# A CASE STUDY FOR MODELING MACHINE TOOL SYSTEMS USING STANDARD REPRESENTATIONS

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## ABSTRACT

*Machine models play an important role to support decision making for purchasing, scheduling, and routing in manufacturing. However, it is challenging to share a machine model that is developed using proprietary formats. A model of a fully assembled machining system in a neutral format can help overcome this challenge. Standard-based machine tool models will not only facilitate information reuse but also enable model exchange between systems. In this paper a case study is discussed to demonstrate the initial effort of a standard representation for a machining system including both component geometric and kinematics information. This standard-based machine model will be easily imported to another tool.*

**Keywords** –CAx tools, kinematics, interoperability, machine model, standards, smart manufacturing systems, STEP

## 1. INTRODUCTION

Smart manufacturing systems (SMS) are fully integrated, collaborative manufacturing systems that will respond in real time to meet changing demands and conditions in factories, in their supply network, and in customer needs [1] [2] [3] [4]. SMS requires the digitalization and integration of components of a manufacturing enterprise including manufacturing resources such as computer numerical control (CNC) machining systems [5].

A CNC machining system is a fundamental element in production systems and typically consists of a machine tool, cutting tools, auxiliary devices, material-handling devices, and fixtures. A CNC machine model is a conceptual representation of the machine tool and has a logical framework that enables the representation of the machine's functionalities. The information built into a machine model can be used throughout the life cycle of a machining system and by various users in the decision-making processes. Examples of model use include manufacturing capability evaluation, process validation, and production planning [6] [7]. It consists of modules for describing the configuration of the overall structure, geometric shapes of the mechanical units, as well as the kinematic relationships between the mechanical units of the machine. The kinematics model of a machine tool defines the motion constraints for machine components that are related to each other [8]. For example, a five-axis machine is generally defined by two rotational axes to rotate and tilt either the tool or the workpiece and three orthogonal linear axes x, y, and z. The machining functional properties, i.e., mechanical and kinematical properties in the machine model, will define and constrain the movements and speeds of axes [7]. Simulation of kinematics helps identify manufacturing issues at an early stage and correct them before production. Those issues could be errors in the tool path, collisions between machine components and machined parts, and poor quality of the final product. Simulation is the safest and most cost-effective way for verification of a multi-axis program, and it supports the concept of virtual machining [6] [9].

Computer-aided (CAx) tools normally provide a virtual environment that enables the simulation of machining processes with a realistic representation of the kinematics, static, and dynamic behavior of the real machine tool [6]. The x in CAx is an abbreviation for the family of computer-aided tools that are used to create virtual environments, for example, Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), or Computer Aided Engineering (CAE). A variety of commercial CAx tools from different vendors are available and have been used by manufacturers to represent their products and resources to support design, operation, and maintenance activities. These activities involve process planning, tool path verification, cost estimation, process simulation, and CNC programming [6] [7].

With the multiple CAx tools provided by different vendors serving the same purpose, barriers for sharing and exchanging machine models with kinematic and geometric information between different systems exist [10]. Because each vendor has its own CAx environment, which is non-homogenous, users are stuck with the specific format of the CAx software they use. Redundant efforts have to be made for recreating the same machine model using different CAx tools within a company; machine models with complex kinematics may be difficult or very time-consuming to remodel or convert. In addition, all these issues also make it difficult to efficiently define and analyze manufacturing capabilities for production planning and equipment procurement. For example, when purchasing a CNC machine tool, it is normally hard for final users to determine whether their workpiece(s) will fit on that machine, or even if they do fit, is there an accurate, efficient location for the parts? Having machine models beforehand will allow users to better understand the machines' capability and easily compare candidate machines through "try before they buy." However, it is impossible for users to gain access to all the vendor-specific tools and machine models before the procurement. A neutral format, which is a non-proprietary format that can be used to represent machine models and recognized by all vendors, of the machine models will provide the final users a convenient way to evaluate the capabilities of candidate machine tools.

Efforts for international standards, to govern the representation of geometrical and functional information, have been made in parallel as the machine tool manufacturers developed their proprietary techniques [7]. Attempts have been made to provide a standardized solution for model and data exchange between CAx systems, but so far it is mainly the product geometric data and definition that have been widely exchanged by the support of ISO 10303, which is also called Standard Exchange of Product Data (STEP). Many CAx tools can export geometric models to the STEP format and vice versa. Standard solutions for the exchange of kinematics information have not been used in practice and industry does need a standard way to exchange complete machine model information including the product geometry, kinematics, tolerances, and classification [10].

The increasing use of software to represent a machining system in a virtual representation, from a manufacturing perspective, implies an increased need to be able to reuse the information. Manufacturing companies are investing more to digitizing their enterprises and as more information is digitally available, the interest and urgency of information reuse will increase. Interoperability for systems and models will be more crucial and will motivate manufacturers to seek solutions that support standard representations of their resource, product, and production data. The stakeholders to this approach are manufacturing companies that need to exchange these kinds of data, both internally and externally. For example, internally, the same machine model may be developed multiple times using different software, models have issues with different version of the software, or different units used by the different component models that need to work together; externally, model exchanges and communications among supply chain partners, CAx developers, and machine vendors may be required.

This paper introduces a case study that demonstrates the feasibility of representing a complete machining model, including both geometric and kinematics information, using the STEP standard. This case study reports the initial effort of converting a vendor-specific (PTC Creo) machine model to the STEP AP 242 representation. PTC Creo was selected because (1) it is a commonly used CAx tools and (2) we have a machine model available in Creo format for this case study. The research contributions of this paper include (1) a general approach for converting a vendor-specific machine model in proprietary format to a standard format (STEP) and (2) lessons learned through the implementation of the case study.

The rest of the paper is organized as follows: Section 2 discusses the existing relevant standards and related efforts for solving the problem of non-homogenous CAx environments. Section 3 presents the general approach of how to address this problem so that a specific approach can be derived depending on the CAx tools used and interfaces required. Section 4 introduces the context and settings for this specific case, and presents the development of the STEP generator. Section 5 discusses the challenges encountered in this study and finally Section 6 concludes the paper.

## 2. RELEVANT STANDARDS AND RELATED EFFORTS

This section discusses relevant standards that support the work, interfaces that enable the conversion of data from proprietary formats to the standard formats, and related efforts in the field.

### 2.1 Standards: ISO 10303 – STEP and ASME B5.59

Two standards for representing machine models are briefly introduced in this subsection: ISO 10303 and ASME B5.59. The standard ISO 10303, or STEP, was developed to unambiguously represent and exchange computer-interpretable information for a product [11]. STEP consists of a set of standards to facilitate data modeling throughout the entire lifecycle of a product, and has become widely accepted and applied internationally for exchanging product data in the manufacturing field. Information models and nearly all parts of STEP are defined using the EXPRESS modeling language, the standard ISO 10303-11 [12] [13]. The EXPRESS modeling language defines entities and the relationships between entities. Files that are created based on this standard are also referred to as physical files or part21/p21 files. The instances of an entity can be exchanged by the support of p21 files or shared within applications through the Standard Data Access Interface (SDAI) [14]. The information models can be categorized into application protocols (AP) or integrated resources (IR). APs are developed for specific application domains, such as aerospace in AP 203 and automotive in AP 214 and they are designed for fulfilling the industrial requirements [12]. AP 242, managed model-based 3D engineering, presents a data model schema to integrate the kinematics, geometry, and assembly models [15]. However, AP 242 is still a work in progress and has not been widely implemented in industry [10]. Figure 1 provides an example of the EXPRESS schema for AP 242, which defines a kinematic joint. [16] lists a complete documentation of the AP242 EXPRESS schema. IRs are context-independent, and an example of IR is ISO 10303-105 that defines an IR for kinematics data. IR for kinematics for 10303-105 specifies the structure, motion, and analysis for kinematics mechanism and is possible to use in any industrial domain [17] [18].

```
(* SCHEMA step_merged_ap_schema; *)

-- DIFF IN AP214
-- CASE DIFF IN AP238 STEP-NC
-- IN AP214/AP238 STEP-NC/AP242
ENTITY kinematic_joint
   SUBTYPE OF (edge);
      SELF\edge.edge_start : kinematic_link;
      SELF\edge.edge_end : kinematic_link;
   UNIQUE
      ur1 : edge_start, edge_end;
   WHERE
      wr1:
         edge_start :<>: edge_end;
END_ENTITY;
```

**Figure 1** – An example from of the AP242 EXPRESS schema for defining kinematic joints [16]

ISO is not the only standardization organization involved in standardizing how machine models can be represented on a neutral format. Another standard that defines information models and formats for machine tool data is B5.59 from the American standardization organization, American Society of Mechanical Engineers (ASME) [9]. The eXtensible Markup Language (XML) is used for representing the specification of machine tools (milling and turning machines). The focus of the standard is on properties that describe capabilities and performance of a machine tool at a specific instance of its life cycle, e.g., in the specification or operation stage of the machine tool. The standardization efforts made from multiple standardization bodies indicate the importance of this topic and a standardized solution is needed for sharing and exchanging manufacturing resource and product models.

### 2.2 JSDAI

There are several available interfaces to support the translation of machine models in a vendor-specific format to the STEP format, e.g., STEP Tools [19], OpenCascade [20], PythonOCC [21], and Java-based SDAI (JSDAI) [22]. JSDAI was selected for the case study reported in this paper because it supports most of the APs in ISO 10303 and is a Java-based open source Application Programming Interface (API). JSDAI also supports the development of EXPRESS data models and their implementation in Java. It enables the reading, writing, and runtime manipulation of object-oriented data defined according to an EXPRESS data model. JSDAI provides a library that contains EXPRESS schemas for most APs in ISO 10303. JSDAI uses the EXPRESS schema defined for AP 242 to represent the kinematics information.

JSDAI facilitates the linking of CAD, CAM, CAE, CNC, Product Data Management (PDM), and Product Lifecycle Management (PLM) systems [22] [23].

### 2.3 Related efforts

Since the introduction of STEP in 1994, examples of how it can be used to share data on a standard format have been reported in scientific publications. Among the contributors, Li et al. [10] [24] have made efforts for converting kinematics modeling using Siemens' NX CAD software to the STEP format. The case study in this paper uses a similar approach, but a new STEP generator was developed for a different CAD tool and applied to a different machine model.

## 3. THE GENERAL APPROACH FOR CONVERTING MACHINE MODELS

To extract kinematics data from a machine model defined in a vendor-specific CAD system and integrate it with a STEP model that contains the geometric data of the same machine model, an application needs to be developed. Figure 2 shows the general approach of how this could be done as a guideline for readers with various CAx tool to follow. Section 4 will explain the case specific settings for the case study in this paper and Figure 3 depicts the specific procedure for the case study.

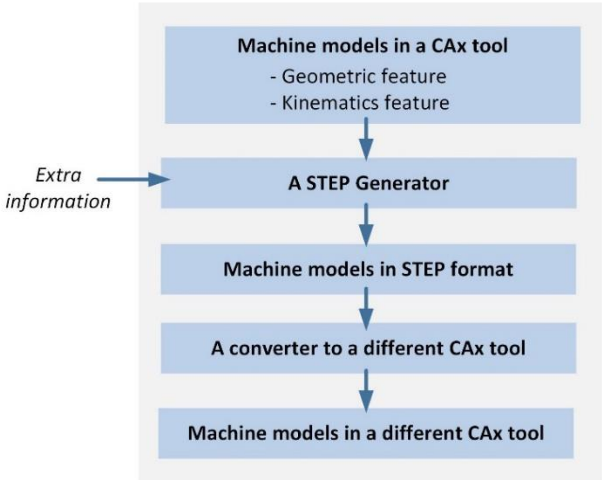


**Figure 2** – The general approach for creating a complete machine model in STEP format with both geometric and kinematics information

A machine model may be developed in a vendor-specific format with a complete description including geometric and kinematics information; this is a foundation for us to be able to translate the complete virtual machine model to a standard format. Most CAx software today provides the functionality to automatically export geometric information in the STEP format. However, a vendor-specific application (i.e., an interface or adapter) is required to extract the kinematics data. Examples of interfaces that support the development of such applications include J-Link for PTC Creo and NX Open for Siemens. These interfaces of vendor-specific tools enable the development of the STEP generator.

After both geometric and kinematics data sets have been extracted from the machine model in a CAx tool, the "STEP Generator" integrates them into a complete machine model in STEP. For example, JSDAI can be applied for integrating the information from both sources to create a final complete STEP model containing all the information of the machine model from the CAx tool. To ensure that the STEP file is complete, there may be extra information such as users' input that needs to be added. With vendor-specific converters/adapters, the complete machine model in STEP format can be imported into other CAx environments. The vendor-specific STEP generators vary depending on the specific interface requirements and programming language used. The STEP generator used for the case presented in this paper will be further explained in the next section.

## 4. A CASE STUDY – A STEP GENERATOR FOR PTC CREO

We have applied the approach described in Section 3 to a specific use case. Figure 3 shows an instance of the general approach depicted in Figure 2. The machine tool model is defined in PTC's CAD software, Creo. The geometric information of the model is exported to a STEP file. The STEP file will be integrated with the kinematics information generated by using J-Link and JSDAI. J-Link is a Java-based API that is provided by PTC to enable the interactions between the machine model in Creo and other applications. Through J-link, kinematics information from the model can be extracted. The geometric information in the STEP file and the kinematics data are integrated into one STEP file by the STEP generator. The following subsections will explain each step in more details.

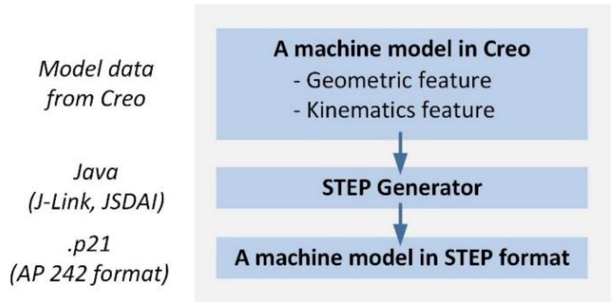


**Figure 3** – The case study approach: integrating a Creo machine model's kinematics and geometric information in STEP AP242

### 4.1 Machine model in Creo

The machine model in the case study is a 5-axis Hurco CNC machine tool, VM10UI. It is developed in PTC's CAD environment, Creo Parametric professional version 6. The J-Link API is an add-on module of the software. The Hurco machine model in Creo is shown in Figure 4.

It consists of a spindle and the y slide representing a machining table. The table can move in x-axis and y-axis, and rotate to adjust the angle of a part in relation to the spindle head. VM10UI_MAINCYS is the coordination system for the machine model of the HURCO machine, and ADTM1, ADTM2, ADTM3, and ADMT4 are the four planes that serve as reference for a planar surface. Defined planar enables motion settings of the machine parts with the same reference. The tree structure to the left in Figure 4 contains the kinematics information on how the different parts and assemblies of the machine model are related to each other, which determines how they move. HURCO_VM10UI is the name and model of the machine tool, and FRAME, Y_SLIDE and SPINDLE_HEAD are components constituting the machine model. Each of the components in the tree structure has a breakdown structure where more information is contained for the machine model, such as the kinematic information, which defines either the rotational or translational movement in the x- and y-axis. Figure 5 shows the breakdown structure for the component SPDINLE_HEAD.

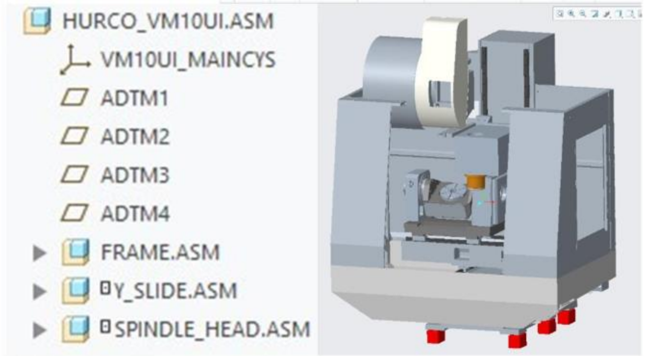


**Figure 4** – The Hurco machine tool model in Creo Parametric

A representation of the spindle head of the machine (marked with green lines) is shown in Figure 5. The tree structure of the spindle head is expanded in the list to the left, representing the information for the spindle head, which includes kinematics information about the alignment and rotation. Placement contains the kinematic data with information of the axis alignment and the rotation of the spindle head. A tool is attached in the spindle head and the rotational movement determines how material is removed during machining. DEFAULT_CSYS is the coordination system defined for the spindle head and ASM_RIGHT, ASM_TOP, and ASM_FRONT are planes applied for this machine part.

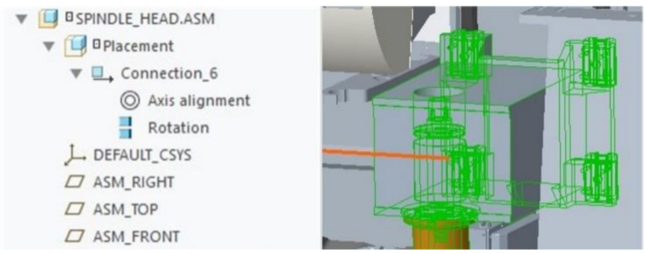


**Figure 5** – A view of the spindle of the machine and its tree structure

### 4.2 Geometric data in a STEP file

The geometric information of the machine model is exported into a STEP file using the standard interface provided by Creo. The export functionality automatically generates a .stp file; a portion of the exported STEP file is shown in Figure 6. The STEP file (.stp) contains all the geometric data starting from the line defining DATA. The schema used for defining the model is CONFIG_CONTROL_DESIGN from AP203.

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION((''),'2;1');
FILE_NAME('HURCO_VM10UI_ASM','2019-10-08T15:57:32',('mvb1'),(''),
'CREO PARAMETRIC BY PTC INC, 2019010','CREO PARAMETRIC BY PTC INC, 2019010','');
FILE_SCHEMA(('CONFIG_CONTROL_DESIGN'));
ENDSEC;
DATA;
#2=DIRECTION('',(0.E0,-1.E0,0.E0));
#3=VECTOR('',#2,2.099999999997E1);
#4=CARTESIAN_POINT('',(-2.88E2,5.367064179908E2,-7.709115937861E2));
```

**Figure 6** – A snap view of the STEP file that is exported from Creo and contains all the geometric information of the machine tool model

### 4.3 The STEP Generator using JSDAI and J-Link

The Java development environment used in this study is Eclipse. JSDAI provides plug-ins that are compatible with Eclipse. JSDAI also provides an EXPRESS compiler for compiling the EXPRESS files and creating .jar files for use in Java programs to represent the data model.

The STEP Generator uses an iterative process to evaluate the characteristics of the kinematics information and add it accordingly to the STEP file. To allow JSDAI to manipulate the model data, the read-and-write access is used for accessing the data in the generated STEP file with geometric data and for writing kinematics data to the STEP file to create a complete STEP model according to the AP 242 EXPRESS model. A repository is created for JSDAI to store the temporary kinematics data.

The kinematics information in the Hurco machine model is defined as constraints. For each constraint, an array will be created to store the data. This data is written to the STEP model according to the EXPRESS schema used, i.e., AP 242, and an example is shown in Figure 7.

```
ComponentFeat componentFeat = (ComponentFeat) selectedFeature;
ComponentConstraints constraints = componentFeat.GetConstraints();
if (constraints == null || constraints.getarraysize() == 0) {
    DisplayMessage("Selected Feature does not have any constraints");
    return;
}
```

**Figure 7** – An example of code where the kinematic data of model feature is extracted for conversion to the STEP format

After going through all the kinematics constraints, a STEP model representing both geometrical and kinematics data is generated from JSDAI as a .stp-file and a section of such a model is shown in Figure 8.

```
FILE_SCHEMA(('IDA_STEP_AIM_SCHEMA'));
ENDSEC;
DATA;
#1=APPLICATION_CONTEXT('CONFIGURATION MANAGEMENT');
#2=APPLICATION_PROTOCOL_DEFINITION('INTERNATIONAL STAND
    2019,#1);
#3=MECHANICAL_CONTEXT('AP242_MANAGED_MODEL_BASED',#1,'M
#4=PRODUCT('TestID','TestName','TestDescription',(#3));
#5=KINEMATIC_LINK('33233');
```

**Figure 8** – An example of a complete STEP file (.stp file) generated by the STEP generator

## 5. DISCUSSION

This work contributes to the field of system interoperability and information reuse for machine modeling. During this study, challenges and issues have been identified, and more research and development efforts are required to address them. The challenges are elaborated in the following subsections from different perspectives: (1) challenges with the applications of STEP, JSDAI, and J-link, (2) challenges with converting the machine models and kinematics information including aspects of verification and validation of the developed approach, and (3) challenges with the commercial software and data reuse for end users.

### 5.1 Challenges with the applications of STEP, JSDAI, and J-Link

The STEP standard has been a work in progress since its introduction in 1994 and there are continuous improvements and new additions to it. One of the latest developments is the AP 242 edition 2 that integrates the definitions from both AP 203 and AP 214, which are originally developed for different manufacturing industries. The new AP becomes more complex and is harder for users to understand and use. Because the STEP definitions are cumbersome, it requires a specific software for editing and manipulating a STEP file.

JSDAI covers most definitions that are needed for writing, reading, and modifying STEP models. This makes JSDAI applicable to the development of the kind of STEP generators we described in this paper. However, the complication of the STEP definitions has also added more complexity to the JSDAI applications. Since JSDAI is an open source API, there are few examples demonstrating real use cases of where JSDAI has been used. The technical support from the developer of JSDAI is hard to get and the documentation of JSDAI is not up to date. With better documentation, more examples, and further developments, JSDAI can facilitate the implementation of the STEP standard more efficiently. The effort required for this implementation was about 4 months for a person with basic programming skills. By referring the approach proposed and the lessons learned in this paper, an industry application could be implemented in a shorter time. More JSDAI implementations would also motivate the enhancement and the support of technology.

J-Link enables the interaction between a Creo model and JSDAI. J-Link provides documentation, guidelines, and program examples to support developers and users of Creo. Since the interface and programming environment are vendor-specific, developers of STEP generators will need to have knowledge and programming skills for multiple tools. How the machine model is defined in a CAx specific software will impact how the data that represents the feature, part, and object of the machine can be manipulated.

### 5.2 Challenges with the converting of machine models and kinematics information

In this study, a couple of constraints (kinematic properties/pairs) have been converted to the STEP format. However, automatically identifying and converting all constraints of the machine model is still challenging. More effort is needed to ensure the correct usage of the EXPRESS schema when generating the STEP representations automatically, i.e., the machine model data exported from the CAD software is converted correctly to the STEP format. This involve the STEP generator including the integration of J-Link and JSDAI applications for exporting the complete machine model on a neutral format. This leads to an important topic, the verification and validation (V&V) of the converted machine model. Is there anything missing during the model conversion? Does the newly generated STEP machine model exactly represent the original vendor-specific machine model? Although V&V has not been a focus of this study, techniques for V&V of the machine models have been investigated.

Kinematics information is crucial for the behavior of a machining system and the accuracy of the kinematics model determines the precision of the overall machining. Kinematics modeling is one of the most common sources of errors for a machine model. Therefore, when remodeling of kinematics information of a machine tool, it is important to ensure the kinematics information is converted completely and correctly between various systems and formats using the STEP generators. In order to do that, a fundamental requirement is that the coordinate systems in ISO 10303-105 (STEP part21 file) and in the CAD software need to be the same. In ISO 10303-105, a link frame is used to define the local coordinate system of a kinematic pair and all relevant geometric definitions are defined relative to this link frame. On the other hand, commercial CAD software has its own way of defining coordinate systems. Many of them use a world coordinate system (or a global coordinate system). So before converting the machine model to the STEP format, the coordinate system needs to be converted; this includes the location and orientation information of each pair, in Creo, and it is for each constraint. The terminology usage in different CAD environments for the same concept also causes a lot of confusion which was encountered in the case presented here; what is referred to as a part in one software may be called a feature in another software. What is called constraints in Creo will be called pair or link in STEP. This poses implications for the extraction of kinematics data and needs to be adjusted for each vendor-specific CAD software. Since the terminology for each vendor-specific software already exists and is being used, this needs to be considered during the model conversion. It could also be argued that the terminology should be standardized but it will be a long way to go not only for the development of the standard, but also for all vendors to comply with the standard. Note that also the complexity of the conversion will increase with the number of axes, e.g., a five-axis machine is more complex than a three-axis machine.

There are also remaining challenges for the definition of kinematics in AP 242. It was first introduced in 2014 but is still not widely used or implemented in industry. Is AP 242 a perfect solution for representing all machine models? In other words, are the definitions in AP 242 complete for all the needs of the kinematics definitions? This needs to be further investigated.

The current situation is that kinematics information is managed manually in some companies by using a text-based description or a spreadsheet-like tool. Manual steps involving humans always has the risk of creating errors. Most other smaller companies are not even capable of dealing with kinematics settings at all because of the lack of knowledge and access to the information. This may cause production delay, product quality issues, more vendor dependency, and cost increase.

### 5.3 Challenges with commercial software and data reuse for end users

Even though STEP is now an integrated interface in most CAD software, there is still an unwillingness from the CAx developers for further implementation of STEP representations of kinematics modeling. This is because of the complexity of the implementation, but also because the vendors and solution providers would like to take advantage of the situation with customer retentions and lock-in effects [7]. Most CAx software developers provide vendor-specific solutions so that customers need to depend on their software. This situation causes information silos and makes it difficult for interoperability. It also causes more issues for model and data reuse for manufacturers because of the diverse landscape of software and systems they use. It used to be the same situations for post-processing and Geometric Dimensioning and Tolerancing (GD&T), which have currently been implemented using a standard format by most CAx vendors. So, we hope kinematics modeling is the next one that people will turn to standardized solutions since there is a clear need for it from the manufacturing community that could motivate the CAx software to provide a standardized solution in the same way as it is for GD&T now.

## 6. CONCLUSIONS AND FUTURE WORK

The case study presented in this paper demonstrates the feasibility of generating a complete STEP model that includes both geometric and kinematics information of a machine model. This is done by developing a STEP generator to extract geometric and kinematics data and integrate it into the STEP model according to the EXPRESS schema. The results of the paper include:

- A general approach has been developed for how kinematic and geometrical data can be extracted to a neutral format. The general approach is meant to be applicable to all CAx tools.
- Explaining how the general approach was used for a case specific setting, including a description of the interfaces and software that were used. This is specific for the tools selected and interfaces determined for the case study.
- The translation of a machine model to the STEP standard format was explained for a real machine model developed in the CAD software, PTC Creo.
- The case study with the PTC Creo machine model serves as a feasibility study and demonstrates step-by-step how this can be done.

The work has real industrial impact and the standards-based digital representations of a complete machine tool model enables better information reuse, better interoperability, and more consistent management. It will help support decision making throughout the different phases of a production system including machine tool procurement, efficient machining capability definition and analysis, dynamic planning and scheduling by facilitating last-minute adjustments to adapt current conditions, and configuration validation. Furthermore, it will save both time and money for the manufacturing companies.

This is a preliminary study. More real-world industrial cases will be implemented. Also, more CAx software specific adapters need to be developed. One scenario could be a real-world study with supply chains involving several companies using different systems and those companies representing both large enterprises and small and medium-sized enterprises. Supply chains in both process and discrete manufacturing may be used to demonstrate how existing challenges in information sharing and model exchange could be addressed.

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**Disclaimer**

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