

# ISO 10303 AP209—Why and how to embed nonlinear FEA

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## ABSTRACT

ISO 10303 STEP AP209 edition 2 ISO (1994), ISO (2014a)[1,2] is a data model standard intended for data exchange and storage of simulation information. The standard has a wide coverage of FEA (Finite Element Analysis) information, but is missing certain features such as nonlinear FEA. This paper gives an introduction to the STEP AP209 standard and presents projects in which AP209 has been implemented.

The study then identifies requirements that should be supported by a standard FEA data model, but are not fully covered by AP209. Each requirements are discussed in the context of how they are supported by existing major solver applications. Without giving detailed solutions for how these should be implemented in AP209, starting points for further research is suggested.

## 1. Introduction

Nowadays all aspects of life involve information that is stored digitally as data. In the industry or privately, data is stored as files on hard-drives either locally, on servers, or dispersed in cloud systems. The average person may be interested in *where* their data is stored, but not necessarily *how* it is stored. We rely on the availability of applications to be able to open our files and to interpret their formats to view or edit the information. The reason we can use different software from different providers for these tasks on the same files, are the defined file formats. File format definitions are either open, that is, publicly available, or proprietary. Anyone may create applications to access the content of files in open formats; the details of proprietary formats are only known to a few and are kept confidential for business reasons. From a user's point of view, open formats are more attractive as they usually give a wider selection of applications to choose from and, thus, more user control over the data.

For instance; image files can be stored in formats well defined by standards such as JPEG [3], PNG [4], BMP [5] etc., and are therefore understood by many applications. The same applies to music, video and text documents. In industrial domains, we can find open formats for 2D and 3D models such as, DXF [6], OBJ [7], STL [8], X3D [9] etc.

The more complicated and rich the data is, the more advanced becomes the data format.

Engineers depend on tools for many different and advanced domains, such as, CAD (Computer Aided Design), FEA (Finite Element Method),

CFD (Computational Fluid Dynamics), photometric simulation, control engineering, electronic circuit design, etc. For each domain, the engineer may choose from multiple tools from different providers. Companies will usually select the application that best supports their workflows.

Some of these application may only support proprietary formats, some may use standard formats, and others may support both. However, the standard format will usually only cover a subset of the application information scope.

Depending on the selected applications, exchanging engineering data across different parties within the same engineering domain or among different domains often leads to unnecessary additional work. When cooperation between different engineering teams requires information to be transferred between two non-interoperable applications, conversions or redundant input of data are necessary.

In the context of CAD data, many CAD software vendors have implemented standard formats for import and export. However, CAD applications may offer data types and user operations that only exist within that tool. These special features may lead to limitations on how big parts of the application data model can be shared by a standard data model. Anyway, a standard that covers the majority of the data would still greatly simplify CAD file exchanges.

Multiple open formats support CAD data exchange. Most of these are limited to a certain subset of geometric definitions. Pfouga and Stjepandić [10] and Fröhlich [11] summarizes and compares some of the most broadly adopted 3D model formats. The most widely

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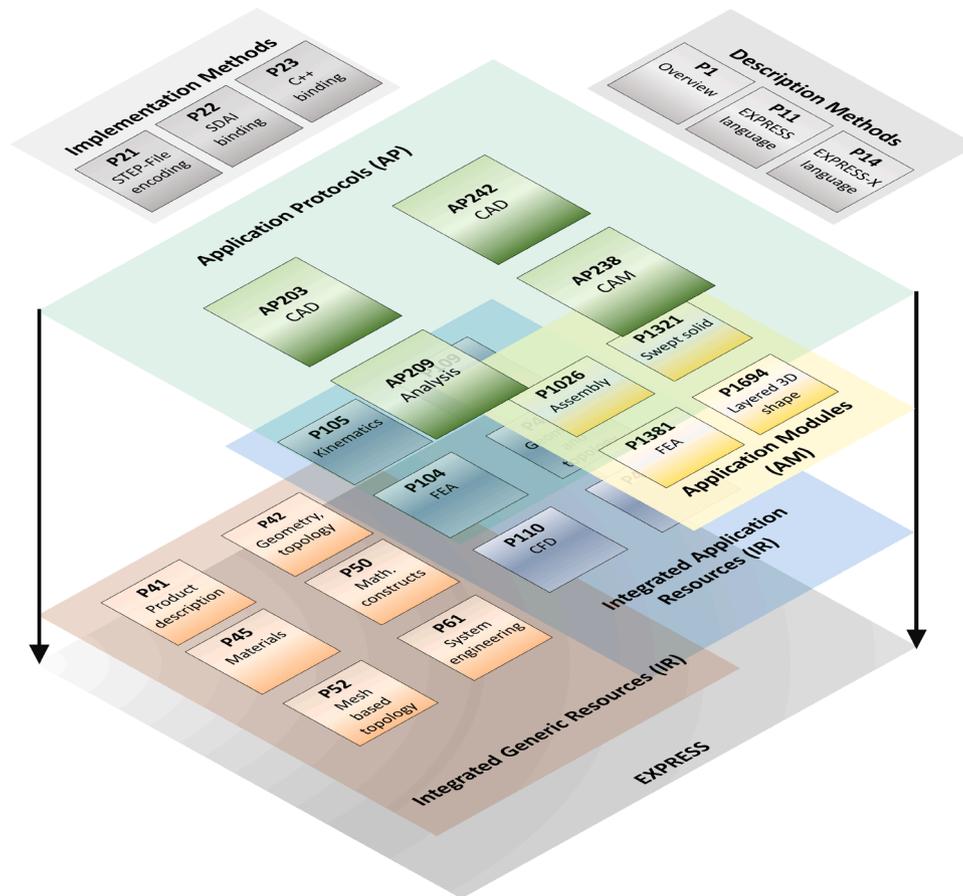


Fig. 1. Overview of STEP ISO-10303 documents. Each layer shows examples of documents. Documents in a layer may reference documents in lower layers.

implemented and used non-proprietary exchange format for CAD [12], is ISO 10303 [1] (commonly known as STEP). It includes a wide variety of geometric and topological definitions and links those to PDM (Product Data Management) information, other engineering domains and product lifetime data in general.

The benefit for CAD users, from vendors implementing such a standard, is that it enables them to share models across multiple CAD tools. Standard formats such as STEP are also backwards compatible with newer versions. This is not always the case for the proprietary formats, which may modify their format with new releases, unabling the opening of files from previous versions.

Despite having been a crucial part of product development for many decades, FEA applications rarely offer standard exchange formats.

Data is exchanged between different solvers, but often only mesh data is well implemented in export and import. Analysis information, such as load case definitions, loads, boundary conditions and additional analysis specific data, often need to be exchanged manually or through custom routines. Some solvers will accept NASTRAN and Abaqus input file formats to import and export such analysis information, in addition to mesh data, but often with limited scope.

A widely implemented FEA standard will give the same benefit the CAD domain already has; to allow engineers to share between, and work across, FEA solvers from different vendors. Equivalently significant, is the ability it gives to archive FEA information to be retrieved in the future, regardless of the originating application releasing new versions.

The mentioned STEP standard does have considerable support for FEA through one of its Application Protocols known as AP209 [2].

Other attempts for defining a standard format for simulation data are; FEMML [13–15], SysML [16] and PAM [17].

The purpose of this study is to give an overview of STEP AP209 and its capabilities, as well as identifying some missing domain coverage of FEA. Focus is given to nonlinear FEA, and without going in details, initial suggestions are given for how potential extensions to the standard could be done.

The paper is organized as follows; Section 2 gives an overview of the STEP standard and AP209. Section 3 presents completed and ongoing use cases and projects where AP209 has been applied. In Section 4 concepts that AP209 does not cover are identified and discussed with respect to how they are supported in major FEA solvers. Finally Section 5 concludes the study and suggests future work.

## 2. The STEP ISO 10303 standard

### 2.1. How STEP enables interoperability of engineering data

As discussed in Section 1, standard formats simplify reuse of data by providing portability that enables data file exchange and database sharing. The goal of STEP is to offer to the public a consistent suite of data definitions for all major engineering domains. Being consistent, means that interoperability is not only possible within the same domain, but also between overlapping domains. For example, the subsets of STEP that are known as AP203 [18], AP214 [19] and AP242 [20] cover among others, CAD and PDM data. Part of the definitions used in these subsets, such as the definitions of geometric surfaces, are also relevant in the FEA domain. AP209, a superset of AP242, has, in addition to all the content of AP242, support for FEM and other simulation types. PDM information, which links data of all domains into consistent product descriptions, is part of all subsets of STEP, that is, Application Protocols.

The structure of the STEP standard is relatively complex; a short introduction is therefore included here. Other suggested resources to get a better understanding are; *STEP in a Nutshell* [21], chapter 2 of *Relating structural test and FEA data with STEP AP209* [22] and *STEP Application Handbook* [23].

The standard is managed by ISO [24] as the ISO 10303 series and is divided in a set of several hundreds documents. The documents are organized into categories, such as; *Description methods*, *Implementation methods*, *Integrated application* and *Integrated generic resources* (IR), *Application modules* (AM) and *Application protocols* (AP). Fig. 1 shows this classification.

The main concept of the standard is that it defines data models; these consists of a set of *entity* data types and other supporting data types. An entity is essentially the same as a class in an Object-Oriented language; it can inherit from other entities and hold attributes. Each attribute is of either an entity data type or any other data type.

The *generic* and *application* IR documents are the foundation of the STEP product model and hold also the formal definitions of the entities and data types. An important part of the STEP standard is that these definitions are written in a formal lexical and graphical data modeling language, *EXPRESS*, which is itself defined by the standard in the *Description methods* documents as ISO 10303-11 [25]. Definitions written in EXPRESS are computer readable (as well as human readable), and may be processed by software applications. The AM documents reference IR documents and other AM documents, and may add semantics to the content from the IR documents. Each AP is a collection of all the necessary AMs that together define a complete data model schema for a specific domain. An AP, thus, groups, specializes, and adds to the content from the STEP resources for a specific engineering domain and/or product life-cycle stage. An application that supports STEP does this by reference to a specific AP. For example, most CAD software supports one or multiple of the APs; AP203, AP214 and AP242.

From a developer's point of view, if an application is to support a certain AP, the AP schema is the core specification from which the service is developed. As the schema is written in EXPRESS, APIs and frameworks may be generated by the developer, or already existing third-party applications may be reused.

The process of creating interfaces, is also, to some extent, standardized by STEP. The standard specifies a generic interface (SDAI; Standard Data Access Interface) to access STEP data stored in a database systems that uses EXPRESS schemas as basis for their database dictionaries. For certain languages (C, C++, Java), the standard also specifies how to generate an interface layer on top of the SDAI interface, specifically for allowing applications to work with STEP databases. This greatly simplifies the implementation of the standard. Some implementations and analyses of STEP interfaces are presented in Botting and Godwin [26], Goh et al. [27], Ma et al. [28].

PDM and SDM applications, which may cover multiple engineering domains, can implement multiple APs. An overview and discussion on the STEP standard in the context of PDM is presented in Mehta et al. [29]. Multiple implementations of PDM/PLM (Product Lifecycle Management) systems using STEP as a database backbone and for data exchange are outlined in Brun et al. [30], Han et al. [31], Yang et al. [32], Shih [33], Iliescu et al. [34]. An SDM/PDM implementations using an extended AP209 schema is presented in Charles and Eynard [35], Ducellier et al. [36].

As all APs are based on the same low level details of product structure, properties, units, etc., the application may create direct references between models of the different APs. For example, a SDM application may accept both CAD and FEA STEP models and hold relations between them, such as an applied FEA force on a CAD edge or a set of finite

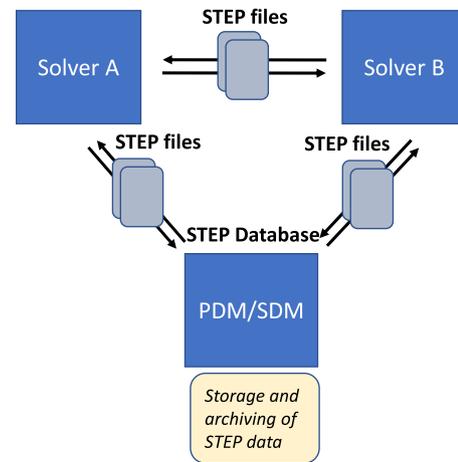


Fig. 2. AP209 for file exchange and database integration and storage.

elements on a geometric surface. Applications with such functionality currently only exist using proprietary formats. The data may be stored and exchanged as an ASCII STEP file [37] or as a binary database [38] based on the schema of the AP.

The most common APs used in the industry are AP203, AP214 and AP242, whereas AP203 and AP214 are by now deprecated, and are replaced and upward compatible with AP242.

These are supported by most CAD applications and by some PDM/PLM applications.

## 2.2. Analysis of the industrial relevance of AP209

The Application Protocol AP209 (ISO 10303-209) has the title *Multidisciplinary Analysis and Design*. The newest version of AP209 is called AP209 edition 2 (or AP209e2), and AP209 edition 3 is currently being developed. In this paper, AP209e2 will be referenced as just AP209. The purpose of this part of the STEP standard is to serve as (Fig. 2):

1. A file format to share data between simulation solvers.
2. A database schema for PDM and SDM applications to integrate, share, and archive simulation data, independent of any proprietary format.

The AP209 standard has not yet been widely implemented by FEA tool vendors, but several trial implementations by different vendors and organizations exists. Some of these implementations are described in Section 3.

One of the major benefits of a universal data exchange format for FEA (and other domains) is the reduction in number of converters required for an application. As shown in Fig. 3 the number of converters required for an engineering process expands more than linear when the number of involved applications with proprietary formats grows. Without a central format, the number of two-way converters for a single application is calculated by:  $\sum_{n=1}^{N_f-1} n$  where  $N_f$  is the number of formats. With a central format, the number of converters for all involved applications is equal to the number of applications.

There are many possible reasons for why AP209 or other FEA standard formats have not been widely implemented, some of which are:

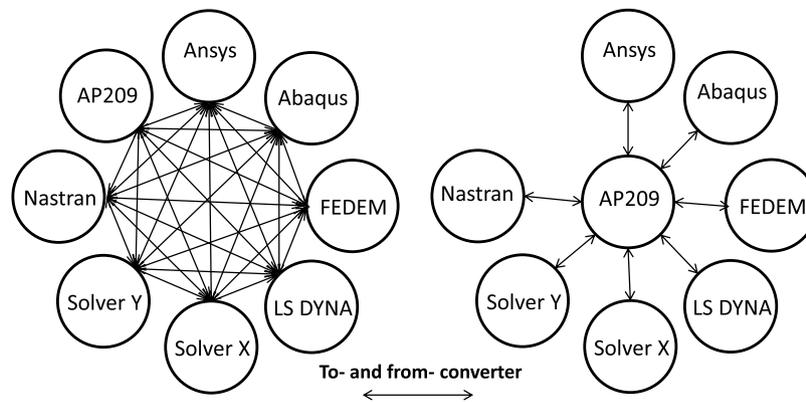


Fig. 3. AP209 as a central format.

1. Vendors want to keep their customers

- Naturally, vendors want their customers to use their software as much and as long as possible.
- Rather than focusing on interoperability with other systems, the focus is on interoperability within the vendor's suite of applications.

2. A data exchange standard is not interesting for a vendor before it is a user requirement.

- As long as a data exchange standard is not widely used or is an outspoken user requirement, it is difficult to justify spending resources on implementing it.
- It is easy to see here the danger of a deadlock situation; a standard will not be widely used before it is widely implemented. This may be resolved by powerful user organizations, such as government bodies or industry associations who demand such solutions.

3. STEP ISO 10303 is a complicated standard

- STEP covers many large and complex engineering domains, and even understanding just a subset of the standard, still requires knowledge of its overall intention and structure.

4. FEA is a complicated domain

- FEA is a very large discipline, and not every aspect of it is implemented in the exact same manner. A FEA solver calculates the simulation results by solving a huge number of equations. Different mathematical optimization methods may be used for this, and these may vary across solvers. Conceivably they should give the same results, but small discrepancies will occur. This is especially true for nonlinear solvers, where the algorithms are significantly more complex than for linear ones. Many solvers will also have functions for automatic time stepping, where solution time steps are decided by the solver based on certain criteria. These decisions and criteria will also depend on the particular solver implementation.

Other examples are how the solver decides whether the solution has converged, how many iterations are used in a solution step, how element contact algorithms are implemented, and many more. All of these may have parameters for fine tuning the methods. In some solvers these may be fixed, in others they may be user specified, which across the solvers may have varying default values.

5. STEP AP209 has a limited scope

- AP209, at its current state, is designed to cover linear static and linear modal analysis, while also being capable to be extended to

cover nonlinear analysis.

As stated in Hunten [39] the scope of AP209 "...will address 60 to 90 percent of the analysis needs of an enterprise." and "roughly 90 percent of the nonlinear problem is addressed at the present time".

The majority of all FEM analyses done are linear static. According to [40] this could be as much as 90%. However, for AP209 to gain more interest from FEA solvers, it is highly important to cover the remaining 10%.

Other causes, for lack of support of digital formats in general for PDF (Product Data Technologies), are outlined in Gielingh [41]. In this paper some of the above items are addressed with focus on the last one, that is; How can AP209 be extended to also cover nonlinear finite element analysis?

### 2.3. Improving application protocols

STEP is a powerful standard covering a wide variety of engineering data for data exchange and storage. However, the engineering domains are continuously evolving, and the standard needs to be updated to cover all aspects of domain interoperability. This continuous improvement of STEP competes with the introduction of new standards that have a rather limited, but overlapping scope with STEP; the latter are on one hand often quicker and simpler to implement, but on the other hand will not have the same degree of interoperability.

Improving an application protocol, or the use of an application protocol, can be performed in a few different ways, depending on the modifications required:

1. **Extending application scope support:** Many applications do not cover the full scope of an application protocol. When applications extend their support of an AP, this is a considerable improvement for the user that did not require any change to the standard itself.
2. **Extending recommended practices:** While the APs describe the very detailed and formal definitions of the data model, other documents, such as *Recommended Practices* and *Handbooks*, describe how the data model should be implemented. These documents are crucial for implementors and ensures that the standard has consistent implementations across the different applications. Often these documents will specify how generic parts of the data model shall be implemented for specific use cases. Such updates improve the usability of the standard considerably without changing the standard

itself. Updates to recommended practices require, however, agreement by the document owners; for STEP and AP209 this is the CAX-IF project that is jointly run by prostep iVIP, AFNeT and PDES, Inc.

3. **Extending application protocol scope:** Adding completely new concepts to the scope of an application protocol and/or to its constituents requires updates to the the AP (and the IGR, IAR and AM data models). Such updates must be done in accordance with the respective ISO working groups and follow ISO rules and processes.

### 3. State of the art of existing AP209 implementations

This section presents some use-cases where AP209 has been tested and implemented. From the results and experiences of these implementations and projects, certain missing concepts in AP209 have been identified. These are summarized in chapter 4.

#### 3.1. Early implementations

Some of the first implementations of AP209 are presented in Hunten [39], Hunten et al. [42], Stanton et al. [43]. These were centered on exchanging analysis, and especially composites information between different applications (including MSC/PATRAN), by exchanging the data via AP209 files. The studies are also summarized in Hunten et al. [44].

Additionally, Bartholomew and Paleczny [45] presents the development of a translator between AP209 and the FEA solver SAMCEF for a usecase in the EU project *ENHANCE* [46].

#### 3.2. CAX-IF and LOTAR

AP209 and other STEP parts, are documented in ISO documents as described in Section 2.1. These documents provide the very formal definitions of the STEP data model. They do not, however, describe in details, implementation methods and use cases for the standards. CAX-IF [47] (Computer Aided X Implementor Forum and recently renamed to MBx-IF; *Model-based X Interoperability Forum*), is a joint effort between PDES, Inc., ProSTEP iVIP and AFNeT, with the objective of accelerating CAD, CAE (Computer Aided Engineering) and other industrial data translators and ensure their compliance with the respective standards. CAX-IF performs test rounds where different software vendor participants develop translators between the standards and their own applications. Translations from and to the standard across the participants tools are then tested and verified by CAX-IF workgroups. By doing this, conformance with the standard is ensured, the applicability of the standard is verified, and potential improvements are suggested. Based on experience from these test rounds, Recommended Practices are documented and published. These documents, in contrast to the official ISO documents, focus rather on the implementations of the standard in translators. They are generally generic as to be applicable to any systems, and are essential for developers that are responsible of implementing support of the standard in their tools.

LOTAR [48] (Long Term Archiving and Retrieval) is an international organization, which aims to develop, test, publish and maintain standards for long-term archiving. LOTAR EAS [49] (Engineering Analysis and Simulation) workgroup joined CAX-IF in 2017 to handle the test rounds for AP209 FEA converters. A test round starts with an original set of files in the NASTRAN format, which are converted by all parties to AP209 and then shared to be imported and checked by the other parties. Statistics are calculated and checked by the EAS working group to verify the validity of the converters. From these results Recommended

Practices and handbooks for AP209 are written and updated. Currently the following are published; Recommended Practices for AP209ed2 [50], STEP AP209 ed2 Linear Static Structural FEA Handbook Volume 1 [51] and Volume 2 [52].

#### 3.3. TERRIFIC

Terrific [53] was an EU funded R&D project (2011–2014) with the goal of improving the interoperability among applications for design, analysis and optimization of products. The focus was on further developing and applying isogeometric analysis (IGA), that is an innovative approach to close the gap between the 3D product representations in design and analysis [54]. A finite element mesh is not any more created from scratch on an idealized shape; instead, the NURBS (non-uniform rational B-splines) [55] of the original CAD design shape are reused as analysis mesh by just changing their parameterization. In Terrific, the process of updating AP209 and AP242 for IGA was started [56,57]. Particularly, locally refined B-splines were introduced to enable adequate re-parameterization of CAD-shapes for the purpose of engineering analysis.

#### 3.4. Cloudflow

Another EU funded R&D project related to AP209 was Cloudflow [58] (2013–2017), which aimed at smoother manufacturing processes by improved interaoperability of engineering applications within a cloud computing framework [59] for European manufacturing enterprises. CAD, CAM (Computer Aided Manufacturing), CFD and PLM were all part of cloud workflows using STEP-standards to more easily connect. In the CFD implementation, AP209 was used for managing simulation data on the cloud.

#### 3.5. VELAССo

VELAССo [60], an EU funded R&D project (2014–2016), aimed to provide new visualization methods of large-scale simulations. The project developed the VELAССo platform for accessing, visualizing, and querying distributed simulation information stored across multiple servers [61]. In the project, AP209 was validated and Discrete Element Method (DEM) extensions were proposed. AP209 was used for storing simulation data.

#### 3.6. CAXMan

CAXMan [62], also an EU funded R&D project (2015 - 2018) involving cloud systems, had the purpose of delivering Cloud based toolboxes and workflows to optimize design, simulation, and process planning for additive manufacturing. The goal was to be able to reduce material usage in additive manufacturing by simulating against both structural and thermal constraints and by providing automated feedback to the original design [63]. The various simulations and their links to the original design shape were facilitated by AP209.

#### 3.7. CRYSTAL

More recently, Jotne EPM [64] and Lockheed Martin [65] has through the project CRYSTAL [66], developed AP209 converters for both Abaqus and NASTRAN formats. During this same project extensive support for AP209 was implemented in the SDM application EDMo-penSimDM [67]. This allowed to relate CAD, FEA and PLM information

**Table 1**  
Categorization of analyses provided by different solvers.

NX Nastran 11.0	Abaqus CAE 6.14	Ansys MPADL 19.0
SOL101 - Linear Statics	Static, General	Static Structural
SOL103 - Real Eigen Values	Static, Riks	Transient Structural
SOL103 - Response Dynamics	Dynamic Implicit	Rigid Dynamics
SOL105 - Linear Buckling	Dynamic Explicit	Harmonic Response
SOL106 - Nonlinear Statics	Buckle	Modal
SOL107 - Direct Complex Eigenvalues	Frequency	Explicit Dynamics
SOL108 - Direct Frequency Response	Static, Linear Perturbation	
SOL109 - Direct Transient Response	Steady-state dynamics, Direct	
SOL110 - Modal Complex Eigenvalues	Substructure generation	
SOL111 - Modal Frequency Response		
SOL112 - Modal Transient Response		
SOL129 - Nonlinear Transient Response		
SOL601(106) - Advanced Nonlinear Statics		
SOL601(129) - Advanced Nonlinear Transient		
SOL701 - Explicit Advanced Nonlinear Analysis		

in the same system stored in the same format; AP209. CRYSTAL took this one step further by also using AP209 for representing structural testing. This further allowed sensors and test results to relate to corresponding FEM analyses information. Having this data, from these different domains, in the same repository, and in the same format, enabled a more efficient way of retrieving, querying, and processing the engineering data. The study behind this integration is presented in Lanza et al. [22].

### 3.8. Arrowhead tools

Arrowhead Tools [68], is yet another ongoing EU project. Its goal is to reduce engineering costs by 40-60% for automation and digitalization solutions, by developing an open-source platform for design and run-time engineering of IoT (Internet of Things) and System of Systems [69,70]. In the Arrowhead Tools project, AP209 will be used to represent and exchange simulation, sensor, and IoT information.

## 4. Recommended FEA extensions to AP209

The AP209 standard covers many of the data concepts needed for FEM analysis. Still, for a standard to be widely accepted, "many" may not be enough.

This section goes through the different aspects of FEA that would be expected in a standard format, which are either missing in the AP209 standard, or exist, but their use have never been implemented or documented in documents such as AP209 Recommended Practices or AP209 handbooks.

Section 4.1 describe certain requirements for AP209 as a FEA standard, and discuss how these are implemented in some of the major solvers. Without going in details, Section 4.2 presents suggestions for how these requirements could be implemented or addressed in AP209.

The choice of solvers investigated was based on their market share and availability. The chosen ones were:

1. Abaqus 6.14 [71]
2. NX Nastran 11.0 [72]
3. Ansys MAPDL 19.0 [73]

These were all mentioned as leading vendors in TechNavio [74] together with MSC Nastran [75].

### 4.1. FEA requirements for AP209

#### 4.1.1. Analysis type categorizations

Table 1 shows an overview of how solver categorizes their supported analyses. In the table the term analysis categories is used as opposed to analysis types. The category names are based on what the solvers provide as analysis setups or solutions, which may involve multiple analysis types available for their load cases.

It is important to note that in most solvers, a set of load cases on a finite element model, that relate, or are sequential, is often referred to as a solution. In most cases it is the solution that is initialized as a certain analysis type or category. The load cases that take part of this solution are then generally restricted to be only of one or a few specific analysis types, depending on the chosen solution. The specific limitations varies across the different solvers.

The exact type of analysis also depends on the analysis parameters that the user select. For example; Ansys provides the solution called "Static structural", but will then provide a choice to set it as linear or nonlinear, which are, in the context of this study, two different analysis types.

Depending on the analysis categories in Table 1, a solver will decide which routines or algorithms to use in the analysis process and will require user input for certain parameters. The amount and type of user modifiable parameters varies for each solver.

#### 4.1.2. Analysis parameters

In linear FEA, there are very few parameters that affect how the analysis is performed. Most solvers will solve a linear analysis using similar algorithms and give similar results. However, for nonlinear analyses, analysis parameters are very important. By analyses parameters, we mean settings the user may set that affect how the analysis is performed. This can be parameters such as the solver's; time step sizes, number of increment, maximum iterations, line search settings, type of convergence criteria, etc.

For nonlinear analyses, solvers always have different settings that may be set to specify how the model is solved. Some modifiable settings are common across most solvers, while others are specific to the individual solvers.

In Appendix A, Table A.2- A.6, shows the most common analysis parameters for each analysis category and for the selected solvers for the FEA concepts of increment, arc-length, iteration, convergence and line-search parameters, respectively.

#### 4.1.3. Variable depending loads and constraints

A common way of defining loads or constraints, especially in dynamic analyses, is to have a load or constraint magnitude that depends on time. It is also common, in both dynamic and static analyses that a load is defined as a field and depends on variables such as model coordinates. Typical examples are loads and constraints that are scaled throughout the analysis based on either a time dependent function or tabulated values, or a load depending on space dimension.

NX Nastran, Ansys and Abaqus all allow loads and constraints to be defined from a table or function with variables such as time, coordinates, temperature etc. In NX Nastran and Abaqus this is done by defining a load, such as nodal loads or element pressure, and then applying a

tabular or functional amplitude to it. In Ansys, you may not amplify an existing load, but load values may be defined by a table.

#### 4.1.4. Nonlinear material properties

There exists a wide range of different nonlinear material models. Every nonlinear capable FE solver offers the use of a subset of these. Some of the most general material models are; perfectly plastic, bi-linear and multi-linear plasticity material models. One thing to note however, is that each of these may be defined differently, for example via stress and strain values, or multiple E-modulus values. When defined by stress and strain pairs, these may be input as either true or engineering stress/strain values, depending on the solver.

NX Nastran, Ansys and Abaqus, each covers the material models mentioned above, as well as many other specific material models which will not be described in details.

#### 4.1.5. Element contact

Element contact is when two element regions come into contact, and the solver uses algorithms to prevent the regions to overlap. Instead of overlapping, collision is simulated by calculating the appropriate deformations on the regions.

In solvers, contact is usually defined by first defining one or more regions, then defining interaction properties between or within the regions.

In NX Nastran regions are defined by selecting the nodes of faces on volume elements, or element sides on surface elements. In Abaqus, a surface on volume elements is defined by selecting the face IDs. For surface elements it is similar to Nastran. In Ansys however, contact regions are always defined by selecting nodes. The program then generates special contact elements based on the elements attached to those nodes.

In all three solvers, contact interaction properties may be defined and related to single regions or pairs of regions. A list of available contact parameters offered by these solvers are listed in [Appendix B](#) in [Table B.7](#). The listed parameters are the most common ones which may be found across the different solvers. There are, however, multiple more, which are very specific to each solver and their implemented algorithms.

#### 4.1.6. Element gluing

By element gluing we mean two or more node or element regions that are defined to not separate by not allowing any deformation between them. The term *glue* is used in NX Nastran, while in Abaqus the equivalent is referred to as *tie*, and in Ansys, as *bonded*.

The solvers might implement this gluing differently, but essentially, for the user it is very similar to defining element contact as mentioned in [Section 4.1.5](#).

#### 4.1.7. Superelements

Superelement (also known as substructure) reduction is a technique where parts of the FEM are divided in element groups; superelements. On each superelement, exterior nodes are defined, which can be used to connect to other superelements or normal elements. The model of the superelements are mathematically reduced such that their structural behavior may be defined by only the degrees of freedom of the exterior nodes. This can greatly reduce computation time for large FE models.

NX Nastran, Abaqus and Ansys, all support the concept of superelements.

#### 4.1.8. CAD-FEM relations

Generally, CAD/FEA applications allows for a mesh to be defined on

a CAD model. Mesh regions can be created on CAD lines, surfaces and volumes. If the CAD shape is modified, the related mesh can then be regenerated. Similarly, loads, boundary conditions, contact regions, and other analysis definition, can be defined on the CAD geometry. The application will then automatically determine which nodes or elements these analysis definitions will be applied on.

The major FEA solvers have very good solutions for this type of FEA/CAD associations. However, this information is only stored in the application's proprietary formats. The information in the files of these formats are not accessible outside the application, and are often only applicable for the specific version used. The FEA input files of the application contains only the FEA information, meaning that all CAD/FEA information is lost if the user wish to use another application.

The AP209 format support the representation of the CAD and FEA information, as well as their relation, such as the topological relation of geometric shapes in the CAD model, and elements or loads in the FEA model.

To be able to exchange such information between different systems, is very useful for engineers. The AP209 data model does support this sort of representations, but this capability has not been adopted or implemented by FEA/CAD applications.

## 4.2. Recommended extensions

### 4.2.1. Analysis type categorizations

In an AP209 model, the type of analysis type used is specified at the load case level. The type of entity used to define a load case, defines the type of analysis for that specific load case. Currently only linear static and modal analyses are supported in AP209.

The entity **control** represents the collection of load cases in the analysis; the solution. Load cases are represented by the entity **control\_analysis\_step** which has subtypes specific for linear static and linear frequency analysis. New subtypes could be added to this entity for each type of analysis to be supported. Ideally this could be organized as a hierarchy of sub-entities, such that these are organized based on being for example, static or dynamic, and linear or nonlinear. Special solutions, such as buckling analysis should also be considered.

Such extension would use method (c) **Extending application protocol scope**.

### 4.2.2. Analysis parameters

AP209 does not have any specific entities for analysis parameters, and there are no documentations which describes how this should be represented.

There are a huge number of different existing parameters, and their availability vary with each solver and analysis type. Because of this, it is suggested that a generic method is used to represent each parameters. A generic method would mean an entity holding a parameter name, representing the actual parameter, and its value. The parameter names could be defined in a Recommended Practices, defining its meaning and appropriate use. The actual entities representing these parameters, should then reference a **control\_analysis\_step** (load case), or **control** (complete analysis) entity, if applicable for the whole analysis.

Such extension would use method (b) **Extending recommended practices**.

### 4.2.3. Variable depending loads and constraints

The existing entities for applying FE loads in AP209, does not have any options for representing a load value that varies. However, Part 50

[76] defines mathematical constructs such as function and tables, and Part 107 [77] defines how to represent relations between content in Part 50 and Part 104 [78]. Part 104 is the STEP part which defines most FEM specific data types, including applied loads. All of these are part of the 209 application protocol.

Using the content in those parts of the standard, and describing their implementation methods in a recommended practices, could enable AP209 to cover the above cases.

Such extension would use method (b) **Extending recommended practices**.

#### 4.2.4. Nonlinear material properties

AP209 has specific entities only for defining linear material properties, such as E-modulus, poisson ratio, mass density, shell bending stiffness and more. Although, there are no specific entities for specifying nonlinear material properties, there are generic entities for material properties. These generic entities may be used to hold any type of values together with a material property name. Again, updated Recommended Practices could specify how to use these generic entities to represent nonlinear material properties.

Such extension would use method (b) **Extending recommended practices**.

#### 4.2.5. Element contact

AP209 can collect elements in groups, but not which of the element faces belong to it. Meaning that you can't define element surface regions. There are also no specific entities for describing contact properties.

A possible simple extension, could be to create a new entity, inheriting from the the entity **element\_group** and introducing an attribute that references the type **element\_aspect**. **element\_aspect** is a STEP *SELECT* type, which can represent types such as **volume\_3d\_face**, **surface\_3d\_face**, etc. This way, surfaces could be defined using element groups. Additionally, for surfaces composed of sets of element faces with different IDs, AP209 already has the capabilities to relate multiple entity groups.

For defining the actual contact within or between the region(s) another new entity might be required. In AP209 the entity **state\_definition** is a supertype of everything that is load or boundary condition related, or that somewhat defines the *state* of the FEA model. The most appropriate way to add contact definitions would be to extend the **state\_definition** with new subtypes. It could be considered to add different entity types for specific cases, such as surface to surface contact and surface self contact. Another consideration, which hasn't been mentioned, are edge contacts, specially for 2D mesh models.

Parameters defining the properties and configuration of the contact could follow a similar generic approach as was discussed with analysis parameters in Section 4.2.2.

Such extension would use method (c) **Extending application protocol scope**.

#### 4.2.6. Element gluing

In the context of AP209, glueing should be implemented similarly to contact. The element region implementation could be used for both contact and glued regions. Specific entities for defining the actual glued connection between the regions, should also be done by extending the **state\_definition** entity.

Such extension would use method (c) **Extending application protocol scope**.

#### 4.2.7. Superelements

AP209 contains the concept of *element substructures*, but this is not well documented and has not been implemented in previous AP209 studies. The entity **substructure\_element\_representation**, is a subtype of **element\_representation**. This entity can collect multiple elements to define a superelement.

Such extension would use method (a) **Extending application scope support** and possibly (b) **Extending recommended practices**.

#### 4.2.8. CAD-FEM relations

The AP209 format support the representation of the CAD and FEA information, as well as their relation, such as the topological relation of geometric shapes in the CAD model, and elements or loads in the FEA model.

To be able to exchange such information between different systems, is very useful for engineers. The AP209 data model does support this sort of representations, but this capability has not been adopted or implemented by FEA/CAD applications.

Such extension would use method (a) **Extending application scope support** and possibly (b) **Extending recommended practices**.

## 5. Conclusion and future work

The point of having a standard data model for a domain such as FEA is to be able to store and exchange data regardless of its original format. An ISO standard model is maintained and ensured to be backwards compatible. The model is also *open*, meaning it is available to anyone who wish to adopt and implement it.

Such a model solves the problem of having to perform duplicate work when migrating or exchanging data from one system to another. It also prevents problems such as files being incompatible with newer versions of applications.

In addition to these mentioned benefits, data represented in STEP from any domain, may be related to other domains through it's PLM support.

In the CAD domain, STEP has shown, to a certain degree, to solve these problem and is widely used to move data between different systems.

As have been mentioned, the standard seem to lack support from FEA solver vendors. The main reason for this, is assumed to be lack of information scope for certain analysis types. To reconcile this, AP209 should extend its domain to be compatible with the type of advanced analysis that are available in existing solvers. The standard already has all the major generic building blocks (entities and data types) for many of the missing items, allowing it to easily extend its scope.

Future work is highly suggested to address the topics mentioned in Section 4, and to define how these improvements should be implemented in the standard. Some of this work has been done and is presented in Lanza et al. [79]. This should be further pushed to the ISO STEP 10303 committee and documented in associated Recommended Practices.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Solver analysis parameters

**Table A.2**  
Increment parameters available per analysis type and solver.

	NX			ABAQUS			ANSYS	
	SOL106	SOL129	SOL601	Static, general	Static, Riks	Dynamic Implicit	Static	Transient
Step time period				STATIC		DYNAMIC	TIME	TIME
Initial number of increments		TSTEPNL - NDT					NSUBST - NSBSTP	NSUBST - NSBSTP
Fixed number of increments	NLPARM - INC		TSTEP - Ni				NSUBST - NSBSTP	NSUBST - NSBSTP
Max number of increments	NLPARM - INC		TSTEP - Ni	STEP - INC	STEP - INC	STEP - INC	NSUBST - NSBMX	NSUBST - NSBMX
Min number of increments							NSUBST - NSBMN	NSUBST - NSBMN
Initial increment size		TSTEPNL - DT	TSTEP - DTi	STATIC		DYNAMIC	DELTIM - DTIME	DELTIM - DTIME
Fixed increment size		TSTEPNL - DT (ADJUST = 0)	TSTEP - DTi	STATIC		DYNAMIC	DELTIM - DTIME	DELTIM - DTIME
Max increment size			NXSTRAT - ATSMXDT	STATIC		DYNAMIC	DELTIM - DTMAX	DELTIM - DTMAX
Min increment size			NXSTRAT - ATSSUBD	STATIC		DYNAMIC	DELTIM - DTMIN	DELTIM - DTMIN
Tabular number of time steps			TSTEP - Ni				*	*
Tabular fixed step size			TSTEP - DTi				*	*
Tabular output Nth increment			TSTEP - NOi					
Max step size adj. Ratio		TSTEPNL - MAXR						
Min step size adj. Ratio		TSTEPNL - MAXR						
Step size adj. every n-th step		TSTEPNL - ADJUST						
Step size adj. function		TSTEPNL - MSTEP/RB						
Output Nth increment		TSTEPNL - NO	TSTEP - NOi					
Output all or last increment	NLPARM - INTOUT							

**Table A.3**  
Arc-length parameters available per analysis type and solver.

	NX			ABAQUS			ANSYS	
	SOL106	SOL129	SOL601	Static, general	Static, Riks	Dynamic Implicit	Static	Transient
Min. arc length adj. ratio	NLPCI - MINALR							
Max. arc length adj. ratio	NLPCI - MAXALR							
Min. arc length adj. ratio to initial	NLPARM - MAXR						ARCLEN - MAXARC	ARCLEN - MAXARC
Max. arc length adj. ratio to initial	NLPARM - MAXR						ARCLEN - MINARC	ARCLEN - MINARC
Min. arc length increment				STATIC				
Max. arc length increment				RIKS				
Fixed arc length increment				STATIC				
Initial arc length increment	NLPARM - NINC (*)			RIKS			TIME + NSUBST - NSBSTP(*)	TIME + NSUBST - NSBSTP(*)
Max increment number	NLPCI - MXINC		NXSTRAT - LDCSUBD	STATIC				
Arc length scale factor	NLPCI - SCALE			RIKS				
Arc length method type	NLPCI - METHOD			STATIC				
Start displ. at node			NXSTRAT - LDCDISP					
Max. displ. at node			NXSTRAT - LDCDMAX	STATIC			ARCTRM - VAL	ARCTRM - VAL
Max. LPF				RIKS				

**Table A.4**  
Iteration parameters available per analysis type and solver.

	NX			ABAQUS			ANSYS	
	SOL106	SOL129	SOL601	Static, general	Static, Riks	Dynamic Implicit	Static	Transient
Max. iteration per increment	NLPARM - MAXITER	TSTEPNL - MAXITER	NXSTRAT - MAXITE				NEQIT - NEQIT	NEQIT - NEQIT
Advanced iteration parameters				CONTROLS - PARAMETERS = TIME INCR.	CONTROLS - PARAMETERS = TIME INCR.	CONTROLS - PARAMETERS = TIME INCR.		
Bisection controls	NLPARM - MAXBIS	TSTEPNL - MAXBIS						
Update stiffness matrix on first iter.	NLPARM - METHOD							
Update stiffness matrix at Nth iter.	NLPARM - METHOD/ KSTEP			SOLUTION TECHNIQUE		SOLUTION TECHNIQUE		
Newton Raphson (full)	NLPARM - METHOD/ KSTEP	NLSTEP - KUPDATE		SOLUTION TECHNIQUE		SOLUTION TECHNIQUE	NROPT - FULL	NROPT - FULL
Modified Newton Raphson	NLPARM - METHOD/ KSTEP						NROPT - MODI	NROPT - MODI
Quasi Newton				SOLUTION TECHNIQUE		SOLUTION TECHNIQUE		

**Table A.5**  
Convergence criteria parameters available per analysis type and solver.

	NX			ABAQUS			ANSYS	
	SOL106	SOL129	SOL601	Static, general	Static, Riks	Dynamic Implicit	Static	Transient
Displacement (incl. rotation)	NLPARM - CONV	NLSTEP - CONV	NXSTRAT - CONCRI					
Displacement				CONTROLS - FIELD = DISPLACEMENT	CONTROLS - FIELD = DISPLACEMENT	CONTROLS - FIELD = DISPLACEMENT	CVNTOL - Lab = U	CVNTOL - Lab = U
Rotation				CONTROLS - FIELD = ROTATION	CONTROLS - FIELD = ROTATION	CONTROLS - FIELD = ROTATION	CVNTOL - Lab = R	CVNTOL - Lab = R
Force (incl. moment)	NLPARM - CONV	NLSTEP - CONV	NXSTRAT - CONCRI					
Force							CVNTOL - Lab = F	CVNTOL - Lab = F
Moment							CVNTOL - Lab = M	CVNTOL - Lab = M
Work	NLPARM - CONV	NLSTEP - CONV	NXSTRAT - CONCRI					
Displacement tolerance (incl. rot)			NXSTRAT - DTOL					
Displacement tolerance	NLPARM - EPSU	NLSTEP - EPSU		CONTROLS - FIELD = DISPLACEMENT	CONTROLS - FIELD = DISPLACEMENT	CONTROLS - FIELD = DISPLACEMENT	CVNTOL - TOLER	CVNTOL - TOLER
Rotation tolerance				CONTROLS - FIELD = ROTATION	CONTROLS - FIELD = ROTATION	CONTROLS - FIELD = ROTATION	CVNTOL - TOLER	CVNTOL - TOLER
Force (incl. moment) tolerance	NLPARM - EPSP	NLSTEP - EPSP	NXSTRAT - RTOL					
Force tolerance							CVNTOL - TOLER	CVNTOL - TOLER
Moment tolerance							CVNTOL - TOLER	CVNTOL - TOLER
Work tolerance	NLPARM - EPSW	NLSTEP - EPSW	NXSTRAT - ETOL					

**Table A.6**  
Line-search parameters available per analysis type and solver.

	NX			ABAQUS			ANSYS	
	SOL106	SOL129	SOL601	Static, general	Static, Riks	Dynamic Implicit	Static	Transient
Line search on/off	SOL106 NLPARM - MAXLS	SOL129 TSTEPNL - MAXLS	SOL601 NXSTRAT - LSEARCH	Static, general CONTROLS - PARAMETERS = LINE SEARCH	Static, Riks CONTROLS - PARAMETERS = LINE SEARCH	Dynamic Implicit CONTROLS - PARAMETERS = LINE SEARCH	Static LNSRCH	Transient LNSRCH
Max. line search iterations	NLPARM - MAXLS	TSTEPNL - MAXLS		CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH		
Max. correction factor				CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH		
Min. correction factor				CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH		
Residual reduction factor terminate				CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH		
Ratio new to old cor. fac. terminate				CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH	CONTROLS - PARAMETERS = LINE SEARCH		
Relative energy error tolerance	NLPARM - LSTOL							
Error tolerance for W criterion	NLPARM - EPSW	TSTEPNL - EPSW						
Lower bound for Line Search			NXSTRAT - SLOWER					
Upper bound for Line Search			NXSTRAT - UPPER					
Line search convergence tolerance			NXSTRAT - STOL					

**Appendix B. Contact parameters**

**Table B.7**  
Contact parameters available per analysis solver.

NX	ABAQUS	ANSYS
static friction coefficient	BCTSET - FRICi	FRICITION
min. search distance	BCTSET - MINDi	
max. search distance	BCTSET - MAXDi	SURF. INTERACTION - TRACK. THICKNESS
handling of initial penetration	BCTPARA - INIPENE	SURF. BEHAVIOUR - PRESSURE- OVERCLOSURE
contact algorithm: Constraint function	BCTPARA - TYPE	
contact algorithm: Segment method	BCTPARA - TYPE	
contact algorithm: Rigid target	BCTPARA - TYPE	
contact algorithm: Direct		SURF. BEHAVIOUR - DIRECT
contact algorithm: Penalty		SURF. BEHAVIOUR - PENALY
contact algorithm: Augmented lagrange		SURF. BEHAVIOUR - AUGMENTED LAG.
contact algorithm: Multipoint constraint		
contact algorithm: Lagrange		
contact algorithm: Lagrange / penalty		
double sided contact	BCTPARA - NSIDE	SURFACE (not specifying face/edge)
contact surface thickness	BCTPARA - OFFTYPE / OFFSET	SURF. INTERACTION

**Supplementary material**

Supplementary material associated with this article can be found, in the online version, at [10.1016/j.advengsoft.2021.102976](https://doi.org/10.1016/j.advengsoft.2021.102976)

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