, [redacted] This was not found to be used by the CAE engineers, most likely because it is too expensive and the parametrisation needs to be implemented very neatly in order to function on both tools. (see B.5, B.16)

Company 11 developed their own automation for fatigue simulations, which made up a significant amount (around 20 %) of their simulations. The mesh still needs to be created manually. After this, they can run a Python-based script all the way to the results report (see B.13, see also subsection 4.3.1). Similarly, **Company 10** developed some automated CAE simulations which can be run by their CAD engineers (see B.10).

PLM, SDM, and Version Control

Most interviewees do not use a data management tool, but organise their data on a file-basis. **Company 02** was one exception to use SDM with [redacted] (see B.2). **Company 04** uses SIEMENS Teamcenter for visualisations (see B.4) and **Company 11** uses Windchill (see B.13), both PLM systems. Only the CAE engineers at **Company 11** use a version control (see B.13). The other engineers use lists to keep track of their simulation runs and changed parameters, which are not integrated in a data management system. **Company 14** does offer an SDM solution, but their applications are normally integrated into external PLM or SDM systems (see B.16).

4.4.2 Technical Issues in CAE

Most issues faced by the CAE engineers are common concerns observed by all three groups. As the interviewees from this group represent rather small companies, their main problems lay with the integration of diverse software solutions.

Several issues connected to simulation tool integrations came up: The 3D modelling and meshing are currently done in tools separate from the solvers. An inclusion at least on the interface level would help slim down the tool chain for the engineers (see B.4, B.13). Other important points are the availability and documentation of APIs (see B.3) as well as integrated I/O functionalities for standardised formats (see B.5, B.7).

CAE engineers are not looking for an integration into PLM and SDM platforms, as versioning and keeping track of simulation parameter changes is not a big issue for them. Additionally, existing SDM solutions are mostly too expensive for SMEs. The lack of demand for PLM integration came down to the very separate workflows and management structures among the CAE departments / companies and the rest of the PD structures. If such an integration was available, though, it would probably be better accepted as an integrated adapter or plug-in solution, rather than an external tool (see B.1, B.2). Even for an integration on a data level, separate interfaces for PLM and SDM would still be appropriate, considering the very different usages. For this connection, versioning and links would probably suffice, instead of using common numerical data (see B.13).

4.4.3 Main Goals & Expected Benefits in CAE

Four main possible improvements could be identified for CAE engineers:

1. Being able to track geometry difference would help connecting these to different results, as well as judging when a simulation needs to be rerun. (see B.2)

2. A standardised data connection would help especially service companies to be integrated more deeply into their customers' workflows, and

3. To communicate with their software line-up (see B.3).

4. For the whole simulation, the goal is ”making the chain more light and less complicated” (B.4, 47:30), meaning fewer and less separate interfaces.

4.5 Existing Integration Attempts

To allow a better Data Continuity for simulation workflows, three approaches were identified:

1. Connecting the software setup using the available API functionalities.
2. Standardising SPDM on a PLM level.
3. Harmonising the link from CAD to CAE to speed up model creation and simulation runs.

4.5.1 Utilising Software Compatibility

SCALE and Audi developed an integration between their SDM and PLM systems via their CAD tool: Their installation of PTC Creo was integrated into their SDM system. This allows the simulation engineers to directly access, lock, manipulate and export the CAD data in the company's PLM system. ([redacted], see also [6])

At **Company 11**, the simulation results can be reduced to relevant parameters and exported into VTK. These reduced result files can be linked to the product in the PLM system, viewed by the engineers in the open-source ParaView tool, and compared to their CAD model. As an additional trade-off, these files are significantly smaller than the native result files. **Company 11** intends to include the VTK viewing capacities into CATIA to allow an overlay of geometry and simulation results. They still do face the difficulty, that for the translation of Output Database (.odb) result files an additional license is required. When they create links to the results in their PLM, the correct versioning is still taken care of manually. (see B.13)

At **Company 10**, the integration into PLM systems is not the main focus, but the better integration of their simulation disciplines into their CAE framework. To achieve this, they use a self-developed SDM tool across departments, which is based on open-source solutions and features intelligent storage rules and an included task and resource management. To go with this, they develop company-global CAE standards for comparable results, and maintainable code for automated simulation. (see B.10)

Company 14 also provides a solution to import parameters from external CAD applications, i.e. CATIA. For this, they can prepare entirely repeatable workflows from geometry import to simulation and results. This is only used by a few for their customers. **Company 14** can also create their own parameters and evaluate surfaces as results. This solution can be unidirectional or bidirectional. They have an interface to update the improved geometry directly in CATIA, which can be tricky from an organisational point of view and is not always welcomed by the designers. Additionally, the model needs to be defined in a very robust way in advance. (see B.16)

4.5.2 Standardising Formats and Processes

In standardisation, the CAx-IF [see 24] tries to establish AP209 as a standard including both CAD and CAE data, with the issues discussed above (see [4, 25], 2.3.1). As another standardisation approach, ProSTEP iViP published the SimPDM recommendations for the integration of simulation data in PLM systems [see 5].

Companies 09 and 10 introduced design rules to allow for a smoother data exchange between design and simulation (see B.11, B.10). SMILE goes in the same direction, improving the model creation by defining re-applicable modelling guidelines to speed up and unify pre-processing and simulation runs (see subsection 4.5.3).

4.5.3 Improving the Model Creation: The SMILE Language

A currently upcoming solution in enhancing interoperability within workflows connecting CAD and CAE engineers is the SMILE language. Developed by HTW Berlin [redacted], this project aims at democratising the CAE workflow, i.e., making it more accessible to non-CAE engineers. In the past decade, the variety of simulation tools has increased along with the complexity of product requirements and development speeds. This means that engineers need to have a specific understanding of their software applications and the numerical bases and put these in perspective to their field of application. If either of these conditions change, new knowledge needs to be acquired which can be a lengthy progress with uncertain success.

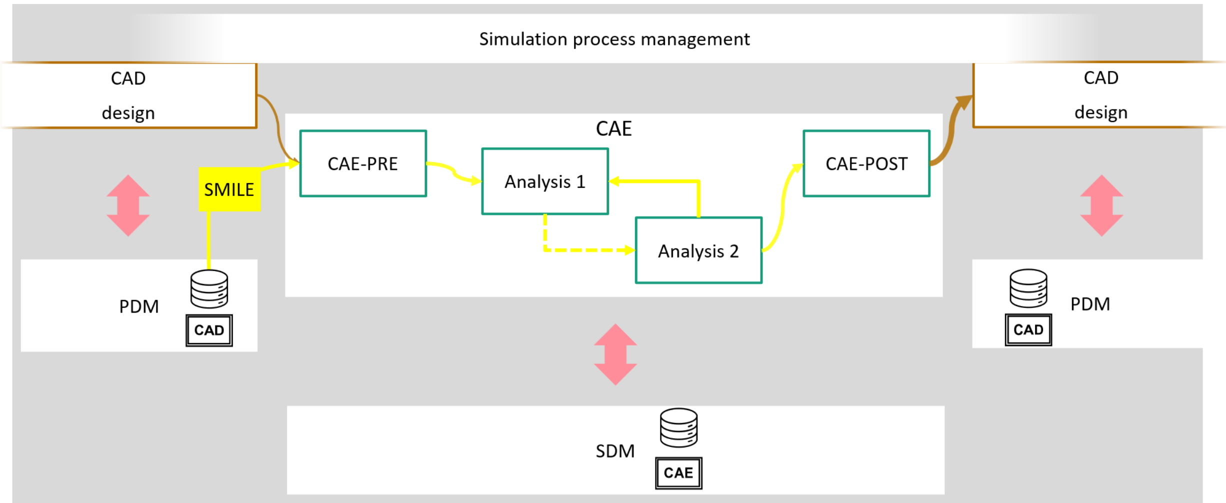

Figure 4.3: The SMILE process (yellow) in a CAD-CAE-workflow. It includes the model creation from a CAD model, the pre-processing and the simulation (chain). Native data of the simulation tools can be exchanged with the SDM system, CAD data is exchanged with the PDM system. The whole process can be monitored by the SPDM.

To solve this, the SMILE language ”provides a syntactical basis for the description of a component in terms of its physical properties solely.” [43, p. 2] This model can then automatically be translated to different numerical representations by scripts or preprocessors. The translation needs to be defined only once for each tool. The utilisation case is defined in modelling guidelines. These, as well as the model file describing the physical properties, and the configuration file, describing boundary conditions and potentially merging different model files, are written in the standardised XML language. Collectively, these standardisations allow for automated workflows from the physical representation to the solver-specific results. The way the engineering process is transformed is shown in Figure 4.4. [43]

SMILE is generally open to include any CAE model format. So far, though, it still lacks the ability to depict element histories aggregated during the manufacturing simulation chain. This could be solved by an inclusion of VMAP into the standard. [redacted]

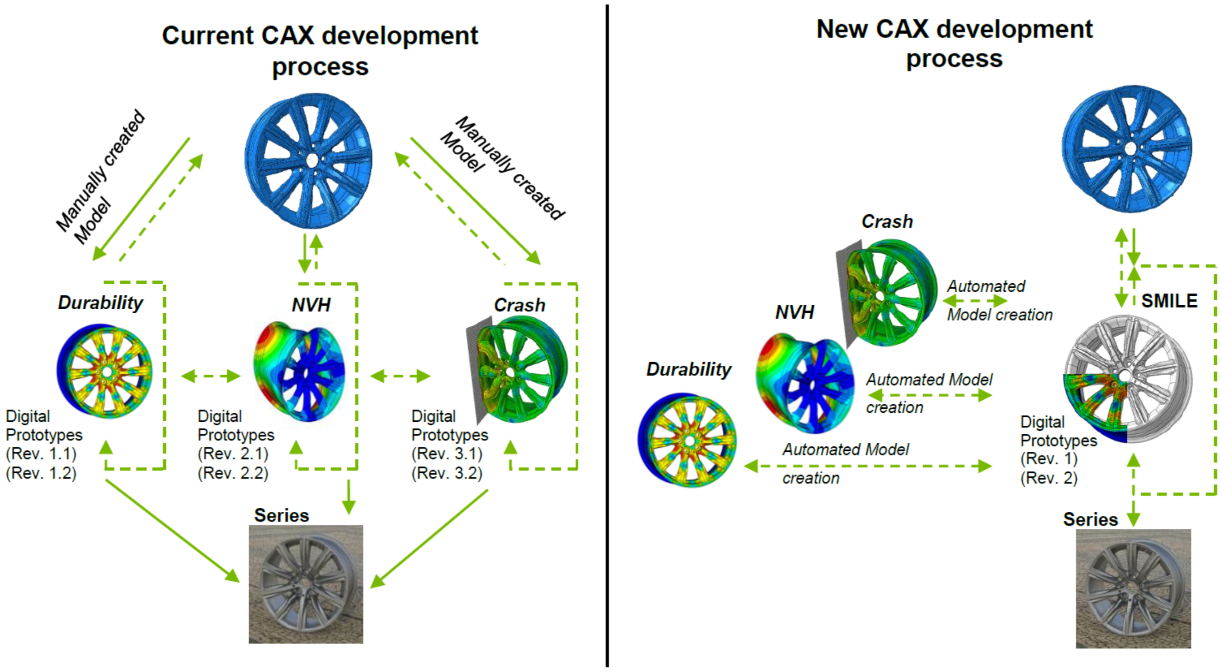

Figure 4.4: Comparison of the development processes. Left: Currently, a simulation model needs to be created manually for each simulation domain separately, and repeatedly for each desing update. Right: With SMILE, the model creation can be defined once in SMILE and then automatically be applied for each simulation domain and after updates. [43, p. 3].

5. Proposing Development Directions for STEP and VMAP

Summary: The users of STEP and VMAP are very happy with the improvements over previously used formats (IGES or STL, and STL or JT, respectively, or native formats). This implies, that both should be developed further to allow a continuous and broadened use in industries.

In general, both standards could still be established better in the existing software line-up. For STEP, the existing export functionalities should include more features, such as versioning and parametrisation (see sections 5.2 and 5.4.1). For VMAP, I/O libraries should be implemented in more simulation tools (see B.5) and the export should be possible within the software interfaces instead of using external wrappers (see B.7).

Export and exchange of CAD data should also become smoother. This lies especially in the hands of the CAD software vendors who implement the export functionalities. These often still depend on the now withdrawn AP203 standard (see D). Alternatively, an external checking tool could be developed, to verify the import capabilities of geometry files for a CAE application, which also vary a lot.

Apart from the continuous introduction to industry, five project proposals utilising the standards are identified based on the results of the requirements engineering analysis:

1. A generic VMAP viewing tool.
2. Exchanging geometry parametrisation.
3. Harmonising material data.
4. Managing simulation workflows in a VMAP-based SDM
5. Bridging the gap between VMAP and STEP on a data level.

For each project proposal, important aspects to be considered are described in the following sections.

5.1 A Generic VMAP Viewer

The development of import capabilities for VMAP files into an open-source viewing tool such as ParaView would allow for wider post-processing options for the standard. On one hand, it would allow industries already using the tool to switch to VMAP more easily (see B.13) and vice-versa (see B.1).

ParaView already includes an extensive UIs (see Figure 5.1). It is also compatible with other HDF5-based file formats such as VTK, HDF5 Particle (H5part) files, and many other binary formats [45]. Additionally, it can be used to view CAD files

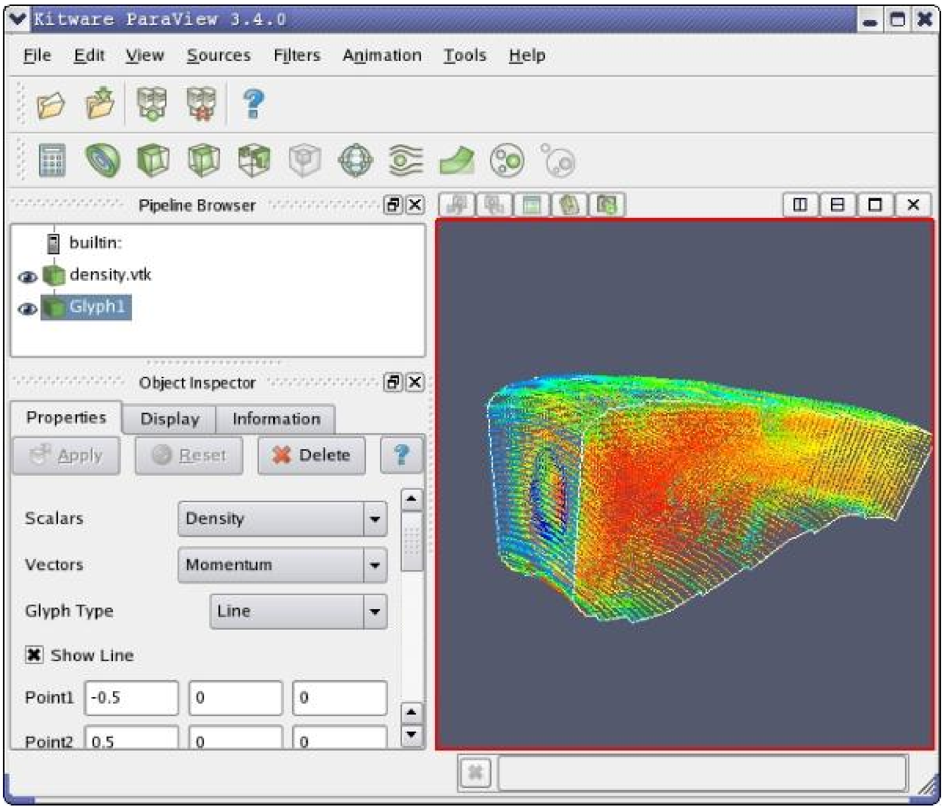

Figure 5.1: A demonstration of the viewing capabilities of simulation data in the ParaView UI. [44]

such as STL, which would allow for overlapped viewing and comparing capabilities for connecting the simulation results to the geometry. Alternatively, native formats and Part21-files can be translated to VTK using other open-source APIs like FreeCAD. As the ParaView API is open-source and well documented, the development of a plug-in appears a viable option to propel the VMAP standard forward. [see 45, 46]

5.2 Exchanging Geometry Parametrisation

A common geometry parametrisation for both STEP and VMAP could provide easier model configuration, better change management and improved optimisation automation. The acceptance of these may be mixed, though:

Definitions for parametrised geometries such as extrusions and rotations do exist in STEP, developed in the Construction History And Parametric Specification (CHAPS) project for AP203. They are also included in AP214 and AP242 (see Figure 5.2). However, these are often not implemented in the current Part21-file exports. This was tested for FreeCAD exports, which used AP214 (see Appendix D).

Instead, the Part21-file-exports often reduce geometries to edges to construct surfaces and closed volumes from these, as demonstrated in subsection 2.3.1. This has three reasons:

1. At the time of the development, parametrisation was not required by the users.

Instead of creating the digital twin, the idea at the time was to exchange neutralised models without keeping the modelling history and identifications.

2. It became clear, that parametrisation works very differently for different CAD tools. There may be a common basis, but the specific functionalities are very application-dependent. Thus, a full coverage of parametrisations would not have been possible.

3. Additionally, in the years after the CHAPS project, the import of neutralised files improved significantly. As such, CAD tools are now able to do educated guesses on the imported geometry. Examples for these functionalities are Live Shape from Dassault Systèmes and Direct Modeling Express from PTC. (see B.6, D)

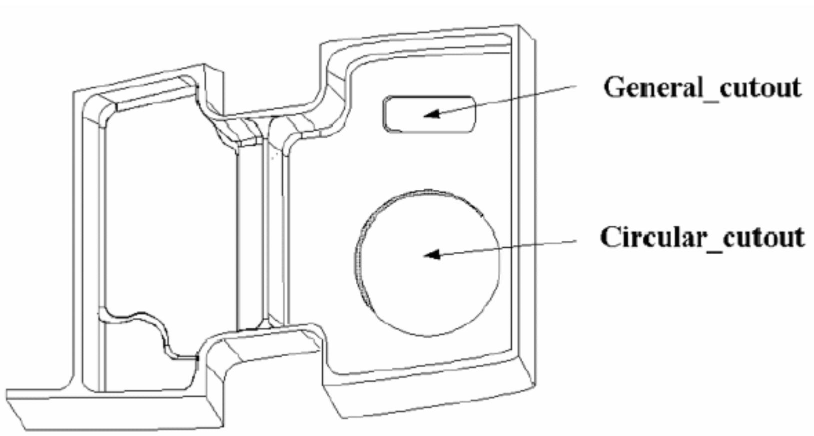

Figure 5.2: A demonstration of instances of Cutout_feature as depicted in the STEP Application Module 1814, an AM integrated in AP242. The extrusion is defined by the base surface (circle and rounded rectangle) and the axis of the extrusion. [16]

In conclusion, although the simulation community may be more proactive with introducing new software solutions and data features, the past experiences of STEP development show that the effort for harmonised parametrisation may exceed its reward.

5.3 Harmonising Material Models

Material models vary between both solvers and data management systems, and exchange between these is often difficult to implement or not possible because of the different types of information. For example, the manufacturer of a material may be required by the PLM, while the friction coefficient may be required by the SDM - and not vice-versa. In a similar way, simulation domains may require very different scales of material information. (see Figure 5.3)

Despite standards such as STEP and VMAP, which do address the exchange of data including material models, even formalising the fundamentals of material science is still an ongoing effort. This means, that although both STEP and VMAP include possibilities for material property definitions, the included information may not be interpretable across domains. [see 8, 16, 3]

Harmonising material data for simulation is one of the key objectives of the smartMpCCI project. It defines Material as "a substance, which possesses technically exploitable properties in at least one aggregate state and which is technologically and economically producible and which is during and after use ecologically compliant." The project sub-categorises ceramic, composite, glass, metal and polymer materials. [8, p.18]

SmartMpCCI aims at developing an ontology for the digital twin, organising digital twin interoperability projects, and creating connections to established standards and ontologies. For material modelling, these are VMAP and STEP, as well as the European Materials Modelling Council (EMMC)'s works on the European Materials Modelling Ontology (EMMO) [47] and Ontology for Simulation, Modelling and Optimization (OSMO) [48], and the MaterialDigital platform [49]. [see 8]

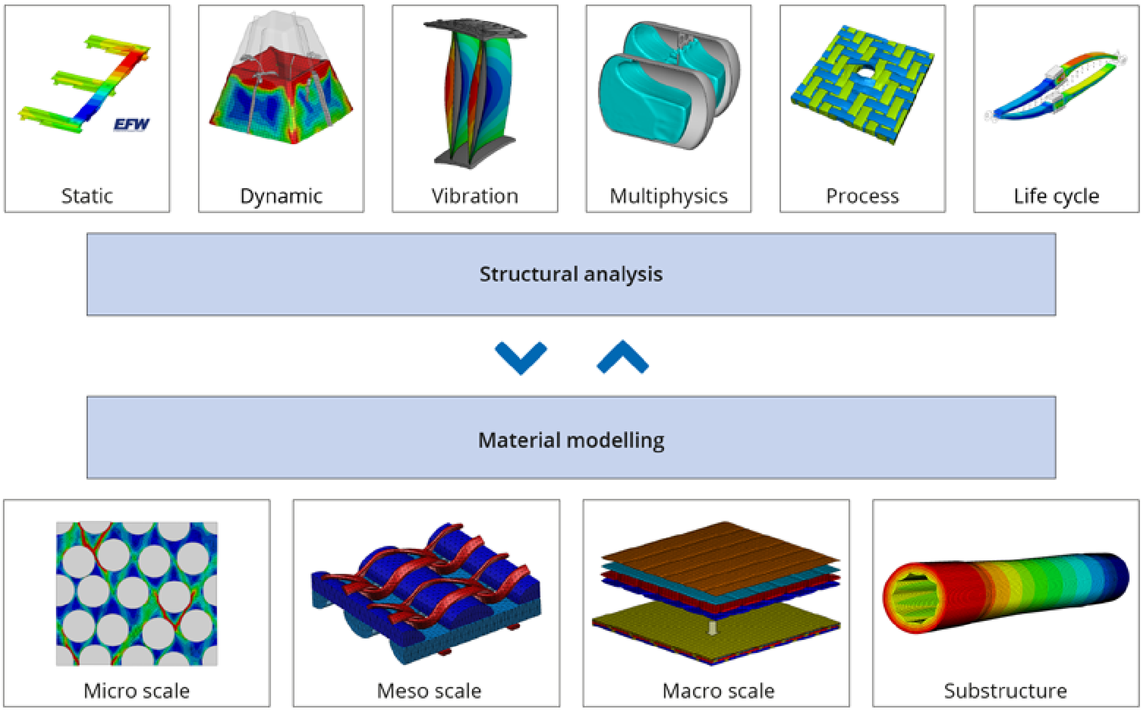

Figure 5.3: Structural analysis and different scales of material modelling. Depending on the simulation, different scales of information about material behaviour need to be modelled. [50]

5.4 Managing Simulation Workflows in a VMAP-Based SDM

A central issue for SMEs was the lack of an affordable SDM solution. VMAP already offers the use of a data container across tools and enjoys a growing acceptance in simulation. This could be used in an open-source SDM to include central aspects of simulation processes and workflows.

5.4.1 Key Features of an Open-Source SDM

Versioning Across Domains and Locations

Often, version control is already lost by exporting models in Part21-files outside of the PLM. An open-source SDM, should be programmable to read and keep track of versioning. Ideally, it could incorporate the versioning capabilities of the STEP data model for defining product IDs. The AM 1018 defines the scheme product_identification, which could be utilised [16].

Additionally, the SDM should be capable of referencing data independent of different locations, such as on HPCs, local file servers, or personal computers.

Standardised and Customisable Results Exports

In the same way, result exports should be customisable to allow engineers to include all vital information. At the same time, generic drafts should help to create commonly required information.

Hub-and-Spoke Setup

As the use of versioning fields in standardised formats is up to the software vendors, and as native formats often do not include this functionality, the exports from any tool need to be linked to its imports. This requires a neat connection with software tools' APIs. As these would need to be customised, the SDM should include a clear documentation and recommendation for these connections, to allow for independent interfaces to different software tools.

Simulation Process Definitions

An SPDM would include simulation process definitions in addition to the data management structures, going from numerical definitions such as boundary conditions up to ERP information such as the engineers' role and software application version. This understanding could be derived from the existing structures of AP209 or from the Simulation Entity part of the smartMpCCI project. [8, pp.24ff],[4]

Compression

Using the compression features of HDF5, VMAP data in the SDM could be compressed further. Additionally, concepts of FEMZIP or SDMZIP could be applied. (see [51, 52], B.2)

5.4.2 SDM Development Strategies

For such a solution, three development directions are possible:

1. Ontologically Creating an SDM Structure

   In the smartMpCCI project, also simulation processes will be defined. These could be used to create a top-level data management structure, which can then be filled with VMAP files.

The advantage of utilising the smartMpCCI findings for an SDM is, that it also aims at including definitions for PLM and product design. This would allow for a smoother integration in to a similarly developed PLM system.

2. Expanding VMAP Using STEP's Data Management Definitions

   To build an SDM environment around VMAP, the existing simulation process definitions in AP209 could be applied. This would, however, require a laborious process of interpreting the STEP definitions and aggregating them into an implementation recommendation.

3. Including VMAP in the AP209 Simulation Management Structure

   AP209 can be very powerful in capturing the simulation (process) management level, i.e., capturing which simulations were run and preserving cross-links to engineering data. This is already implemented at [redacted]. Their integration works mostly on FE data as it "is universally agreed to be the low hanging fruit" (B.6, 27:25). This approach is discussed further in section 5.5.

5.4.3 Existing Solutions to be Considered

An attempt at an open-source SDM development should look into the prostep iViP recommendations for SimPDM [5]. [redacted] (see B.10) and the inclusion of boundary conditions and simulation parameters in the SMILE language ([redacted] [43]) should also be considered.

5.5 Bridging the Gap Between VMAP and STEP on a Data Level

Like for an open-source SDM system, existing data management systems and business units using CAD and CAE data in connected workflows could profit from the sensible integration of VMAP data for their simulation (see item 3). The main issue to be considered here, is the format in which the inclusion should be implemented. There are three main options:

1. A standardised link between STEP and VMAP data down to the element level would require a thorough research, a lengthy standardisation through the International Organization for Standardization (ISO), and may fail because of different overlaps in customisable data fields. (see section 2.4)

2. Instead, a recommended practice could be developed, which defines the integration of VMAP files into a STEP-driven data management system. This may also allow for VMAP users to adapt a generic data management for their SDM. For verification of such a recommendation, a collaboration with [redacted] would be useful. This format would be most suitable for large enterprises, who can afford to access the required STEP documentations.

3. The documentation of a software solution could serve for a recommended practice, too. The establishment of an integration tool to translate STEP data into VMAP and vice-versa could be used wherever either of the standards are already in use. The tool might take the shape of an external adapter, a plug-in for applications or systems, or an online-tool.

   A software solution would introduce an additional tool to the already large software landscape of simulation and design engineers, and might therefore not be accepted well. However, it would be suited for both large enterprises and SMEs, as it can be offered open-source or at a lower cost. Large enterprises could use a plug-in function or an API to integrate the tool into their existing solutions. The integration could allow two main features:

   a) Continuing the versioning which was already defined in the STEP environment. This can be read from Part21-files and written to an empty VMAP container in unambiguously defined meta-data fields. The container can then be filled as usual, using any pre-processing tool with VMAP export capabilities.

   b) Writing a common versioning to both the Part21-file and an empty VMAP container. This option may even be used most, as CAD tools often do not use the versioning capabilities of STEP. This would allow for manual versioning in SMEs and small simulation departments, and for automated versioning in larger data management environments, utilising an API function.

6. Summary and Outlook

Achievements

The thesis touched on the subject of the course of studies 'Virtuelle Produktentwicklung' in two ways: On one hand, the thesis is part of the PD for the VMAP-STEP-project. On the other hand, it researches a fundamental part of modern PD processes in the industry.

Over all, the conducted research allows for a deep insight into various processes concerned with simulation in PD for industrial manufacturing. It showcases the variety and spectrum on which the applications, workflows and needs of engineers in virtual engineering are located. As intended, it additionally implies directions for further development of the STEP and VMAP standards.

The survey shows, that the implementation of a Digital Thread faces issues that go far beyond the data representation techniques, but are more deeply connected to the companies' workflow management and culture. This diversity, along with the diversity of tasks, the related software solutions and their data interpretations, results in a variety of circumstances. To take account of these, the understanding of working cultures and workflows needs to be deepened while generalising the offered solution to accommodate the whole landscape. This may be done with the aid of ontological approaches supported by cooperation across the market.

Further Market Research

Given more resources, additional research on a larger scale should be conducted, covering more manufacturers and software developers in particular, to generate a more holistic overview of the situation and needs in CAD/CAE interoperability.

To allow future efforts to seamlessly build up on the conducted research, a comprehensible survey and results documentation is available in this thesis.

Further Technical Development

This thesis is a depiction of the current situation in manufacturing engineering. With the development of, for example, Artifical Intelligence (AI)-driven data analysis and processing, traceability of features such as parametrisation or material modelling may become more feasible in the next years.

The findings of this thesis point towards developing a better connection on a data level, resulting in the five project proposals described in chapter 5. These should be approached in the upcoming VMAP-STEP-project.

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A. Interview guidelines

A.1 Initial Questionnaires

Table A.1: Initial Questionnaire for CAE experts. Questions posed to the interviewees are printed bold. Other points are filled in by the interviewers and asked for specifically where necessary.

Topic/Question	Notes	Minute mark
Introduction (see Notes)		
What are your typical applications involving CAE and CAD?		
Materials		
Simulations		
CAD processes involved (Optimisation/ manufacturing/ . . .)		
Data formats involved		
Tools involved (both CAD and CAE tools)		
More notes		
We know you develop [...] Could you tell us which standards/formats you support? Which simulation domains do you support?		
Standards/formats (name + domain + stage in workflow) e.g. STEP, PDM, exporting CAD model to CAE or VMAP, SDM, transferring CAE model between simulations		
Domains (FEM/CFD/meshfree/...)		
More notes		

Continued on next page

Table A.1, continued from previous page.

Which difficulties are you / your users facing on an interoperability / digital thread / data continuity level?		
Which standards would you like to support but cannot?		
Which workflows would you like to support but cannot? (e.g. export back to CAD)		
More notes		
What additional interoperability features should a solution such as a platform-integration or a plug-in offer? What could be your benefits?		
Which kind of tool would they prefer? (Platform / Plug-In / extra Software)		
For which exact steps in the engineering workflow would the solution need to be validated?		
Could you try to quantify your gains from this solution? (number or benefits in words)		
More notes		

Table A.2: Initial Questionnaire for OEM representatives. Questions posed to the interviewees are printed bold. Other points are filled in by the interviewers and asked for specifically where necessary.

Topic/Question	Notes	Minute mark
Introduction (see Notes)		
What is a classic CAD/CAE use case we could talk about here?		
Materials		
Simulations		
Product development processes involved		

Continued on next page

Table A.2, continued from previous page.

Data formats involved
Tools involved (both CAD and CAE tools)
More notes
Which tools and data formats are you using for PLM, CAD and PDM, CAE and SDM?
Tools (name + domain + stage in workflow) e.g. BETA CAE, FEM, verification for final CAD
Data formats (name + domain + stage in workflow) e.g. STEP, PDM, exporting CAD model to CAE or VMAP, SDM, transferring CAE model between simulations
More notes
Which difficulties are you facing on an interoperability / digital thread / data continuity level?
Do different departments need to interact?
How is data transferred for traceability from CAD to CAE? Export from which tool(s)? Import to which tool(s)?
How is data transferred for traceability within CAE? Export from which tool(s)? Import to which tool(s)?
How is data transferred for traceability from CAE to CAD? Export from which tool(s)? Import to which tool(s)?
More notes
What are your current solutions?
Self-written code? Which language? Open-source?
External tool?

Continued on next page

Table A.2, continued from previous page.

Does this solution satisfy?		
More notes		
Which features would you like to add to your solution? How could these be embedded in your workflows? / What would be your preferred solution? What could be your benefits?		
For which exact steps in the engineering workflow would the solution need to be validated?		
Which kind of tool would they prefer? (Platform / Plug-In / extra Software)		
Could you try to quantify your gains from this solution? (number or benefits in words)		
More notes		

Table A.3: Initial Questionnaire for PLM, PDM, and SDM experts. Questions posed to the interviewees are printed bold. Other points are filled in by the interviewers and asked for specifically where necessary.

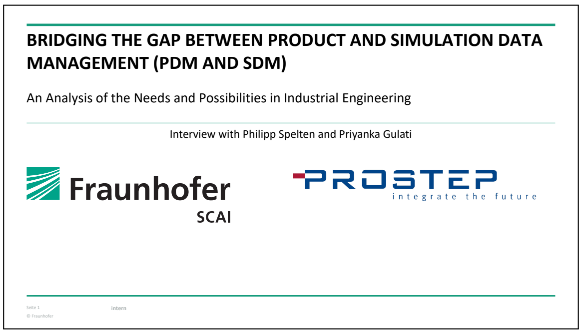
Topic/Question	Notes	Minute mark
Introduction (see Notes)		
What kind of use cases do your customers have?		
Materials		
Simulations		
CAD processes involved (Optimisation/ manufacturing/ . . .)		
Data formats involved		
Tools involved (both CAD and CAE tools)		
More notes		

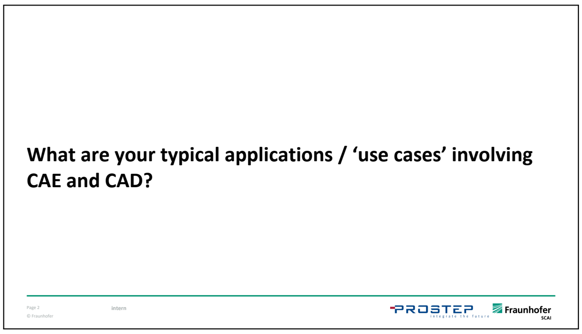
Continued on next page

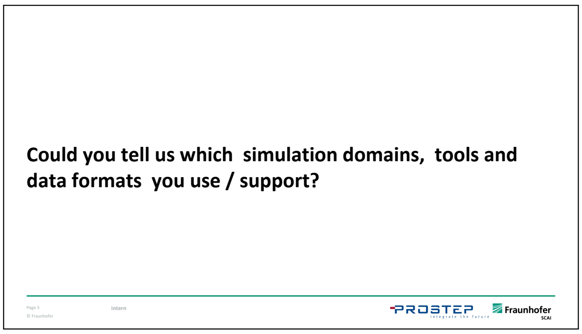
Table A.3, continued from previous page.

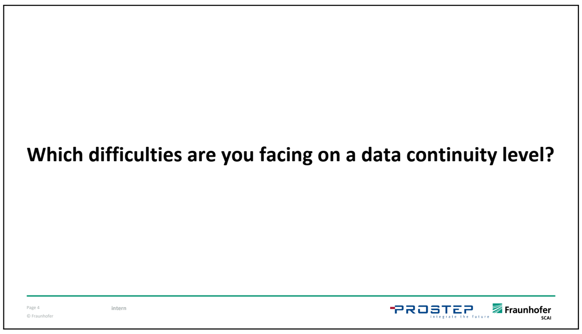
Which tools do you develop? Which data formats do you support? Which simulation domains do you support? How deeply can you support exchange between CAD and CAE?
Tools (name + domain + stage in workflow) e.g. BETA CAE, FEM, verification for final CAD
Data formats (name + domain + stage in workflow) e.g. STEP, PDM, exporting CAD model to CAE or VMAP, SDM, transferring CAE model between simulations
Domains (FEM/CFD/meshfree/...)
CAD-CAE interoperability
More notes
Which difficulties are you facing on an interoperability / digital thread / data continuity level?
Which data formats would you like to support but cannot?
Which workflows would you like to support but cannot? (e.g. export back to CAD)
More notes
What additional interoperability features should a solution such as a plug-in offer? What could be your benefits?
Which kind of tool would they prefer? (Platform / Plug-In / extra Software)
For which exact steps in the engineering workflow would the solution need to be validated?
Could you try to quantify your gains from this solution? (number or benefits in words)
More notes

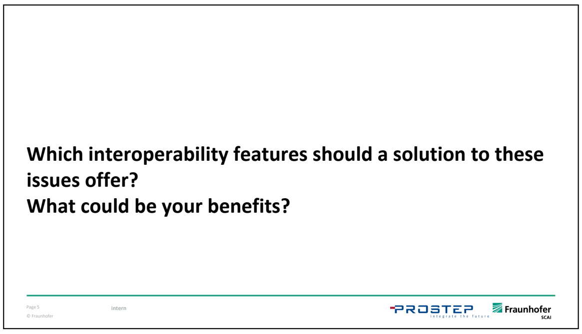
A.2 Interview Presentation











B. Interview Notes

The interview notes are not included in the published version due to confidential information contained.

B.1 Interview Company 01 CAE

B.2 Interview Company 02 CAE

B.3 Interview Company 03 CAE

B.4 Interview Company 04 CAE

Interview Company 04 CAE Initial Questionnaire

B.5 Interview Company 05 CAE

B.6 Interview Company 06 PLM

Interview Company 06 PLM Postscript

B.7 Interview Company 07 CAE

B.8 Interview Company 08 CAE

B.9 Interview Company 09 Sales SDM

B.10 Interview Company 10 SDM

B.11 Interview Company 09 Modelling SDM

B.12 Interview Company 06 Services CAD

B.13 Interview Company 11 CAE

B.14 Interview Company 12 SDM

B.15 Interview Company 13 PLM

B.16 Interview Company 14 CAE

B.17 Interview Company 15 MBSE PLM

C. Aggregated Results

The aggregated results are not included in the published version due to confidential information contained.

C.1 Aggregated Results PLM

Table C.1 Aggregated Results for PLM and CAD related interviews.

C.2 Aggregated Results SDM

Table C.2 Aggregated Results for SDM related interviews.

C.3 Aggregated Results CAE

Table C.3 Aggregated Results for CAE related interviews.

D. STEP AP214 Export of a Simple Geometry

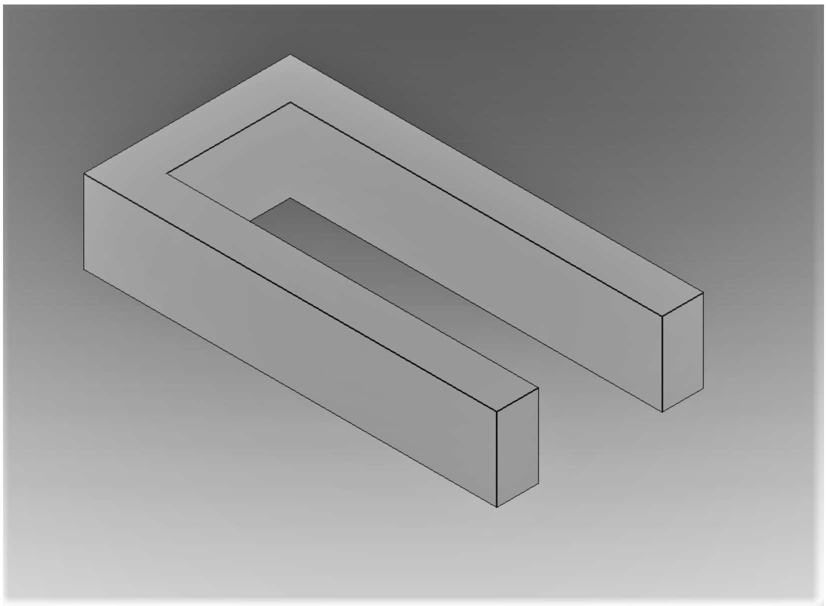


Figure D.1: A simple U-profile which was exported in STEP and re-opened in FreeCAD.

Clear Text Representation in the P21-file:

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ISO-10303-21;
HEADER;
FILE_DESCRIPTION((’STEP AP214’),’1’);
FILE_NAME(’Philipp.stp’,’2020-05-06T16:05:25’,(’ ’),(’ ’),’Spatial InterOp 3D’,’ ’,’
    ’);
FILE_SCHEMA((’AUTOMOTIVE_DESIGN { 1 0 10303 214 1 1 1 1 }’));
ENDSEC;
DATA;
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#2=APPLICATION_PROTOCOL_DEFINITION(’INTERNATIONAL STANDARD’,’automotive_design
    ’,1994,#9);
#3=PRODUCT_CATEGORY_RELATIONSHIP(’NONE’,’NONE’,#10,#11);
#4=SHAPE_DEFINITION_REPRESENTATION(#12,#13);
#5= (GEOMETRIC_REPRESENTATION_CONTEXT(3)GLOBAL_UNCERTAINTY_ASSIGNED_CONTEXT((#16))
    GLOBAL_UNIT_ASSIGNED_CONTEXT((#18,#19,#20))REPRESENTATION_CONTEXT(’NONE’,’
    WORKSPACE’));
#9=APPLICATION_CONTEXT(’ ’);
#10=PRODUCT_CATEGORY(’part’,’NONE’);
#11=PRODUCT_RELATED_PRODUCT_CATEGORY(’detail’,’ ’,(#22));
#12=PRODUCT_DEFINITION_SHAPE(’NONE’,’NONE’,#23);
#13=ADVANCED_BREP_SHAPE_REPRESENTATION(’1’,(#24,#25),#5);
#16=UNCERTAINTY_MEASURE_WITH_UNIT(LENGTH_MEASURE(1.0E-06),#18,’’,’’);
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#19= (NAMED_UNIT(#33)PLANE_ANGLE_UNIT()SI_UNIT($,.RADIAN.));
#20= (NAMED_UNIT(#33)SOLID_ANGLE_UNIT()SI_UNIT($,.STERADIAN.));
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#23=PRODUCT_DEFINITION(’’,’NONE’,#40,#1);
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#25=AXIS2_PLACEMENT_3D(’’,#42,#43,#44);
#28=LENGTH_MEASURE_WITH_UNIT(LENGTH_MEASURE(1.0),#45);
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#44=DIRECTION(’’,(1.0,0.0,0.0));
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#47=ADVANCED_FACE(’’,(#59),#60,.T.);
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#59=FACE_OUTER_BOUND(’’,#79,.T.);
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#202=VERTEX_POINT(’’,#243);
#203=LINE(’’,#244,#245);
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#205=LINE(’’,#247,#248);
#206=LINE(’’,#249,#250);
#207=VERTEX_POINT(’’,#251);
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#211=LINE(’’,#257,#258);
#212=VERTEX_POINT(’’,#259);
#213=LINE(’’,#260,#261);
#214=VERTEX_POINT(’’,#262);
#215=LINE(’’,#263,#264);
#216=LINE(’’,#265,#266);
#217=VERTEX_POINT(’’,#267);
#218=LINE(’’,#268,#269);
#219=VERTEX_POINT(’’,#270);
#220=LINE(’’,#271,#272);
#221=LINE(’’,#273,#274);
#222=VERTEX_POINT(’’,#275);
#223=LINE(’’,#276,#277);
#224=VERTEX_POINT(’’,#278);
#225=LINE(’’,#279,#280);
#226=LINE(’’,#281,#282);
#227=VERTEX_POINT(’’,#283);
#228=LINE(’’,#284,#285);
#229=VERTEX_POINT(’’,#286);
#230=LINE(’’,#287,#288);
#231=LINE(’’,#289,#290);
#232=VERTEX_POINT(’’,#291);
#233=LINE(’’,#292,#293);
#234=VERTEX_POINT(’’,#294);
#235=LINE(’’,#295,#296);
#236=LINE(’’,#297,#298);
#237=LINE(’’,#299,#300);
#238=LINE(’’,#301,#302);
#239=CARTESIAN_POINT(’’,(60.0,25.0,20.0));
#240=CARTESIAN_POINT(’’,(60.0,15.0,20.0));
#241=CARTESIAN_POINT(’’,(60.0,25.0,20.0));
#242=VECTOR(’’,#303,1.0);
#243=CARTESIAN_POINT(’’,(60.0,15.0,0.0));
#244=CARTESIAN_POINT(’’,(60.0,15.0,0.0));
#245=VECTOR(’’,#304,1.0);
#246=CARTESIAN_POINT(’’,(60.0,25.0,0.0));
#247=CARTESIAN_POINT(’’,(60.0,25.0,0.0));
#248=VECTOR(’’,#305,1.0);
#249=CARTESIAN_POINT(’’,(60.0,25.0,0.0));
#250=VECTOR(’’,#306,1.0);
#251=CARTESIAN_POINT(’’,(-30.0,15.0,20.0));
#252=CARTESIAN_POINT(’’,(60.0,15.0,20.0));
#253=VECTOR(’’,#307,1.0);
```

```
#254=CARTESIAN_POINT('',(-30.0,15.0,0.0));
#255=CARTESIAN_POINT('',(-30.0,15.0,0.0));
#256=VECTOR('',#308,1.0);
#257=CARTESIAN_POINT('',(60.0,15.0,0.0));
#258=VECTOR('',#309,1.0);
#259=CARTESIAN_POINT('',(-30.0,-15.0,20.0));
#260=CARTESIAN_POINT('',(-30.0,15.0,20.0));
#261=VECTOR('',#310,1.0);
#262=CARTESIAN_POINT('',(-30.0,-15.0,0.0));
#263=CARTESIAN_POINT('',(-30.0,-15.0,0.0));
#264=VECTOR('',#311,1.0);
#265=CARTESIAN_POINT('',(-30.0,15.0,0.0));
#266=VECTOR('',#312,1.0);
#267=CARTESIAN_POINT('',(60.0,-15.0,20.0));
#268=CARTESIAN_POINT('',(-30.0,-15.0,20.0));
#269=VECTOR('',#313,1.0);
#270=CARTESIAN_POINT('',(60.0,-15.0,0.0));
#271=CARTESIAN_POINT('',(60.0,-15.0,0.0));
#272=VECTOR('',#314,1.0);
#273=CARTESIAN_POINT('',(-30.0,-15.0,0.0));
#274=VECTOR('',#315,1.0);
#275=CARTESIAN_POINT('',(60.0,-25.0,20.0));
#276=CARTESIAN_POINT('',(60.0,-15.0,20.0));
#277=VECTOR('',#316,1.0);
#278=CARTESIAN_POINT('',(60.0,-25.0,0.0));
#279=CARTESIAN_POINT('',(60.0,-25.0,0.0));
#280=VECTOR('',#317,1.0);
#281=CARTESIAN_POINT('',(60.0,-15.0,0.0));
#282=VECTOR('',#318,1.0);
#283=CARTESIAN_POINT('',(-40.0,-25.0,20.0));
#284=CARTESIAN_POINT('',(-40.0,-25.0,20.0));
#285=VECTOR('',#319,1.0);
#286=CARTESIAN_POINT('',(-40.0,-25.0,0.0));
#287=CARTESIAN_POINT('',(-40.0,-25.0,0.0));
#288=VECTOR('',#320,1.0);
#289=CARTESIAN_POINT('',(-40.0,-25.0,0.0));
#290=VECTOR('',#321,1.0);
#291=CARTESIAN_POINT('',(-40.0,25.0,20.0));
#292=CARTESIAN_POINT('',(-40.0,25.0,20.0));
#293=VECTOR('',#322,1.0);
#294=CARTESIAN_POINT('',(-40.0,25.0,0.0));
#295=CARTESIAN_POINT('',(-40.0,25.0,0.0));
#296=VECTOR('',#323,1.0);
#297=CARTESIAN_POINT('',(-40.0,25.0,0.0));
#298=VECTOR('',#324,1.0);
#299=CARTESIAN_POINT('',(-40.0,25.0,20.0));
#300=VECTOR('',#325,1.0);
#301=CARTESIAN_POINT('',(-40.0,25.0,0.0));
#302=VECTOR('',#326,1.0);
#303=DIRECTION('',(0.0,-1.0,0.0));
#304=DIRECTION('',(0.0,0.0,1.0));
#305=DIRECTION('',(0.0,-1.0,0.0));
#306=DIRECTION('',(0.0,0.0,1.0));
#307=DIRECTION('',(-1.0,0.0,0.0));
#308=DIRECTION('',(0.0,0.0,1.0));
#309=DIRECTION('',(-1.0,0.0,0.0));
```

```
#310=DIRECTION('',(0.0,-1.0,0.0));
#311=DIRECTION('',(0.0,0.0,1.0));
#312=DIRECTION('',(0.0,-1.0,0.0));
#313=DIRECTION('',(1.0,0.0,0.0));
#314=DIRECTION('',(0.0,0.0,1.0));
#315=DIRECTION('',(1.0,0.0,0.0));
#316=DIRECTION('',(0.0,-1.0,0.0));
#317=DIRECTION('',(0.0,0.0,1.0));
#318=DIRECTION('',(0.0,-1.0,0.0));
#319=DIRECTION('',(-1.0,-0.0,-0.0));
#320=DIRECTION('',(0.0,0.0,1.0));
#321=DIRECTION('',(1.0,0.0,0.0));
#322=DIRECTION('',(0.0,1.0,0.0));
#323=DIRECTION('',(0.0,0.0,1.0));
#324=DIRECTION('',(0.0,-1.0,0.0));
#325=DIRECTION('',(1.0,0.0,0.0));
#326=DIRECTION('',(1.0,0.0,0.0));
ENDSEC;
END-ISO-10303-21;
```

E. Other

E.1 Interview Introduction

Figure E.1: The common introduction to the interview.

[Priyanka Gulati introduced herself before the recordings and if applicable said some words about the VMAP standard and the intentions of the VMAP-STEP-project.]

Hello [. . .], welcome and thank you for taking the time for this interview. My name is Philipp Spelten, I am a mechanical engineering student currently working for Fraunhofer SCAI and prostep AG. From what I gathered you are working on [. . .]. Your knowledge will therefore be quite valuable for my survey, but maybe you could introduce yourself briefly.

Today, I would like to ask you 4 questions on interoperability issues in CAE/CAD, starting with your current situation, covering you issues and solutions, to conclude in solutions you are still in want of.

As mentioned in the e-mail and at the beginning of our meeting, I am recording this interview. I hope that this will be okay for you, as it will help me immensely with the evaluation. If you want to share confidential information, please inform me. We can also review the points we spoke about at the end of the interview. I will only share or use the information to the extent of your liking. My bachelor thesis will feature the results of our interviews. However, it will be closed from public for the next 5 years. After I hand in the thesis, I will work out a neutralised version which I will be able to share with you by the end of April.

I am looking at the gap between product and simulation data management in industrial engineering. Based on current projects, we identified a need for better Data Continuity within engineering workflows between product and simulation data management. This is why I am looking at VMAP standard and the STEP standard (more explicitly AP242). [As you know,] VMAP is a vendor-neutral standard for CAE data storage to enhance interoperability in virtual engineering workflows. STEP AP242 is a standard for the exchange and long-term storage of product data such as CAD data. For our development we want to rely on to-date information from users.

Therefore, this interview will follow a rough guideline which you will see in this presentation. The questions I pose are trying to drive our conversation in directions which I anticipated to be useful for the thesis question, particularly the solution that could be offered for a continuous Digital Thread on the PLM-SDM-level. However, I would like to invite you to share any additional information that you find relevant. In case you are close on time, we can make sure to wrap up the 4 questions in the next [25] minutes, but if you are open to a longer discussion, we can take longer.

E.2 E-Mail Examples

Figure E.2: An example for the contact e-mail to invite SCAI-related contacts to the interview from Priyanka Gulati.

Dear [...],

I am Priyanka Gulati, a member of the Fraunhofer SCAI MP group. Currently we are working together on the BMWi WIPANO VMAP-STEP proposal and one of our students, Philipp Spelten, is also working on a closely related topic to this proposal.
Philipp is working with us on his bachelor thesis on "Bridging the Gap Between Product and Simulation Data Management" and as part of his bachelor thesis, he has to conduct interviews with OEMs / suppliers, research institutes & software providers who process CAE and/or CAD data in some form and therefore use PLM or SDM software.

The interview will be conducted in English via MS Teams and should last approximately 45 minutes, with 4 key questions. The questions will be of a general rather than specific nature, as we are trying to allow for an open discussion.
Philipp will be the moderator, mainly asking the questions, I will be the assistant moderator, taking notes and assisting as needed. We intend to record this interview so that we can collect any details we may miss during the interview.

We would be very grateful if you would accept our invitation to participate in this interview.

Please let us know if you are available during the this or the next week and suggest some time slots.
If you have any questions, please do not hesitate to contact me.

Kind Regards
Priyanka Gulati

Figure E.3: An example for the contact e-mail to invite prostep-related contacts to the interview from Philipp Spelten.

Hallo [...],

ich schreibe Ihnen, weil Till Pfeiffer von der prostep AG Sie mir für folgendes empfohlen hat:

Aktuell schreibe ich bei prostep und am Fraunhofer Institut SCAI an meiner Bachelorarbeit zum Thema "Bridging the Gap Between Product and Simulation Data Management". In dem Rahmen führe ich Interviews mit OEMs , Forschungsinstituten & Softwareanbietern, die CAE- und/oder CAD-Daten bearbeiten und daher PDM- oder SDM-Software einsetzen. Dafür wäre Ihre Erfahrung [redacted] sehr hilfreich.

Das Interview würde auf Englisch über MS Teams stattfinden und etwa 45 Minuten dauern, mit 4 zentralen Fragen. Die Fragen sind eher allgemeiner als spezifischer Natur, da wir versuchen, ein offenes Gespräch zu ermöglichen. Ich werde der Moderator sein, der die Fragen hauptsächlich stellt, Priyanka Gulati vom Fraunhofer SCAI wird die stellvertretende Moderatorin sein, sich Notizen machen und bei Bedarf assistieren. Wir beabsichtigen, das Gespräch aufzuzeichnen, damit wir alle Einzelheiten sammeln können, die wir während des Gesprächs möglicherweise verpassen.

Ich wäre Ihnen sehr dankbar, wenn einer von Ihnen dazu in der nächsten Woche Zeit hätten. Bitte teilen Sie mir mit, ob einer der Tage für Sie in Frage kommt, und schlagen Sie einige Zeitfenster vor. Ich werde das Treffen dann arrangieren.

Viele Grüße
Philipp Spelten

Figure E.4: An example for the follow-up e-mail.

Dear [...],

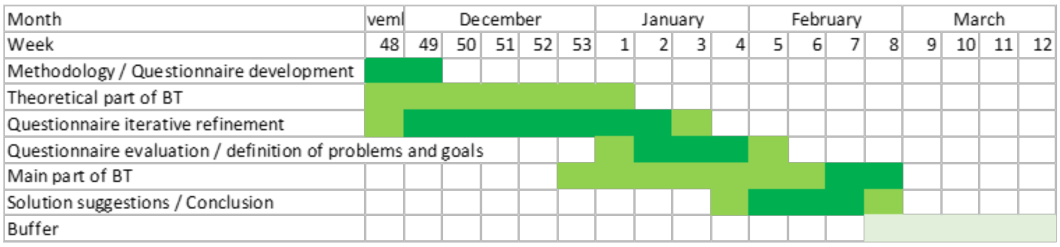
thank you very much again for your input for my bachelor thesis "Bridging the Gap Between Product and Simulation Data Management", particularly your insights into your work as [e.g., a CAE service company]. In case you still have remarks or questions about the interview, please feel free to contact me again. Any feedback will be much appreciated.

After I hand in the thesis in March we will start working on a reduced version containing the main results and send it to you once it is completed.

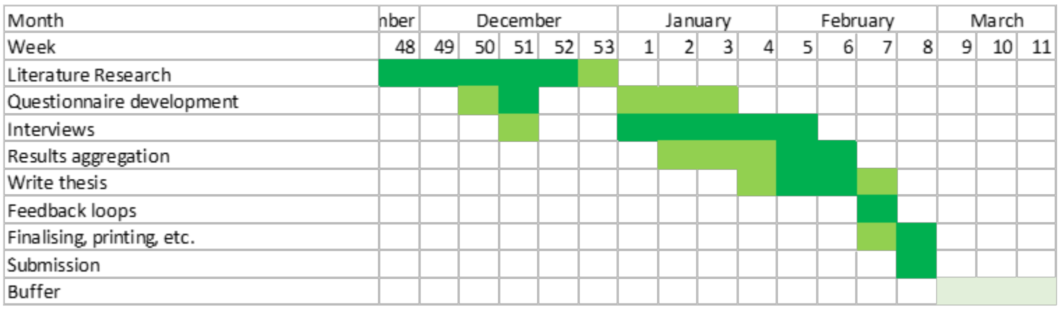
Kind regards

Philipp

E.3 Time Schedule Changes



(a) Original time schedule for the bachelor thesis.



(b) Final time schedule for the bachelor thesis.

Figure E.5: Original and final time schedule for the thesis. The darker and brighter colours represent different intensity / focus on the concerned topic.

Erklärung

Ich versichere hiermit, die von mir vorgelegte Arbeit selbstständig verfasst zu haben. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten oder nicht veröffentlichten Arbeiten anderer entnommen sind, habe ich als entnommen kenntlich gemacht. Sämtliche Quellen und Hilfsmittel, die ich für die Arbeit benutzt habe, sind angegeben. Die Arbeit hat mit gleichem Inhalt bzw. in wesentlichen Teilen noch keiner anderen Prüfungsbehörde vorgelegen.

Mir ist bewusst, dass sich die Hochschule vorbehält, meine Arbeit auf plagiierte Inhalte hin zu überprüfen und dass das Auffinden von plagiierten Inhalten zur Nichtigkeit der Arbeit, zur Aberkennung des Abschlusses und zur Exmatrikulation führen kann.

(Ort, Zeit)

(Unterschrift)