Data Structure for Virtual Commissioning - Exchange Relevant Information Focusing on Integration of Modular Component Models and Wide Compatibility

Master Thesis

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Abstract

This master thesis presents a data structure consisting of CAD data, simulation models, example control code and documentation used for a virtual commissioning. Virtual commissioning is becoming increasingly important in the engineering process of plants and production machines. This increase results from time and thus also cost savings during the entire product development and especially during commissioning as outcome of a virtual commissioning. However, this process also has a drawback in form of an increased effort in the modelling of a virtual plant and the complexity associated with it. The behaviour modeling of the different components can be done in several different tools, mostly depending on the manufacturer. The CAD data is also available in different file formats and are thus no exception of this rule. This variety of possibilities increases the complexity of the integration process enormously. However, for virtual commissioning to be efficient, the integration of the used components should be as simple as it could be. As a possible solution to this problem, this thesis proposes an exemplary data structure to simplify data exchange. This structure consists of the necessary information for a virtual commissioning such as CAD data with kinematization, physical behaviour model, control code and related documentation. The information exchange is done by means of standardised and common interfaces to be able to cover a wide range of possible application areas. Finally, the usage and the resulting benefits of this data structure will be demonstrated with the help of a practical example. In the example shown, the behaviour model and control are executed on two different machines ensuring real-time capability and forming a hardware in the loop (HIL) system. The behaviour models of different subsystems are generated in Simulink and integrated into the PLC run-time using TcCom objects in TwinCAT. The creation of control code for the plant is greatly simplified using ready-to-use code snippets, provided by suppliers in this case. With the help of the proposed data structure, the process of virtual commissioning can be simplified and thus accelerated by a reduction in complexity. No further expertise is required to use the data structure besides the basic knowledge of PLC programming, handling of CAD software and the modeling of systems for example in Simulink. However, there is still room for improvement especially in the exchange of the CAD data with a kinematization and the integration of behaviour models in a PLC.

Keywords: Virtual Commissioning, PLC, Automation, Modularity, Data Structure.

Kurzfassung

In dieser Masterarbeit wird eine Datenstruktur für die virtuelle Inbetriebnahme vorgestellt, bestehend aus CAD-Daten, Simulationsmodelle, exemplarischer Steuerungscode und dazugehöriger Dokumentation. Die virtuelle Inbetriebnahme gewinnt im Bereich der Entwicklung von Anlagen und Produktionsmaschinen stetig an Bedeutung. Dieser Zuwachs lässt sich auf die Zeit- und damit verbundenen Kostenersparnis während der Produktentwicklung und besonders der Inbetriebnahme zurückführen, welche das Ergebnis der virtuellen Inbetriebnahme ist. Jedoch hat auch dieser Prozess eine Kehrseite in Form eines gesteigerten Aufwandes bei der Modellierung einer virtuellen Anlage und die daraus resultierende Komplexität. Die Modellierung des physikalischen Verhaltens der verschiedenen Komponenten einer Anlage kann dabei, in der Regel abhängig vom Hersteller, in einer Vielzahl von unterschiedlichen Werkzeugen erfolgen. Aber auch die CAD-Baugruppen können in unterschiedlichen Dateiformaten vorliegen und sind damit keine Ausnahme von dieser Regel. Diese Anzahl von Möglichkeiten erhöht damit die Komplexität in der Integrierung der Daten enorm, jedoch sollte eine virtuelle Inbetriebnahme so einfach wie möglich realisierbar sein. Als möglicher Lösungsansatz für diese Problematik wird in dieser Thesis eine exemplarische Datenstruktur für die Vereinfachung des Datenaustausches vorgeschlagen. Diese Datenstruktur beinhaltet dabei alle nötigen Informationen für eine virtuelle Inbetriebnahme, wie die CAD-Baugruppen inklusive Kinematisierung, physikalische Verhaltensmodelle, Steuerungscode und dazugehörige Dokumentation. Mithilfe von standardisierten und international gebräuchlichen Schnittstellen kann der Datenaustausch in einem möglichst großen Anwendungsgebiet zum Einsatz kommen. Schließlich wird in dieser Thesis die Verwendung und den daraus resultierenden Nutzen der Datenstruktur anhand eines Beispiels demonstriert. In diesem Beispiel wird das Verhaltensmodell der virtuellen Anlage und die Steuerung auf getrennter Hardware ausgeführt, wobei die Kommunikation in diesem Hardware-in-the-Loop (HIL) System in Echtzeit erfolgt. Die einzelnen Verhaltensmodelle der Komponenten werden in Simulink erstellt und über TcCom-Objekte in die Laufzeitumgebung der SPS integriert. Die Erstellung der Steuerungssoftware für die Anlage wird durch die Verwendung von fertigen Code-Beispielen vereinfacht. Diese Code-Beispiele werden in diesem Fall von den jeweiligen Herstellern zur Verfügung gestellt. Mithilfe der vorgestellten Datenstruktur kann die Komplexität der virtuellen Inbetriebnahme verringert und damit der gesamte Prozess beschleunigt werden. Neben dem bereits vorhandenen Fachwissen der CAD-Planung, Modellierung von Systemen und der Programmierung einer SPS wird für die Verwendung der Datenstruktur kein weiteres Fachwissen benötigt. Jedoch kann die Datenstruktur insbesondere im Bereich des Austausches von kinematisierten CAD-Baugruppen und der Integrierung von Verhaltensmodellen in eine SPS weiter optimiert werden.

Schlagwörter: Virtuelle Inbetriebnahme, SPS, Automatisierung, Modularität, Datenstruktur.

Contents

1. Introduction

1.1. Motivation

The relevance of a virtual commissioning of a new facility is successively increasing in plant engineering [1]. One of the main advantages is the possibility to detect and correct errors in the control system as well as in the hardware at an early stage. This minimizes the costs of a possible change and avoids shutdown times of a running plant. However, one problem in performing virtual commissioning is the generation and integration of simulation models representing the real plant. While special software such as Simulink can be used for modelling, integration is a major challenge in contrast. A dedicated workflow for the integration with a defined data structure for the exchange between customers and suppliers can reduce the effort needed in a virtual commissioning.

1.2. Aim of this Thesis

Aim of this thesis is the development of a data structure and a concept for the integration of simulation models of a plant to be commissioned. These simulation models include different aspects of product development and consist of the components: CAD model, behaviour model based on physics, control code and documentation. Thereby the virtual commissioning is focused on the level of the PLC control. An existing learning factory is used as an exemplary facility for the development of this concept, where the simulation of the plant should be real-time capable.

1.3. Structure of this Thesis

This thesis is divided into several chapters and describes relevant basics, the development and use of a data structure, as well as the evaluation of the results. In the beginning the state of the art in virtual commissioning of a plant and the process of product development are explained (Chapter 2). For the purpose of developing the data structure, necessary information are identified, different methods of implementation are considered and an excerpt from available data formats are described. The data structure for a standardized exchange between suppliers and customers is then proposed and described (Chapter 3). The structure itself and the used data formats are explained and selected in this chapter. Afterwards, this data structure is used in a real-world example and its usability is tested in practice (Chapter 4). In the end, the results are summarized and evaluated in context of virtual commissioning (Chapter 5). And finally, an outlook of possible next steps and further developments are provided (Chapter 6).

2. State of the Art in Virtual Commissioning

2.1. Foundations of Virtual Commissioning

2.1.1. Introduction to Virtual Commissioning

An important aspect of the continual improvement process (CIP) in industry is the reduction of the time required for the completion of a project. This time span includes the initial requirements analysis with first customer meetings and continues through engineering and manufacturing to delivery and commissioning of a new plant. But also the increasing integration of customer wishes and technical progress require a higher flexibility of production systems and thus shorter project times [2]. As shown in Figure 2.1, up to $25\,\%$ of the project time consists of the commissioning of the plant. In the commissioning itself, up to $90\,\%$ percent of the necessary time is spent on the electrical system and the control software. Finally, up to $70\,\%$ of this time demand for commissioning the electrics and software is due to bugs in the software. This high error rate and resulting time need is often the result of sequential development of mechanics, electrics and software and a lack of communication between these departments. In many cases, these disciplines even interact during commissioning for the first time. The consequence of this lack of cooperation is usually the creation of unnecessarily complex software structures with the aim of correcting insufficient interfaces in the hardware and delays due to unnecessary adjustments in these interfaces. This complexity in turn leads to an increased probability of errors in the software and could easily be avoided. [3]

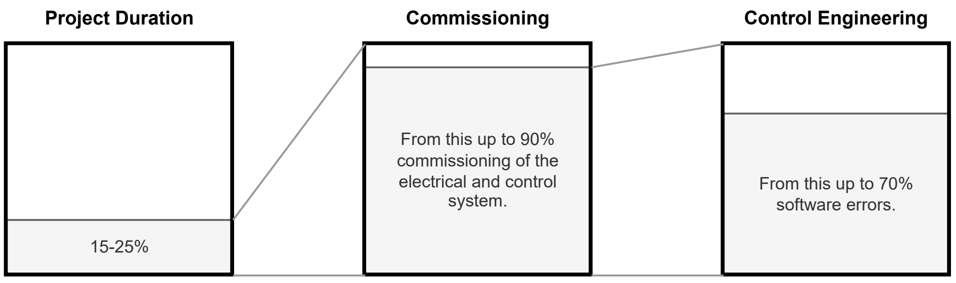

Project Duration
Commissioning
Control Engineering
From this up to 90% commissioning of the electrical and control system.
From this up to 70% software errors.
15-25%

Figure 2.1.: Needed time in a commissioning. [4]

Aiming to shorten the product development process from engineering through manufacturing to delivery, a virtual commissioning can be used. By definition, virtual commissioning describes final or preliminary tests of the control system using a simulation model with a sufficient sampling rate for all control signals [3]. This method reduces the time required for commissioning by virtually reproducing the system and validating the control system under realistic conditions. The comparison of the development of a product with and without a virtual commissioning is shown in Figure 2.2. The virtual commissioning has the drawback of an increased effort at the beginning due to the modelling of the system and the general complexity from a technical and communicative point of view [5]. However, the advantages of this method are the early detection and elimination of problems in the design and the associated safer commissioning of the real system by minimising errors [6]. In general, the modelling of the system should be done at an early stage to allow continuous optimisation and validation in shorter cycles [7].

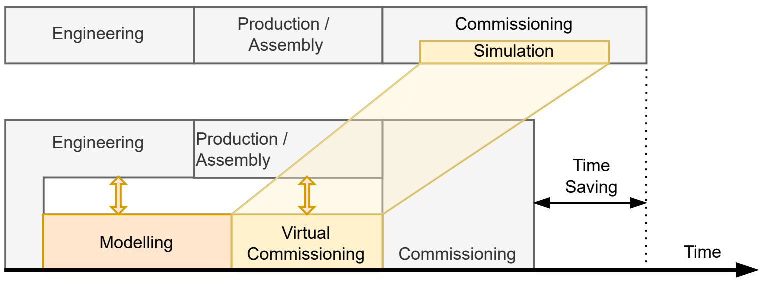


Figure 2.2.: Comparison of engineering with (below) and without (above) virtual commissioning based on [8].

2.1.2. Required Information for Virtual Commissioning

The development of a product or plant includes several stages in different engineering disciplines, which can be described according to VDI/VDE-2206 in a v-model as shown in Figure 2.3. This process starts with the definition of the business case and its specifications. Afterwards, the architecture of the product is then formed and implemented in various engineering disciplines. Finally, the properties of the finished product are evaluated and compared to the initial requirements. [9]

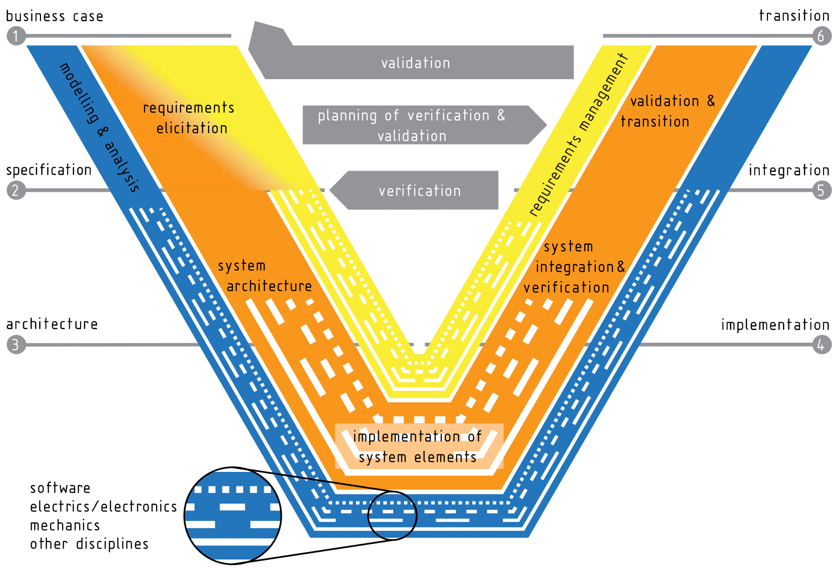


Figure 2.3.: Product development process as v-model [9].

In general, the product development as v-model can be summarised into following stages as seen in Figure 2.4: Process design, mechanical, electrical and software engineering and commissioning. These stages can partly be developed in parallel to save time and costs in the development process, but often are done in sequence. However, special attention must be paid to dependencies between the stages. The first phase of product development includes the general process of defining the objectives, constraints and interfaces. It is part of project management and must be worked out in close cooperation with the customer and possible suppliers. The next step is to develop the product's hardware usually consisting of mechanical and electrical components. The hardware must be developed in collaboration between both disciplines, since changes in the mechanics, for example, often also lead to changes in the electrics. This principle also applies in the opposite way. Parallel to the development of the hardware, the process of software development can be started already. In this way, possible limitations of the software can be identified at an early stage and possible changes to the finished hardware can be avoided. For the completion of the software, however, the hardware must already have been finalized. Only in this case testing and debugging is meaningful. The final step in product development is an optional virtual commissioning followed by an actual commissioning. Depending on the product, the start of series production or delivery to the customer takes place here.

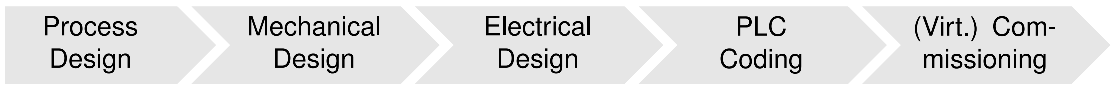


Figure 2.4.: Summarized steps in product development.

Information from all phases of product development are required for the successful execution of a virtual or a real commissioning:

Process Design: Interfaces to other parts of the plant, such as transfer points of raw and finished parts, but also maximum time limits and throughput quantities. The selection and characteristics of used sensors and actuators also belong to this area. The characteristics of the used hardware is particularly important in the creation of behaviour models, where the information is given in data sheets or already integrated in models.

Mechanical Engineering: The general structure of the mechanics and the kinematics of the individual components are defined in this step. The design of the product or plant and the used materials determine the physical behaviour and result in multiple CAD files. This information is often relevant for control systems.

Electrical Engineering: The configuration of the PLC with the used terminals is part of this section. Especially interesting for the development of the software is the mapping between the inputs and outputs of the terminals with the connected devices. Only an exactly documented mapping can avoid wrong connections in the PLC software and the resulting damage of the hardware. The documentation of the mapping and the structure of the PLC can be shown in a tabular form or in a dedicated object in the development environment of the PLC.

PLC Coding: If more complex components are used in the plant, often these are addressed via their own interface. The documentation and the knowledge of handling these interfaces is important for the creation of the software but also for the later commissioning. In the best case examples exist, which explain the handling and therefore ensure a faster implementation. But also an example PLC code of simpler components can often be advantageous.

Since a simulation model of the plant must be available for virtual commissioning, an alternative design procedure is proposed in [10]. This procedure is presented in Figure 2.5 and in general consists of four steps: process planning (1), physical device modelling (2), logical device modelling (3) and system control modelling (4). The key aspect in this procedure is the simultaneous development of the mechanical, electrical and control systems, resulting from the process planning at the beginning. The output of this procedure is a virtual plant consisting of multiple virtual devices and the control code. A virtual device has physical (mechanical properties) and logical (electrical properties) aspects of a real component, that can be developed independently of each other and finally merged (steps 2 and 3). This approach separates the development of the mechanics (step 2) from the electrics (step 3) and the software (step 4).

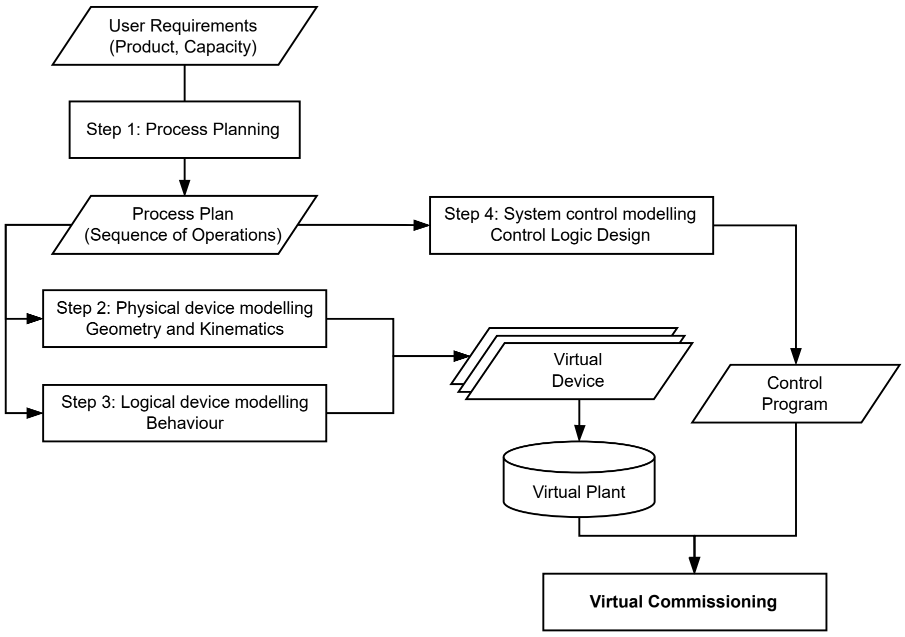

User Requirements (Product, Capacity)
Step 1: Process Planning
Process Plan (Sequence of Operations)
Step 4: System control modelling Control Logic Design
Step 2: Physical device modelling Geometry and Kinematics
Step 3: Logical device modelling Behaviour
Virtual Device
Control Program
Virtual Plant
Virtual Commissioning

Figure 2.5.: Design procedure for virtual commissioning [10].

2.1.3. Possible Configurations for Virtual Commissioning

In general, virtual commissioning at PLC level consists of two parts: the control system on a PLC and the plant to be controlled. Both parts can be either virtual in a simulation environment or real components resulting in four possible configurations for a commissioning as shown in Figure 2.6 [11]:

- The common real commissioning involves a real PLC and a real plant. This is usually the last step in the commissioning of a plant.

- A virtual commissioning can be done as a hardware in the loop (HIL) system with a real PLC and a virtual plant. This method offers advantages especially for complex systems and the second hardware avoids performance problems due to the additional computations of the plant model. Furthermore, this method is the better choice for automated testing, due to a simplified implementation of continuous regression testing. Goal of this type of testing is to detect errors and bugs due to newly created sections of code. The major drawback of this method is the additional communication between the PLC and the model. This communication should be real-time capable to allow a meaningful simulation.

- With a virtual PLC and a real plant a reality in the loop commissioning can be done. This configuration can only be used to a limited extent in the development of the control system, since the real system is required. Nevertheless, this configuration can be used to verify and finalise the control system before the plant is delivered to the customer.
- One of the most common configuration but often limited in practise is the software in the loop (SIL) commissioning using a virtual PLC and a virtual plant. The main advantage of this method is the avoidance of additional hardware for the model instance in comparison with the HIL method. Thus, in addition to the reduced cost of hardware, space in laboratories can also be saved. Finally, this results in a reduced planning effort for the laboratories and the time required for testing is shortened. One of the main requirements of the SIL system is the additional demand that the target hardware must be able to run the model of the plant in parallel with the control system.

Depending on the complexity of the control system and the desired outcome, all methods are suitable for the development and commissioning of PLC software. For example, basic functions and code sections can be tested quickly in a SIL system, thus shortening the development time as seen for example in [12]. For more complex or time-critical controls, however, testing and commissioning is often easier to perform in a HIL system as shown for example in [13]. If the hardware is already existing and the control should be tested a reality in the loop system is also feasible.

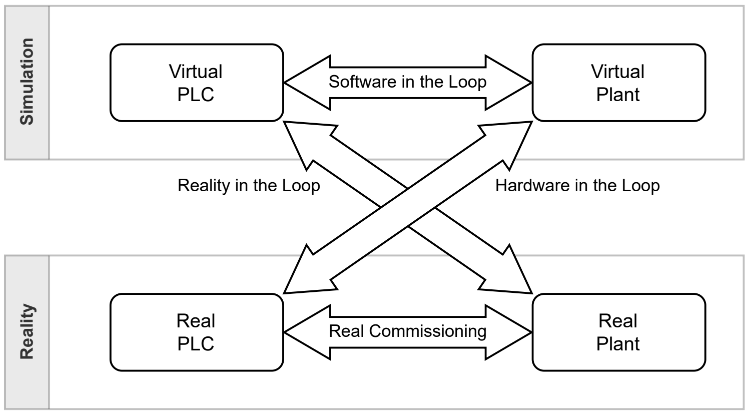


Figure 2.6.: Possible configuration for commissioning with a real commissioning and reality, hardware and software in the loop [11].

2.1.4. Implementation of a Virtual Commissioning

Testing and commissioning of the PLC software via HIL/SIL can be done in different ways, for which several practices are explained in the following lines.

Visualization in the PLC Development Environment

The human-machine interface (HMI) offers a quick possibility for testing the control software. In most cases, a graphical user interface (GUI) can be created directly in the development environment in which current values and outputs of the control software can be displayed and inputs can be set. Depending on the used system this information can be processed even in or near to real-time. In this approach, the human developer imitates the behaviour of the real plant and therefore tries to identify potential problems in the software, but due to this human interaction, fast processes and reactions can only be tested to a limited extent. However, basic code sections and functions can be evaluated during development and in the process of a virtual commissioning. The creation of a HMI is supported by many common PLC manufacturers such as Siemens and Beckhoff.

Plant Model using an Physics Engine

The next step in virtual commissioning is the use of an external physics engine such as Unity. Especially by using existing libraries and well documented interfaces a simple model can be created in a short time. In addition, the handling of the model can be simplified by using the original geometry data. A disadvantage of this method compared to the direct visualization in the PLC development environment is the requirement of an additional communication between the PLC run-time and the physics engine. Nevertheless, depending on the implementation, this procedure can also be carried out in real-time. The area of application includes HIL and also SIL systems. By using the original CAD data, a visually appealing model can be created and controlled via the PLC. This is an important advantage especially in presentations with customers or in sales, in order to be able to address people from the non-technical area as well. But also the start for new employees in the development of the control software is faster with a clear and appealing model. An example for the implementation in Unity and TwinCAT is shown in [14]. Here, a digital twin is tested and used in a HIL system, achieving a communication time of $10\,\mathrm{ms}$. The simulation in Unity achieves a step time of $5\,\mu\mathrm{s}$.

Digital Twin in a Simulation Software

The use of simulation software such as MATLAB/Simulink is particularly advantageous for complex systems or in control engineering. Complex systems can be easily created using mathematics and a GUI. Furthermore, it improves the overview and minimizes the time needed to maintain the models. In this method, the model is executed in the simulation software and for this reason also requires additional communication to the PLC run-time. This communication can be established, for example, via ready-to-use libraries as suggested in [15]. If the system is supposed to be real-time capable, special hardware or precautions are often required. This approach can also be used in HIL and SIL systems and is often found in final testing or the virtual commissioning of the software.

Visualization in a CAD Software

The solution with probably the best overview is visualization directly in the CAD software. Through this possibility, a mechanical problem can be quickly identified and solved accordingly. The company Beckhoff, for example, has recognized this opportunity and is currently developing its own product TE1130, where the visualization can be done in a common CAD software. As said the product is still in development with the planned release date in end of 2022 [16]. In any case, for each CAD tool used, a different interface depending on the manufacturer must be used to implement this possibility in practice. However, in this approach, only the visualization of the current state of the PLC is done in the CAD software and the model of the plant is not calculated.

2.2. Relevant Data Formats

2.2.1. Geometry Data and Kinematization

The branches of industry and their products are very diverse and with them the requirements for the used CAD software. For this reason, depending on the field of application, one specific CAD software may be more advantageous than another. Major CAD software vendors include Creo Elements, Autodesk Inventor, Solidworks or Siemens NX. A key feature in the design of components using CAD software is the handling with direct modelling compared to parameterized modelling. In direct modelling, the geometry is generated using constant values. Through this static processing, the different elements of the geometry remain independent of each other and the model is simplified. This type of CAD software is mainly used in the static field, such as in structural engineering. In contrast, in parameterized modelling, the geometry is generated using dependencies and features. This results in a chronic listing of the steps that lead to the desired geometry. The individual components are then dynamically connected in an assembly, whereby geometric dependencies become visible. Due to this kinematization, the components can be easily moved in the software and attached components move with them. This is particularly advantageous in the dynamic area with moving parts for example in mechanical engineering. [17]
The exchange of CAD data between different tools is usually done via neutral formats such as .step (Standard for the Exchange of Product model data) or .iges (Initial Graphics Exchange Specification). Particularly the .step format standardised in ISO 10303 has established itself as a neutral exchange format in industry not only purely for geometry but also for example for tool data [18, 19]. However, the kinematization is not saved in these formats and therefore only the geometry remains in the distribution of a component. If necessary, in this case the customer has to recreate the kinematization or the CAD exchange has to be done via alternative or native formats. In many areas and also in virtual commissioning, kinematization and thus its exchange is, however, an important prerequisite. The industry has recognized this problem of the missing interface of the kinematization and is therefore working on different solutions. For example, existing CAD data formats can be extended to support features and kinematization. For this purpose, [20] proposes an possible extension of the .step format in order to include the kinematization. However, this extension is not yet part of the standard and therefore not implemented in commercial CAD tools. A second possibility is the development of a new and neutral data format, with the goal to be able to store the geometry and the kinematization. In order to be able to use this format, an integration into existing CAD tools can be implemented or, alternatively, a conversion of the native formats with the help of translators is also an option. However, both methods are feasible but require a major effort in technical and organizational terms. The conversion of native features in the design of a part into a neutral format and back into a second CAD software is demonstrated in [21]. The same approach could be used to export the kinematics as well as the features, as

shown in [22]. As an alternative, the kinematics could be saved in an additional file and linked to the original CAD data. In this case, the CAD software would have to provide a way to save and read the kinematic separately from the assemblies. An example for this implementation is shown in [23]. Again, this method is feasible but requires a lot of effort, since a common agreement on the used data format has to be achieved and then implemented.
A promising solution is the COLLADA format (Collaborative Design Activity), which supports kinematization starting from version 1.5 [24]. The COLLADA format, released back in 2004, is based on .xml documents and is mainly used in the entertainment and gaming industry suffering from the same problem with a large number of incompatible tools. For example geometry, lighting, camera, materials and also kinematic models can be saved in this format [25]. The use in the manufacturing industry is currently not attractive, because suitable tools for the conversion to and from native formats are still missing, but the data format is standardized in ISO 17506 laying the foundation for possible translators [26]. However, the already widely used exchange format AutomationML relies on COLLADA to describe geometry data per default.

2.2.2. Behaviour Modelling

Similar to the geometry data, there is a variety of possible file formats for the description of a physical behaviour model. This is mostly dependent on the discipline and the simulation software used. For example, Simulink and SimulationX are available tools for describing physical systems in a wide range of possible application areas, whereby both tools use a native data format to describe a physical model. Alternatively, the language Modelica can also be used for the description of a system as it is universal and offers the possibility to be integrated in a wide range of different tools.
However, especially in the field of co-simulation a universal interface is required to simplify data exchange [27]. This is needed due to the combination of multiple engineering disciplines and tools for a complete simulation of the device under test (DUT). For this reason, the Functional Mockup Interface (FMI) was defined by Modelica Association already in 2010 and is currently in fact the default format for exchanging models [28]. The basis of this interface consists of C-code, which can be used universally on different devices. Currently this interface is available in version 3 and is already supported by more than 170 different tools. This great popularity is also the result of the publicly available tools for checking the compatibility of FMI objects save as Functional Mockup Unit (.fmu) files and a open source distribution of the sources. [29]

2.2.3. Source Code of PLC Projects

In the area of control engineering and automation using PLCs, the basis is mainly the international IEC 61131 standard. In the context of this thesis, part 3, which defines the programming languages, is of particular interest [30]. This standard is based to a large extent on the organization PLCopen, which has set itself the goal of increasing the efficiency in the creation of control software and to be platform-independent between different development environments [31]. Even more complex tasks like safety and motion control are part of this standardization [32]. To make this possible the PLC project with its code and libraries are saved as .xml files and therefore offering an universal interface reducing problems in data exchange. This exchange procedure with .xml files is standardized in IEC 61131-10 [33]. Most of the PLC manufacturers rely on this standard and offer interfaces for the defined programming languages. As a result, the effort required to exchange the software and thus personal costs can be minimized.

2.2.4. Documentation

Only good documentation readable by humans ensures proper and safe use of a product or plant avoiding incorrect handling. For this purpose, various file formats are available, such as: .pdf (Portable Document Format), ṁd (Markdown) or .html (Hypertext Markup Language). The individual file formats all offer their own advantages and disadvantages, whereby the selection of the suitable format depends thereby strongly on the intended use. For example, a .pdf file offers high compatibility between different devices combined with easy handling. The .md format is mainly used by software developers due to its standard integration with Git and easy handling. Formatting text is intuitive and integration of lists, images and tables is possible. In web-based help pages the .html format is often used. It can be displayed in any browser and is therefore, similar to the .pdf format, independent of the platform.
In any case, the use of plain text files for more complex documentation should be avoided. The missing possibility to embed images and to link between sections and files results in a documentation that is difficult to understand. However, simple instructions are excluded from this.

2.2.5. Exchange Libraries

When data is exchanged between supplier and customer via different tools, there should ideally be no loss of information and no information should be copied manually. This goal cannot always be achieved, but using existing and especially supported exchange formats like AutomationML increases the probability of success. AutomationML is a data exchange format that has been developed primarily for the development and commissioning of production systems. This includes the design phase, the detailed planning as well as the commissioning with system tests and installation of a production system as shown in Figure 2.7 [34]. Moreover, AutomationML is standardised in IEC 62714 [35].

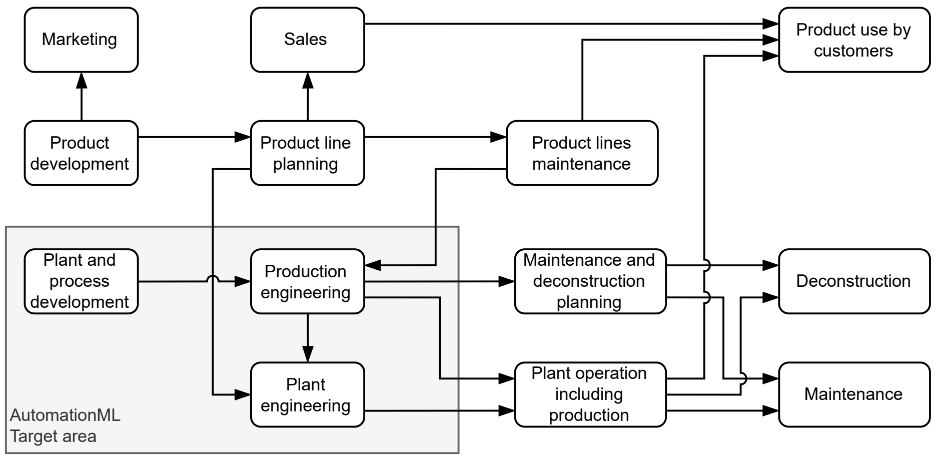


Figure 2.7.: Application area of AutomationML in the development and commissioning of a production system based on [34].

The exchange format is neutral and based on .xml files bundling them into a single format. The design follows an object-oriented approach whereby physical and logical components of a system form a data object. These objects can be hierarchically structured and normally contain the information of geometry and kinematics, behaviour model and topology (for example layout and interfaces). In addition, information of the control system (PLC code), wiring, functional descriptions but also general properties (price, weight, item number) may be represented. For a virtual commissioning, the geometry with the kinematization, the behaviour model and the code for a PLC are of particular interest. In AutomationML, the COLLADA format is used for the mechanical design (geometry and kinematization) and the PLCopen format for the PLC code. Additional information can be added as desired as in the case of behaviour models as .fmu files. This approach is for example seen in [36]. For this reason, AutomationML represents an appropriate exchange format [37]. However, as mentioned above, the lack of support for the COLLADA format from the CAD software side is still a problem. [34]

2.3. Criteria for a Data Structure in Virtual Commissioning

Based on these fundamentals of a virtual commissioning, criteria for a data structure can be identified. With the help of these criteria, the efficiency of a data structure can be determined, whereby these should be fulfilled as good as possible. The identified criteria are:

- Independent of used hardware setup (HIL/SIL).
- Contain all needed information.
- Modular layout in order to represent components of a real plants.
- High compatibility with common software tools (Data formats).
- Use of internationally standard data formats.
- Low level of additional knowledge required / Easy to use.

2.4. Summary

This chapter describes the current state of the art in the field of virtual commissioning of a PLC in combination with a production plant. With that in mind, the basics of virtual commissioning, consisting of the physical structure and the required information, are described at the beginning. This information results from all stages of product development and are available in various data formats. In the second part, relevant data formats for the identified information are described. These data formats include: CAD, behaviour model, source code of the PLC, documentation and existing exchange formats. Based on these conclusions, the development of a data structure for a modular virtual commissioning is done. Finally, criteria are defined by which a data structure for virtual commissioning may be evaluated.

3. Proposed Data Structure for Modular Virtual Commissioning

3.1. Layout of the Data Structure

Based on the previous findings, a data structure is proposed in this chapter. The main objective of this data structure is a high compatibility and a modular design in order to be able to represent the individual sub-components of a real plant. The actual layout of the data structure is kept simple and consists of a root folder with several directories for the relevant information as shown in Figure 3.1. The sub-directories contain the information of kinematization and CAD, physical behaviour model, PLC source code and documentation. An optional ReadMe file is used for general information and revision control of the structure itself. Finally the root folder is compressed into a .zip file for distribution. This structure with sub-directories increases probability to achieve a high level of compatibility among different tools and simplifies the representation of sub-components of a real plant.

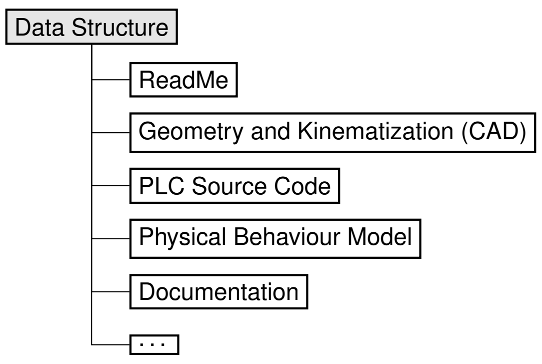
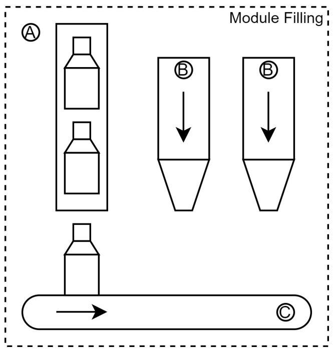
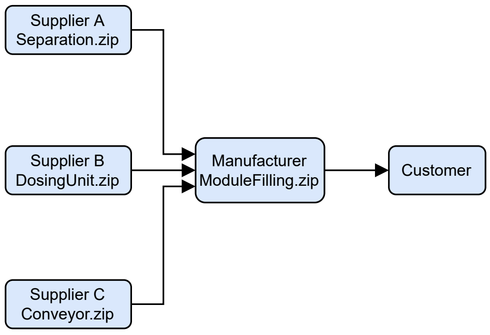


Figure 3.1.: Layout of proposed data structure. The structure consists of a ReadMe file with general information of the structure itself and several folders with the needed information of a virtual commissioning.

Due to the plain and simple structure, it can be easily extended and modular exchanged. In order to show this characteristic, an example of a filling station as part of a larger plant is considered. The design of this station is shown in Figure 3.2a and consists of a separation (A), two identical dosing units (B) and a conveyor belt (C). These sub-components are bought-in parts and are assembled in this station as the product for the customer is the filling station as a complete unit.
The starting point for the development of the filling station are the exchange packages of the three suppliers with the respective product as content. These packages are connected and expanded and finally result in a package with the entire filling station as seen by the customer. In a next step, the customer can use the filling station represented in just one data structure in planning of the remaining plant. This general procedure is shown in Figure 3.2b.



(a) Product overview



(b) File components

Figure 3.2.: Use case to show modularity of a data structure. In this case a filling station is considered consisting of a separation (A), dosing units (B) and a conveyor belt (C). The components are bought and merged into a single module.

3.2. Methods for the Selection of Data Formats

In this section, different methods for the virtual commissioning of a simple component are investigated. For this purpose, the different aspects CAD, physical behaviour model and PLC source code are considered and the suitability of different approaches are evaluated. Based on these results, the selection of data formats in the proposed data structure is afterwards made. The used software for this investigation is listed in Table 3.1.

Table 3.1.: Used software for selection of data formats.

Area	Used Software
CAD	Autodesk Inventor Professional 2022 Autodesk 3ds Max 2022
PLC	Beckhoff TwinCAT 3 Version 3.1.4024.25
Modelling	MATLAB R2020b, Simulink

The assembly from Figure 3.3 is used as an example for a real plant. Here, a PLC is controlling the speed of the disk in the left section and thus the position of the piston in the right section. The CAD assembly is kinematized and the model of the system describes the angular position of the disc and the position of the piston as a function of the current velocity.

3.2.1. Geometry Data and Kinematization

When selecting a suitable format for the CAD data, the support of the kinematics is the main focus. For this purpose, an example assembly of a movable piston is created as mentioned before and shown in Figure 3.3. The kinematization consists of a rotating motion of the disk in the left section and a translational motion of the piston in the right section. These two parts are connect by a connecting rod in the middle area, with a rotational axis in both cases. If the left disk rotates, the rotational movement is then transformed into a translational movement of the right piston.

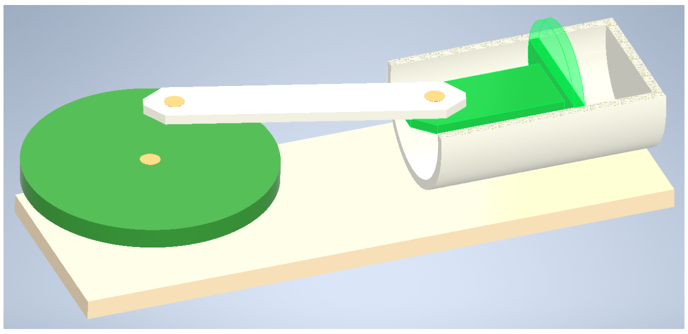


Figure 3.3.: Exemplary assembly for selection of suitable CAD formats. For this a movable piston is considered as a plant. The position of this piston is controlled using the disk on the left side.

The selection criterion for a suitable exchange format is the ability to save the geometry and kinematization of an assembly in combination with a high compatibility with different tools. As a result of these criteria, a neutral exchange format should provide an optimal solution. However, due to the fact that no default exchange format for kinematization exist, different approaches have to be tested. For this purpose, multiple methods of CAD data exchange are investigated and described in the following sections. An overview of the tested methods is provided in Figure 3.4.

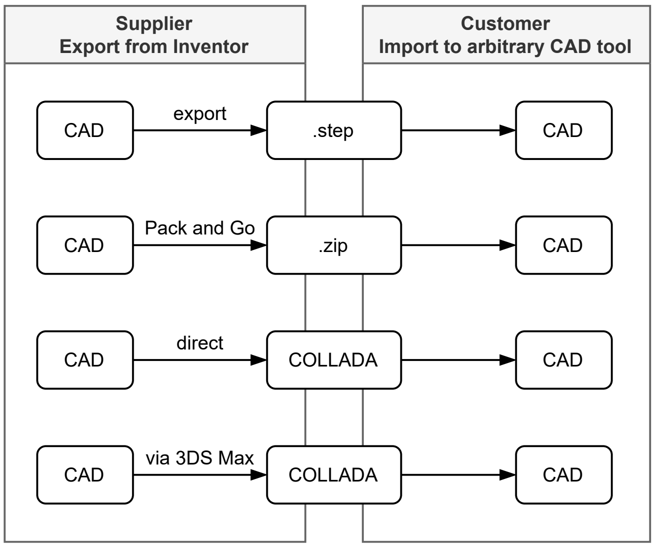


Figure 3.4.: Overview of tested approaches for exchange of geometry with kinematization. In total four approaches are tested, with the neutral .step format, the native Pack-and-Go tool and the neutral COLLADA format being investigated.

a) Inventor to .step and back

The first approach is using the .step format. This neutral format is chosen because it is already widely used for CAD data exchange. The export of the assembly into a .step file is done according to [38] via the menu File - Export - CAD Format. In the appearing window, the target format must finally be set to .step. Additional options are not needed. The import is also intuitive and can be done either in a new file or in an existing assembly, where instructions can be found in [39]. In this case the .step file is opened in a new file via File - Open. Exporting and importing .step files works without any problems, but the missing kinematic is detected when inspecting the imported assembly. However, the pure geometry is imported without errors and even the hierarchy of parts is created by an integrated conversion during import. In any case, the desired criteria are not met and thus this approach does not represent an optimal solution.

b) Inventor to Pack-and-Go and back

In the next attempt, the export and import using the Pack-and-Go tool will be investigated in more detail. Here, the entire assembly is bundled into one .zip file, allowing an easier handling in the distribution of the final data. The export of the assembly into a bundled .zip file is done according to [40] via File - Save as - Pack-and-Go. Here, in addition to the individual components, related project data is also exported. For importing back to Inventor this .zip file only has to be extracted and afterwards can be opened via File - Open. In this case the main assembly of the project can be opened afterwards and no information is lost. Because of this simple handling, exporting and importing is done in a short time and without losing any information between two instances of Inventor. However, by keeping the native file formats, the high compatibility to other CAD software is missing and as a result this way is also not an ideal solution for open data exchange.

c) Inventor to COLLADA and back

Direct export and import of COLLADA files is currently not officially supported by Inventor [41]. Freely available but also commercial 3rd party tools partly offer a possibility to export CAD data. An example of a commercial solution for exporting from Inventor to COLLADA is shown by [42] in form of a Inventor plugin. Importing COLLADA back into the native formats of Inventor is still a challenge, which can only be solved with great effort. In this case, in practice, often the recreation of the COLLADA data in Inventor is a faster solution compared to the time-consuming import. A problem of the 3rd party software is the mostly missing implementation of new versions of COLLADA resulting in the missing support of the kinematization during the export.

d) Inventor to 3DS Max to COLLADA and back

CAD data from Inventor can also be exported to the desired COLLADA format via an intermediate step using the software 3DS Max. The advantage of this compared to the previous approach is the native tool chain of Autodesk with the avoidance of 3rd party tools, but with the limitation of an export of the pure geometry. However, the problem remains similar with feasible support for export, but lack of possibilities for import of COLLADA files. For example, opening Inventor files in 3DS Max is done as described in [43]. Further, a COLLADA file can be then exported using File - Export - Export. In the same way, importing a COLLADA into 3DS Max is done via File - Import - Import without any major difficulties. However, the next step, consisting of exporting to an Inventor file from 3DS Max, is not supported [44, 45]. For this reason, this method is also not a satisfying solution.

3.2.2. Behaviour Modelling

Since the FMI format is supported by a large number of tools, it has already been established as the unofficial standard format for data exchange of models in the industry. For this reason, no other data format for describing behaviour models will be further investigated in this thesis. What is tested, however, is the practical use by means of an example with the given software. For this purpose a model of the moving piston is created in Simulink and is afterwards exported to the FMI format. The final goal of this evaluation is the integration of this model into the PLC run-time. The model describes the position of the piston and the angle of the disk depending on the velocity of the disk. The rotation speed of the disc is the output of the control on the PLC, where the position of the piston should be controlled. This model in Simulink is shown in Figure 3.5.

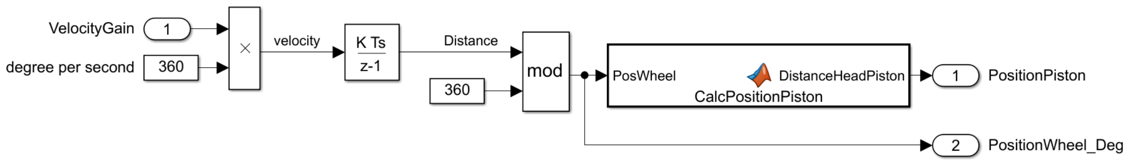


Figure 3.5.: Example for testing the behaviour model.

An overview of the investigated methods to integrate the behaviour model into the PLC environment can be found in Figure 3.6.

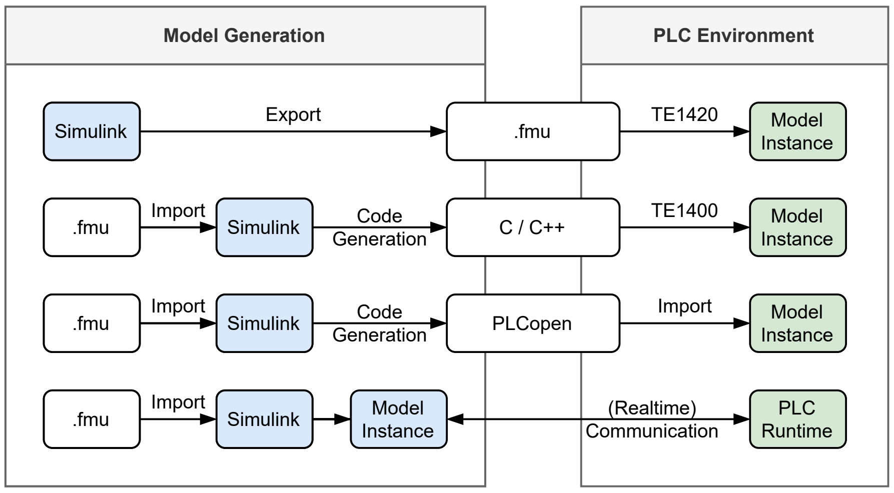


Figure 3.6.: Overview of tested methods for FMI handling. In total four approaches are investigated in order to use a .fmu model in a PLC run time. The blue blocks are required steps in Simulink and the green ones are located in the PLC environment.

a) Run FMI Model directly in TwinCAT

The first approach is also in this case the direct use of the FMI object in TwinCAT. This offers the advantage that the model can be executed directly on the PLC and thus a real-time capability is given without any additional steps. Furthermore, possible restrictions and problems can be avoided when using 3rd party tools. In order to integrate the FMI model, Beckhoff offers the product TE1420 containing the FMI interface to the run-time of a PLC [46]. With this interface it should be possible to create an TcCom object for TwinCAT directly from the FMI file. This object would then have the defined inputs and outputs and could be integrated and linked in the software of the PLC allowing to directly use the current values of the behaviour model. Since this interface is still under development at the time of writing this thesis, alternative approaches for integrating an FMI file in a virtual commissioning have to be found. This method is currently rejected due to the missing interface, but should be investigated again in near future.

b) FMI import in Simulink and export to TwinCAT

In this approach the target for Simulink of TwinCAT is analyzed. This target is part of the product TE1400 and allows the integration of Simulink models into TwinCAT by using the Simulink Coder [47]. In this process, C/C++ code is generated from the model in the first step and further transformed into a TcCom object in TwinCAT. The integration of the model in TwinCAT using this method is done similar to the example "Simple Temperature Control" from the documentation of the product TE1400 [48]. For this, the System target file must be set to "TwinCatGrt.tlc" in the code generation settings of Simulink. The remaining settings of the code generation can be kept, but the solver must be set to the type fixed-step with the step size equal to the task time of the PLC. After successful code generation the TcCom object must be signed as described in [49]. Afterwards it can be included and used in TwinCAT. In this evaluation, first the original model of Simulink is exported and then in the same way the FMI object. The export of the original Simulink model works without problems and a TwinCAT object can be created. In the same way, the model with the FMI object is processed, but In contrast the export of the object fails, due to missing support of the special FMI block in the code generation of Simulink. As a result, this method is not a suitable solution for the given software in virtual commissioning. However, if a supported model is available in Simulink the code generation can be a useful way to include it in TwinCAT.

c) FMI import in Simulink and export to PLCopen

Similar to the previous approach, the code generation of Simulink is further investigated here, but with the difference of the target platform. While in the previous approach C/C++ code was generated from the original model, here it will be exported directly to the PLCopen format. This can be then easily integrated and used in TwinCAT in the next step. The export to PLCopen format via Simulink PLC Coder is done analog to the example "Generate Structured Text Code for a Simple Simulink Subsystem" [50] also first for the original model and then for the model with the FMI object. When using the PLC coder, attention must be paid to the supported blocks used in the model. For example, continuous blocks can only be used in some cases and must therefore be replaced by discrete alternatives. An example of this is a continuous transfer function which is not supported and must therefore first be discretized. The used time-discrete model can be exported without major issues similar to the method before. Additional settings besides the fixed-step solver are not necessary and the model can now be included and used as function block in TwinCAT. As already suspected, the export of the model with the FMI object is not possible. As before, the FMI block is not supported in the code generation of the Simulink PLC Coder, which can also be seen in the list of supported blocks [51]. Like the previous approach, this solution is also rejected for this reason.

d) FMI import in Simulink and communication with TwinCAT

This approach differs from the previous ones by the target of the model run-time. Compared to the other approaches, it is not located directly on the PLC, but remains in Simulink on the engineering system. However, this also results in additional communication between the PLC and the used engineering system. For time-critical applications, real-time capability for this engineering system is also recommended by means of using special hardware and software. In this case the communication to the PLC is done via the ADS interface of Beckhoff. This communication is integrated via special blocks in Simulink and is here done via the block TwinCAT Symbol Interface [52]. These blocks are part of the product TE1410 which contains the interface to Simulink [53, 54] After the configuration of the interface block the PLC variables are available as source/sink in Simulink and can be connected to the model. The solver must also be set to fixed-step again with the same step size as the task time of the PLC. With this method the model can be used in its original form and exported as FMI object. Thus inputs can be read from the PLC and outputs can be written. In other words, this method is not an ideal or real-time capable solution, but it provides a feasible way to integrate FMI objects into TwinCAT and thus perform a virtual commissioning.

3.2.3. PLC Code

The PLCopen format already represents a standardized interface for the exchange of PLC code, since the format is well established in the industry and defined by an international standard. For this reason, the review of alternative formats for data exchange can be skipped and only the implementation of the PLCopen format in TwinCAT needs to be examined. The export and import is tested using again the moving piston. The aim of the PLC is to set the velocity of the disc in order to control the position of the piston. This is done by defining variables for speed and position of the piston. Additionally, a variable for the angular position of the disk is defined, which can be used in a visualization. Depending on the set velocity, the program then calculates the position of the piston. The code is listed in the PLCopen format in Source Code 3.2.1.

Source Code 3.2.1: Example Piston as PLCopen-xml.

```xml
<?xml version="1.0" encoding="utf-8"?>
<project xmlns="http://www.plcopen.org/xml/tc6_0200">
  <fileHeader companyName="Beckhoff Automation GmbH" productName="TwinCAT PLC Control" productVersion="3.5.13.21"
      creationDateTime="2022-08-21T13:19:37.4859706" />
  <contentHeader name="mainPLC" modificationDateTime="2022-08-21T13:19:37.487966">
    <coordinateInfo>
      <fbd>
        <scaling x="1" y="1" />
      </fbd>
      <ld>
        <scaling x="1" y="1" />
      </ld>
      <sfc>
        <scaling x="1" y="1" />
      </sfc>
    </coordinateInfo>
    <addData>
      <data name="http://www.3s-software.com/plcopenxml/projectinformation" handleUnknown="implementation">
        <ProjectInformation />
      </data>
    </addData>
  </contentHeader>
  <types>
    <dataTypes />
    <pous>
      <pou name="MAIN" pouType="program">
        <interface>
          <localVars>
            <variable name="PosDegree" address="%I*">
              <type>
                <REAL />
              </type>
              <initialValue>
                <simpleValue value="0" />
              </initialValue>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> in deg</xhtml>
              </documentation>
            </variable>
            <variable name="PosPiston" address="%I*">
              <type>
                <REAL />
              </type>
              <initialValue>
                <simpleValue value="0" />
              </initialValue>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> in mm</xhtml>
              </documentation>
            </variable>
            <variable name="velocity" address="%Q*">
              <type>
                <REAL />
              </type>
              <initialValue>
                <simpleValue value="0" />
              </initialValue>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> in deg/s</xhtml>
              </documentation>
            </variable>
            <variable name="cycleTime">
              <type>
                <REAL />
              </type>
              <initialValue>
                <simpleValue value="0.01" />
              </initialValue>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> in sec</xhtml>
              </documentation>
            </variable>
          </localVars>
        </interface>
        <body>
          <ST>
            <xhtml xmlns="http://www.w3.org/1999/xhtml">// Position of Disc
PosDegree := PosDegree + velocity*cycleTime;
WHILE PosDegree &gt; 360 DO
  PosDegree := PosDegree -360;
END_WHILE


// Position of Piston
PosPiston := 13 + COS(PosDegree*pi/180)*9 + SQRT(EXPT(25,2)-EXPT((SIN(PosDegree*pi/180 )*9),2));

</xhtml>
          </ST>
        </body>
        <addData>
          <data name="http://www.3s-software.com/plcopenxml/interfaceasplaintext" handleUnknown="implementation">
            <InterfaceAsPlainText>
              <xhtml xmlns="http://www.w3.org/1999/xhtml">PROGRAM MAIN
VAR
  PosDegree AT %I*   : REAL  := 0;    // in deg
  PosPiston AT %I*   : REAL  := 0;    // in mm
  velocity AT %Q*    : REAL  := 0;    // in deg/s

  cycleTime        : REAL := 0.01;    // in sec
END_VAR
</xhtml>
            </InterfaceAsPlainText>
          </data>
          <data name="http://www.3s-software.com/plcopenxml/objectid" handleUnknown="discard">
            <ObjectId>05518f30-63f5-43e5-a500-2e4c842868d1</ObjectId>
          </data>
        </addData>
      </pou>
    </pous>
  </types>
  <instances>
    <configurations />
  </instances>
  <addData>
    <data name="http://www.3s-software.com/plcopenxml/projectstructure" handleUnknown="discard">
      <ProjectStructure>
        <Object Name="MAIN" ObjectId="05518f30-63f5-43e5-a500-2e4c842868d1" />
      </ProjectStructure>
    </data>
  </addData>
</project>
```

TwinCAT 3 to PLCopen

The export and import of PLCopen objects is supported in TwinCAT and is done without difficulty, whereby instructions for this can be found in [55]. Therefore, using the PLCopen format is a suitable solution for data exchange in this case.

3.3. Selected File Formats

As already mentioned in Section 2.2, a wide range of possible data formats exists to represent the required information for virtual commissioning. The focus in the selection of the used formats, should be on the highest possible compatibility between different tools. Only through this approach the format can become accepted in the industry. In this section, the selection of suitable data formats is done.

3.3.1. Geometry Data and Kinematization

For a loss-free exchange of CAD data, the information of the kinematization of the assemblies must be preserved in addition to the raw geometry. As mentioned earlier, this is a major problem in practical use and therefore the COLLADA format would be an ideal solution. At the moment, suitable tools for conversion are missing or do not support the current version of COLLADA implementing the kinematization. As a result, using the COLLADA format is the optimal solution in theory but in practice native CAD formats are proposed to be the better choice if the kinematization should be preserved. Which CAD tool and further which format is finally used has to be defined between the customer and supplier. Alternatively, neutral formats like .step can be used, but with the disadvantage of missing kinematization. For these reasons, although a solution exists for the exchange of CAD data, it is not sufficient in the field of virtual commissioning. For example, Inventor offers a quick way to exchange data via the Pack-and-Go tool [56]. In this case, the entire geometry, dependencies and also materials of an assembly are bundled in one .zip file, which also simplifies the exchange. A similar function is also available in Solidworks [57]. It should be noted, that although the two functions have the same name, they are not compatible with each other.
An overview of the evaluation of the different approaches can be found in Table 3.2.

Table 3.2.: Results of tested methods in CAD exchange evaluated for their usability from bad (○○○) to good (●●●). This table shows the characteristics of the tested methods with respect to save geometry in a CAD file, kinematization of an assembly, a wide support for different tools and an overall evaluation of the usability for a virtual commissioning.

Method	Geometry	Kinematization	high compatibility	Usability
a) Using .step	yes	no	yes	●●○
b) Using native Pack-and-Go	yes	yes	no	●●○
c) Using COLLADA directly	-	-	-	○○○
d) Using COLLADA indirectly	yes	no	no	●○○

3.3.2. Behaviour Modelling

The modelling of the physical behaviour can also be done using various tools. In contrast to CAD data, a neutral and established format for data exchange already exists here: the FMI. A growing number of tools support this format, making it a good choice in a modular virtual commissioning process. In the academic community, but also in industry, Simulink is often used for modelling. This tool is very popular mainly because of its flexibility, and supports the import and export of .fmu files in versions 1 and 2. Instructions for the export can be found in [58] and for the import in [59]. The summary of the evaluation of the tested approached can be found in Table 3.3.

Table 3.3.: Results of tested methods in integrating behaviour model evaluated for their usability from bad (○○○) to good (●●●). This table shows the results of different approaches to include the model from Simulink or as .fmu file in TwinCAT and afterwards using it in a virtual commissioning. The evaluation is based on the feasibility of the approaches.

Method	Working with Simulink model	Working with FMI model	Real time	Usability
a) Model directly in TwinCAT	-	(yes)	(yes)	(●●●)
b) Model to TcCom-Object	yes	no	yes	●○○
c) Model to PLCopen	yes	no	yes	●○○
d) Run Model in Simulink	yes	yes	no	●●○

3.3.3. PLC Code

The exchange of PLC code is almost no problem in practice. This is thanks to the standardization of automation engineering using PLCs, which also describes the possible programming languages and the exchange format as .xml files. In addition to the language basis, more complex functions such as function blocks for movements are also part of the standard and thus easily exchangeable. Thanks to the international validity, many manufacturers rely on this standardization and offer converters to and from the PLCopen format.

3.3.4. Documentation

For the exchange of documentation, the .pdf format has already been proven in practice. One of the reasons for this is the exact same layout of the document regardless of the operating system or a printout on paper. This ensures that the document is available to the reader in exactly the same form as it was when it was created.

3.3.5. Overview of Selected Data Formats

An overview of the selected data formats is found in Table 3.4.

Table 3.4.: Chosen file formats for the proposed data structure.

Discipline	Information	Choosen File Format
Mech. Engineering	CAD (pure geometry)	Neutral formats like .step
	CAD (with kinematics)	Native formats like .iam or COLLADA
	Physical Behavior	FMI as .fmu
Elec. Engineering	PLC layout	Native formats or .pdf
	List of used inputs and outputs	Native formats or .pdf
Coding	PLC Code	PLCopen as .xml
General	Documentation	.pdf

3.4. Workflow of the Proposed Data Structure

The workflow when using the proposed data structure consists of two main parts: generating the data (export) and using the data in a virtual commissioning (import). The export and import respectively consist of the subcategories of the CAD data, the behaviour model and the control code. The whole workflow is shown in the overview in Figure 3.7.
Compared to the import, the export of the data is more straightforward and thus easier to accomplish. The data can usually be generated in just a few steps, with CAD data being the exception to this general rule. In principle, the greatest effort is required when using the data structure in the field of CAD data, due to the lack of an interface for saving the kinematization of an assembly. If only the geometry should or can be transferred, a neutral format like .step or .iges is recommended, which are supported by most of the CAD tools. Until the COLLADA format or alternatives are established in industry, exporting kinematization is proposed to be done in native CAD formats. The choice of the used software should be made in a close cooperation between the supplier and the customer and thus depends on the specific application. In comparison, the export of the behaviour model, the control code of the PLC and, if necessary, a technical documentation do not cause major problems and are supported by the majority of available software.
The process of importing the data, in contrast to exporting, is more complex, where the individual steps strongly depend on the used target system. In the case of CAD data, it is necessary to distinguish between three possible approaches: the assembly is not kinematized (for example .step), the assembly is kinematized in neutral format (for example COLLADA) and the assembly is kinematized in a native format (for example .iam). The native format provides the least effort for integration, followed by plain geometry without kinematization (depending on the complexity of the assembly). The greatest effort represents the import of a COLLADA file, due to the lack of conversion tools. The import of the PLC code is done in the majority of PLC systems without any difficulties thanks to the international standardization of the programming language. As a result sample code can be integrated into an existing project fast and without any difficulties. However, with the behaviour model, a dependency to the used software is once again recognizable. In the best case, the FMI object can already be executed directly in the PLC and linked to the inputs and outputs of the hardware. Alternatively, the model can be executed in software for simulations, which again communicates with the PLC. If virtual commissioning is performed using this method, special hardware must often be used to ensure real-time capability. However, this requirement only applies to time-critical processes.

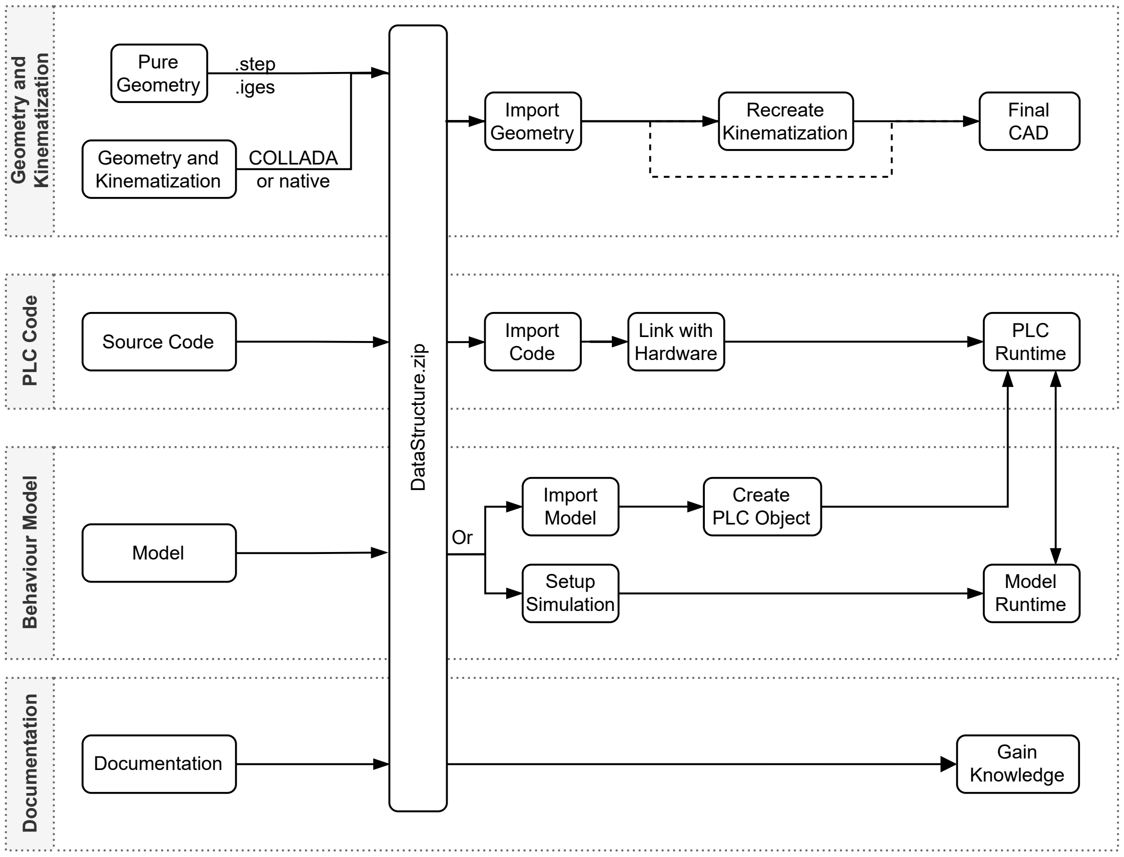


Figure 3.7.: General workflow of proposed data structure. In this picture the most important aspects for the export and import of the data structure are shown and divided into the corresponding categories.

3.5. Summary

This chapter describes the layout and use of a modular data structure. The field of application includes the data exchange for virtual commissioning, where the control is done via a PLC. The foundation of this structure is a single root folder containing the CAD data (native format or COLLADA), the behaviour model (FMI), the control software (PLCopen) and the associated documentation (.pdf). Compressing this structure into a .zip file simplifies even more the distribution and sharing. In the case of CAD data, no optimal solution has been found yet for the selection of data formats, since kinematization is currently only supported with major problems. However, various approaches to solve this problem are in development but still have to prove their usability in practice. The selection for the format for the behaviour models is made on the already widely used and standardized FMI interface and for PLC code in the also standardized PLCopen format. Nevertheless in the case of Beckhoff the integration of a FMI model in a PLC run-time is still under development and therefore alternatives must be found at the moment. Finally, the general workflow in using this data structure is explained. Thereby the general steps in exporting the data and the following import are examined and described in more detail.

4. Exemplary Application using the Proposed Data Structure

4.1. Introduction

The practical use and the individual steps in the implementation of the proposed data structure are shown by means of an example with a Teaching Factory representing a real plant. The aim of this plant is to get familiar with automation technology with the help of a PLC and its programming. It is modular designed in order to provide individual stations with defined learning goals, varying from basic topics like digital and analog signals to also more complex tasks like motor control and serial communication. Furthermore, human interaction and safety are included learning contents. An overview of the whole plant is shown in Figure 4.1.

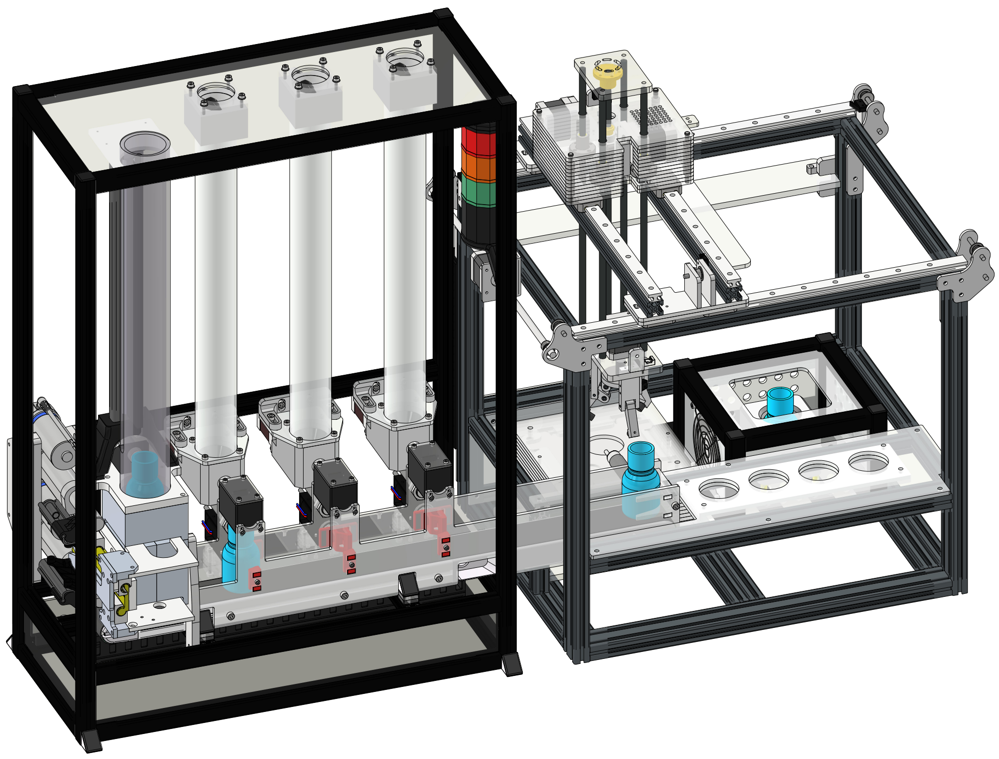


Figure 4.1.: The used Teaching Factory. On the left is the module Separation followed by the Conveyor Belt with three Dosing Units. The right half contains the Cartesian Gripper with a Load Cell (left), Thermal Processing (rear right) and an output storage (front right). For a better overview, further attachments and covers are hidden in this picture.

4.1.1. Module Separation

The first module offers a fast introduction to the programming of a PLC. Here, the first contact with a PLC can be made and at the same time digital signals for input and output can be used. The task in relation to the Teaching Factory is the separation of container from an input storage to the following conveyor belt. The mechanical design of this module is vertically oriented and consists of the input storage in the upper area and the separation in the lower area. The mechanical layout of the module and relevant components for the control are shown in Figure 4.2. On each of the lower three storage positions a capacitive proximity sensor with a digital output is located. This sensor can be used to detect a container on the corresponding position, where in this case the output signal is set. Above and below the lowest position is a piston attached, which is needed for the actual process of separation. These pistons are moved by a linear motor and controlled by a digital retract or extend signal. In the extended state, the containers can pass the piston undisturbed, while in the retracted state they are stopped at the piston.

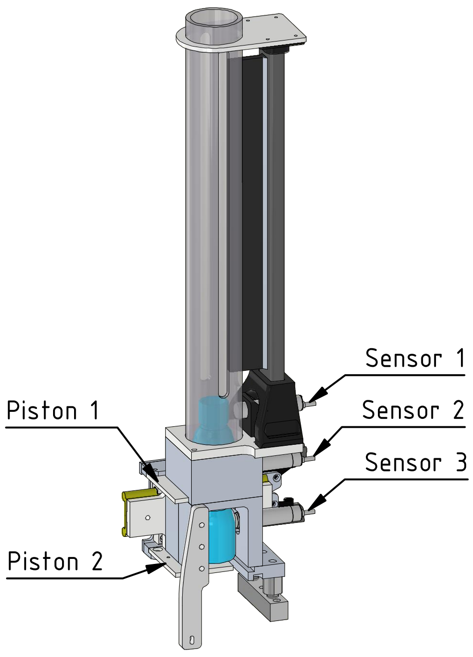


Figure 4.2.: Overview module Separation with the three proximity sensors and the two pistons realizing the separation process.

4.1.2. Module Conveyor Belt

This module is the user's first introduction to the control of electric drives. Using a DC motor with its comparably simple design allows the theoretical background easier to understand and the main focus can lay on the controlling. In addition, an encoder is attached to the motor axis to determine the actual speed and position of the motor. Using this position measurement, an optional servo control of the conveyor belt can be implemented in a further step and thus enable an exact positioning. Moreover, through the feedback of the actual speed of the motor, an undesired stop can be detected immediately. In a second step, the knowledge of motor control is further expanded with stepper motors.

The conveyor belt is the main part of the filling process and is divided into three sections: input, filling (three dosing units) and output. At the beginning of the conveyor belt, the containers are passed from module Separation. After that, the containers go through three identical dosing units used for filling, each consisting of a helix driven by a stepper motor. In order to simplify the filling process of a container, a stopper and a proximity sensor are located under each dosing unit on the conveyor belt. The stopper normally locks the container and can be retracted via a digital signal. The proximity sensors are identical to those of the module Separation and provide a digital output signal when a container is detected. This combination of sensors with the stoppers and the conveyor makes it possible to precisely place a container under a dosing unit. At the end of the conveyor belt, the containers are passed on to the next module, where a proximity sensor is also placed at the defined pick-up position. In this example, the user has to create the control of the conveyor belt in the first step. After that, the software is extended with the digital signals of the stoppers and proximity sensors. Finally, the control for the dosing units has to be implemented, where large parts of the control are identical to the conveyor belt. The mechanical layout and relevant components are shown in Figure 4.3.

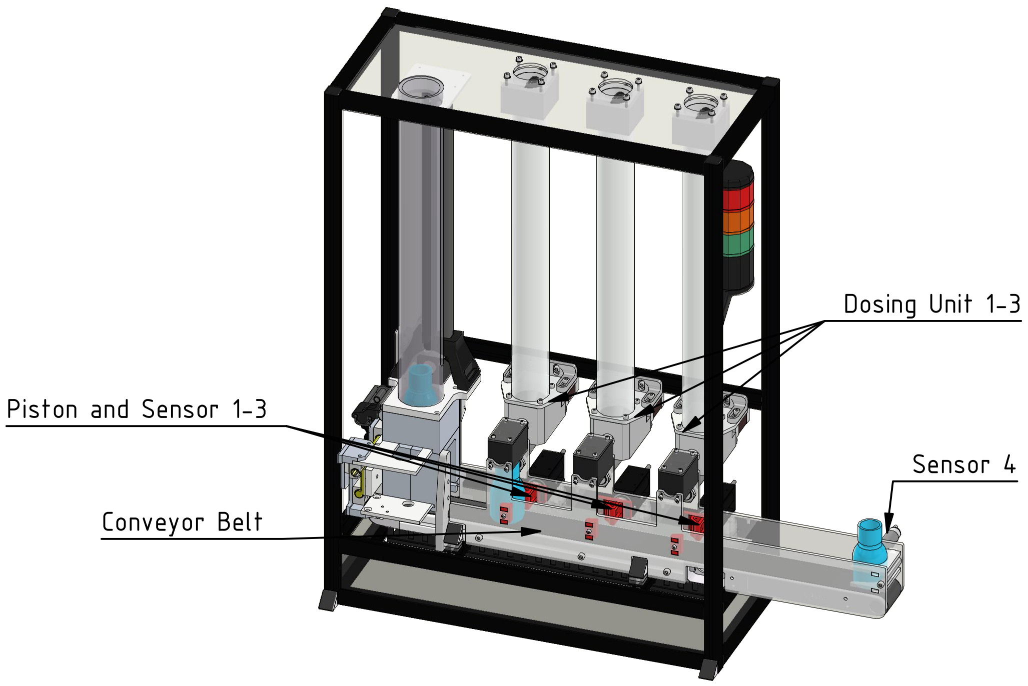


Figure 4.3.: Overview module Conveyor Belt. On the left side the module Separation is shown. In the middle the conveyor belt is located with the three dosing units for filling. On the right side the pick-up position to the next module is shown at sensor 4.

4.1.3. Module Cartesian Gripper

In this module, the subject of controlling a stepper motor is further discussed and expanded. Topics such as moving to a specific position and the zero point can be covered in this module. The mechanical layout itself consists of a gripper and three axes for movement in the X, Y and Z direction. The axes are controlled by a stepper motor and have two limit switches for safety purposes. The gripper itself is also driven by a stepper motor including two limit switches. The mechanical layout of the module and relevant components for PLC coding are shown in Figure 4.4. The cartesian gripper is the main component following the filling of the containers and is responsible for the further transport of these to the final modules. Therefore, the gripper has to pick up the containers from the conveyor belt and place them sequentially in the modules Load Cell and Thermal Processing. Finally, the container has to be placed in the output storage. In order to ensure sufficient positioning of the containers in the modules, the PLC controller must be able to position the gripper precisely. A correctly set reference point for each axis is an essential requirement for this.

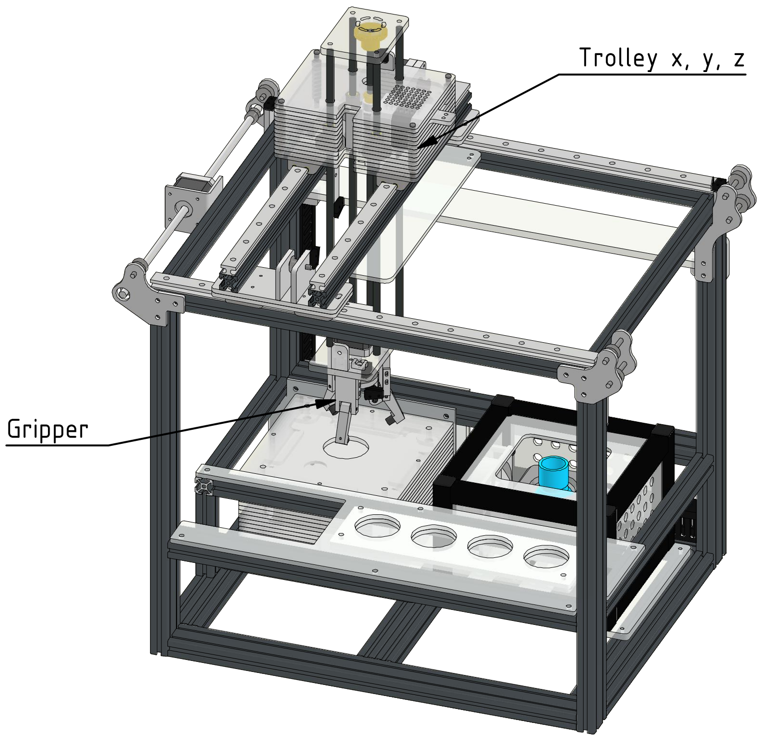


Figure 4.4.: Overview module Cartesian Gripper with the following modules and the trolley. In the lower left corner the container are picked up from the conveyor belt.

4.1.4. Module Load Cell

In this module the filling level of a single container is determined by means of a weight measurement. A laboratory scale is used as load cell, which sends the current measurement result as text via a serial interface and allows the user to get in touch with communication with external devices. As already mentioned, the container positioning is done by the cartesian gripper. The layout of this module is shown in Figure 4.5. The task of the user is to establish communication with the load cell via an RS-232 interface. Furthermore, the scale must be calibrated by sending a defined command and the received messages must be interpreted. Only if the filling level is correct, the containers are passed to the module Thermal Processing.

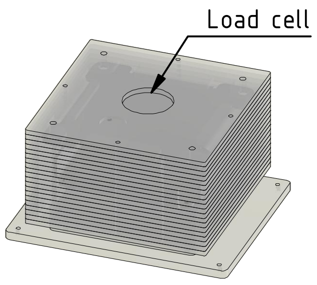


Figure 4.5.: Overview module Load Cell. The containers are placed in the middle of the platform.

4.1.5. Module Thermal Processing

After checking the filling level, a thermal treatment of the containers is done in this module, using four heating cartridges and two thermocouples. These components are used to raise the temperature of the containers to a defined value. The interface for the heating cartridges and the thermocouples are analog signals and thus the user is able to work on this module at an early stage, although it is the last step in the manufacturing process. The structure and the relevant components are shown in Figure 4.6. As mentioned earlier, the task of the user here is to use the analog signals to finally establish a temperature control. In this context, timer components may also be used, for example, to maintain the temperature for a defined period of time.

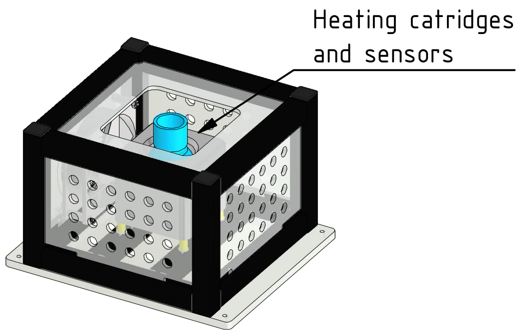


Figure 4.6.: Overview module Thermal Processing. The heating cartridges, thermocouples and the container are located in the central block. For safety purpose and in order to cool the block down fans are mounted on the side.

4.1.6. Setup for Testing

A list of the used software for this example can be found in Table 4.1.

Table 4.1.: Used software in the example Teaching Factory.

Domain	Software	Comments
CAD	Autodesk Inventor	Version: Professional 2022
Behaviour Modelling	MATLAB / Simulink	Tools: Simulink Coder
PLC	Beckhoff TwinCAT 3	Tools: TE1400, TE1410

The physical setup for the virtual commissioning consists of two real-time capable industrial PCs (IPC) on which the TwinCAT run-time is executed. The model of the virtual plant is calculated on the first IPC and the control software to be tested is executed on the second, thereby creating an HIL system. The communication between the two IPCs takes place in real-time via the EtherCAT Automation Protocol (EAP) [60]. The TwinCAT projects for both IPCs are written on an engineering PC and then loaded onto the two IPCs. This physical setup is shown in Figure 4.7.

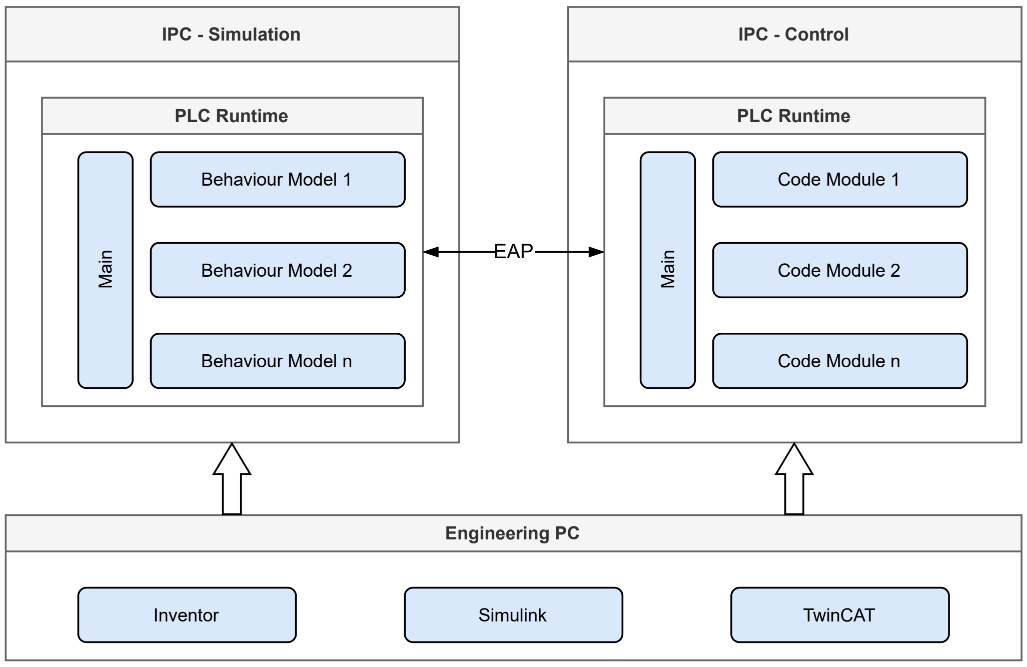


Figure 4.7.: Hardware setup for this example as HIL system. It consists of two real-time capable IPCs running the plant model and the PLC control and a third engineering PC. The communication between the IPCs is done vie EAP in real-time.

The integration of the model description from a .fmu file into a PLC project should be done using a own product called TE1420 for a Beckhoff PLC [46]. With the help of this product a TcCom object is created, which can then be integrated in TwinCAT. The inputs and outputs from this object are the same as the description from the original .fmu file. At the time of writing this thesis, the product TE1420 is still in development and therefore cannot be used for this example. As an alternative, code generation from Simulink and the product TE1400 is used, in order to create a TcCom object directly from the origin model in Simulink [47]. Thus, the generation of this TcCom object is slightly different in the alternative, but the further use is identical. A limitation of this alternative is the mandatory use of Simulink for the model description. The comparison between the ideal way and the alternative code generation is found in Figure 4.8.

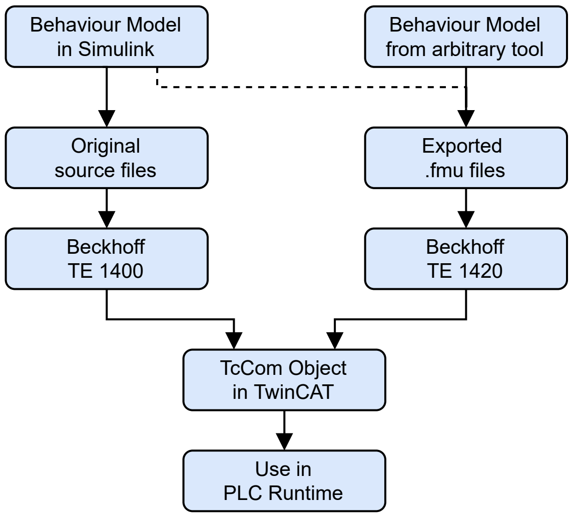


Figure 4.8.: Comparison of the integration of the physical models in TwinCAT. Instead of using a .fmu file to create a TcCom object, the original source from Simulink is used.

4.2. Creation of the Data Structure - Workflow of a Supplier

For exporting the CAD data, this example uses the native format of Inventor for assemblies with kinematization. That is based on the assumption that the transmitter and receiver of the data structure both use Inventor. The structure of the assembly corresponds to the desired kinematization, taking into account required degrees of freedom. If the assembly is purely static and thus no kinematization is required, the .step format is used for exchange, also simplifying the CAD hierarchy, whereby logically linked components are bundled into individual sub-assemblies. The export to the .step format is done as described in [38] and to the native exchange format as shown in [40]. As already mentioned, in this example the original models from Simulink are used as an alternative for the integration into TwinCAT. However, the behaviour model is exported as intended as a .fmu file and included in the data structure. This is done according to [58], using a fixed-step solver with the step size of $10\,\mathrm{ms}$ corresponding to the cycle time of the PLC. The interface of the models reproduces the signals of the real hardware and describes the given system. In addition, some purely virtual variables are used, which are useful for higher-level control and an optional visualization. The level of detail can be arbitrarily precise, whereby the increasing complexity of the required calculations must be taken into account. The source code of the PLC is exported to the PLCopen format for exchange as described in [55].

4.2.1. Module Separation

CAD Data

The CAD model is built based on the desired kinematization of the pistons. In this case, the two pistons each represent a separate sub-assembly to allow easier maintenance and use. As mentioned earlier, the assembly is exported in the native format of Inventor based on the desired kinematization and bundled in a .zip file.

Behaviour Modelling

The behaviour model in this case is created in Simulink and takes into account the influence of gravity on the containers in the incoming storage. Also taken into account is the influence of the actuators on the selected position of the containers in the storage and the resulting signal from the sensors. The entire model with the inputs and outputs is shown in Figure 4.9. For this module, the interface consists of digital outputs for moving the two pistons and digital inputs for each of the three proximity sensors. Furthermore, additional signals are needed for the creation and deletion of the containers. These signals are purely virtual and are thus not connected to the hardware, but are required only in the logic of the module.

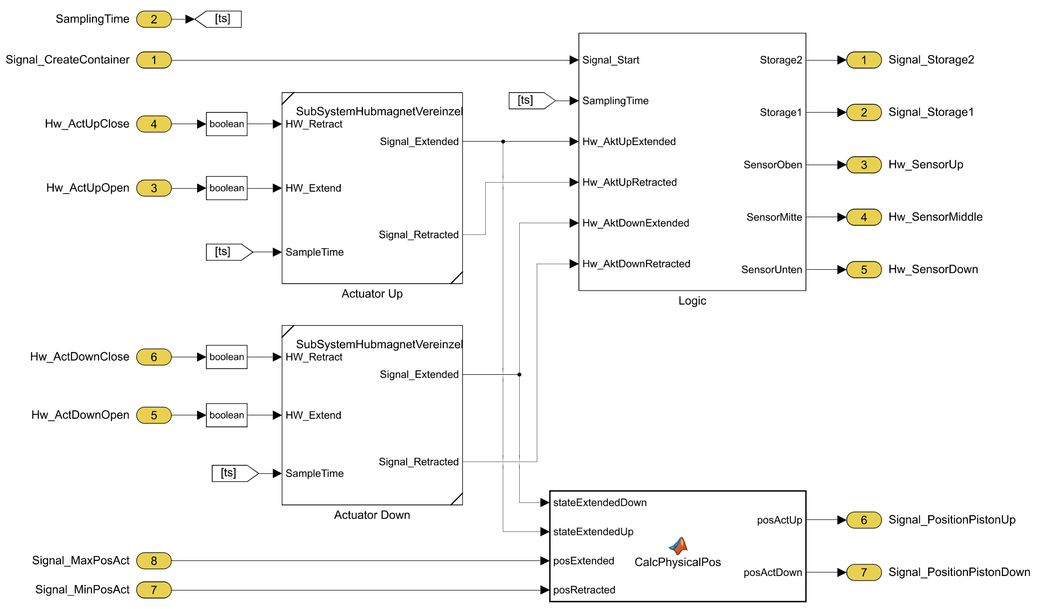


Figure 4.9.: Behaviour model of module Separation describing the physical pistons and the logic of the input storage.

PLC Code

For the exemplary control of the separation a function block is created. By structuring the control as a function block, an instance of the separation can easily be created and used in a higher-level controller. This code basically consists of a state machine in which the two pistons are controlled depending on the current state and the sensor inputs. The resulting .xml file is listed in Source Code A.0.1.

Resulting File

The generated information of the CAD model, behaviour and control are now bundled in the proposed data structure from Chapter 3. The resulting structure for this module is shown in Figure 4.10.

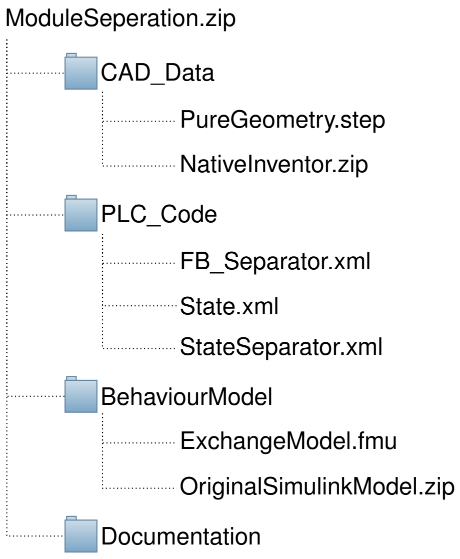


Figure 4.10.: Data structure of module Separation consisting of CAD data as pure geometry and including kinematization in a native format, PLC code and the behaviour model as .fmu and original Simulink files. Additional documentation for this module is not needed resulting in an empty directory.

4.2.2. Module Conveyor Belt

CAD Data

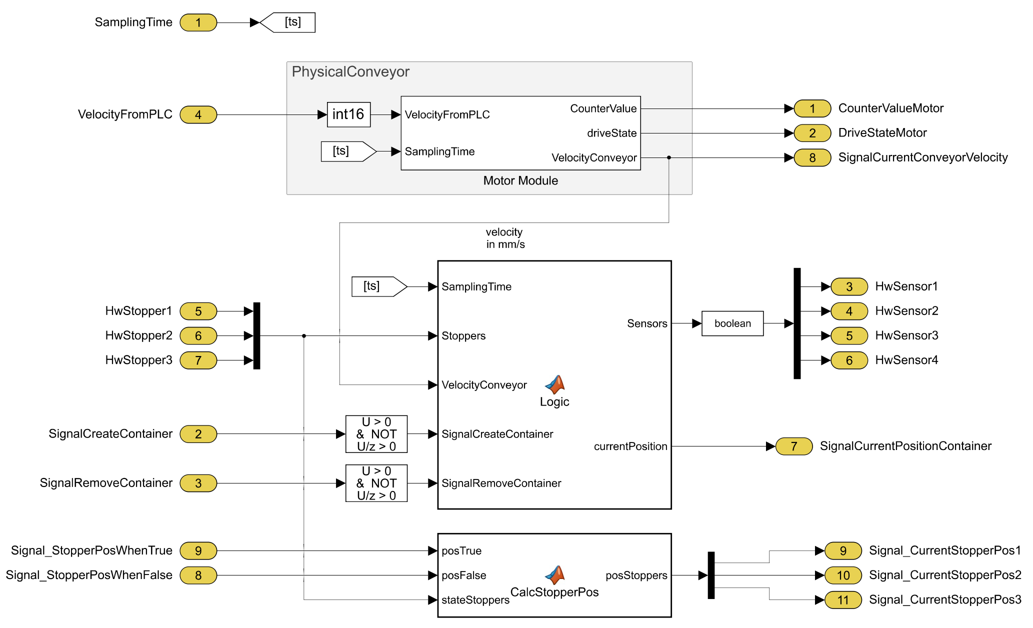
In this module the CAD model of the conveyor belt itself is provided by the manufacturer and integrated in the assembly. The three sliders of the stoppers form again a sub-assembly to represent the kinematization. The conveyor itself does not need any additional kinematization and the remaining components such as attachments and sensors are bundled into a second assembly to avoid any obstacles to the kinematics. The three dosing units are also represented as a own sub-assembly. Since the kinematization of the pistons are supposed to be exported in this example as well, the native CAD format is kept. Alternatively, a pure exchange of the geometry with an .step file can be done.

Behaviour Modelling

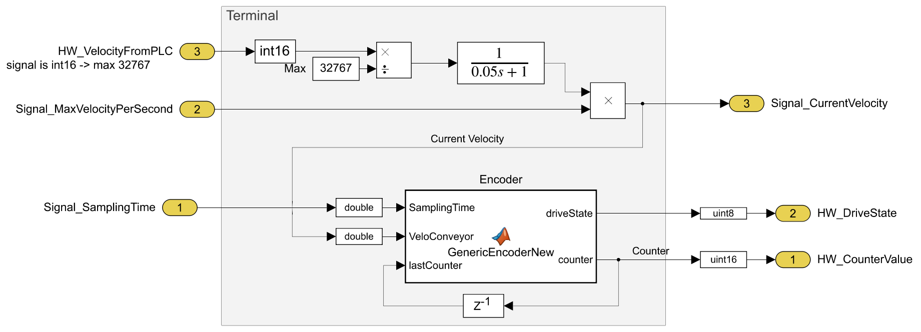
The behaviour model in this module consists of the DC motor of the conveyor belt, a generic drive for the dosing units and a logical combination of the pistons and sensors. The final model in Simulink is shown in Figure 4.11. The modelling of the DC motor is similar to this example from the MATLAB documentation [61], using the characteristics from the data sheet of the used motor. The stepper motors of the dosing units are not modeled as detailed as the DC motor and therefore use a generic description, which also results in a reduction of the required computing power.

PLC Code

The PLC code in this module consists of two function blocks: one block for the conveyor belt and one block for the dosing units. The functionality of these blocks consists in the initialization of the motors and the movement with a constant speed for the conveyor belt



(a) Conveyor Belt



(b) Dosing Unit

Figure 4.11.: Behaviour model of module Conveyor Belt describing the DC motor of the conveyor belt and the stepper motor of the dosing units.

and the traveling of a defined distance for the dosing units. The linking of these blocks remains the customer's task and is not supplied by the manufacturer. The two function blocks are listed in PLCopen format in Source Code A.0.2 and Source Code A.0.3.

Resulting File

The collected information is now merged into the proposed data structure. This data structure is shown in Figure 4.12 and consists of the CAD assembly, the behaviour model and PLC code. In addition some documentation is attached to the data structure.

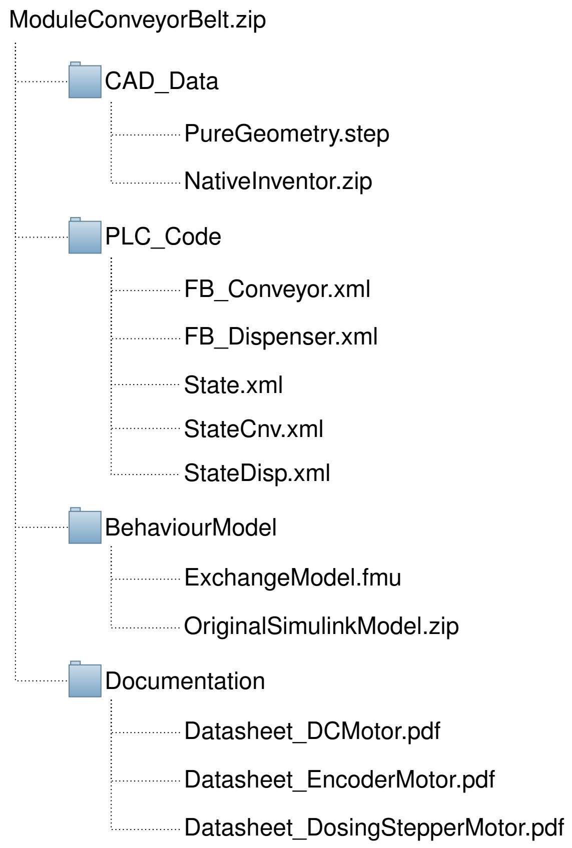


Figure 4.12.: Data structure of module Conveyor Belt consisting of CAD data as pure geometry and including kinematization in a native format, PLC code, the behaviour model exported to a .fmu file and the original source from Simulink and additional documentation.

4.2.3. Module Cartesian Gripper

CAD Data

Similar to the previous modules, the structure of the CAD data reflects the desired kinematization. For this reason, the cartesian gripper consists of three sub-assemblies for the respective axes and one for the remaining components. The degrees of freedom of the three axes are restricted to the desired direction of motion. Since the CAD data along with the kinematization will be sent to the customer, the native Inventor format is used again.

Behaviour Modelling

The behaviour model of the cartesian gripper describes the three axes of motion and the gripper itself. In this modelling process, a stepper motor is merged with the terminal of the PLC into one model and described generically. As a result of the generic model, the level of detail is reduced and so is the complexity of the calculation. Furthermore, the generic model is independent of the selected motor type.

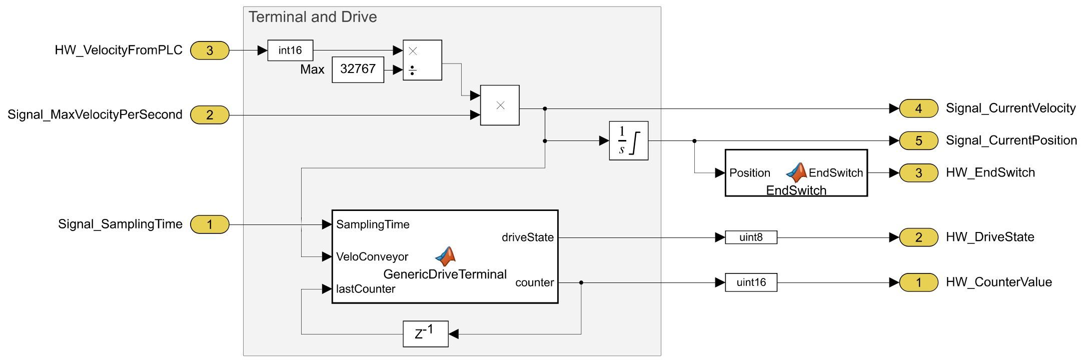


Figure 4.13.: Behaviour model for module Cartesian Gripper describing a generic motor merged with a PLC motor terminal.

PLC Code

In this module, a function block is provided for controlling a motor axis, where this block controls only one axis and must be instantiated later for each motor. This block thereby independently performs the homing to a reference zero allowing an accurate movement to a target point with a desired speed. Again, the control is exported to the PLCopen format and is listed in Source Code A.0.4.

Resulting File

The last step is now to merge the data into the proposed data structure from Chapter 3. This structure is shown in Figure 4.14 and consists again of the CAD assembly, the behaviour model and source code for a PLC.

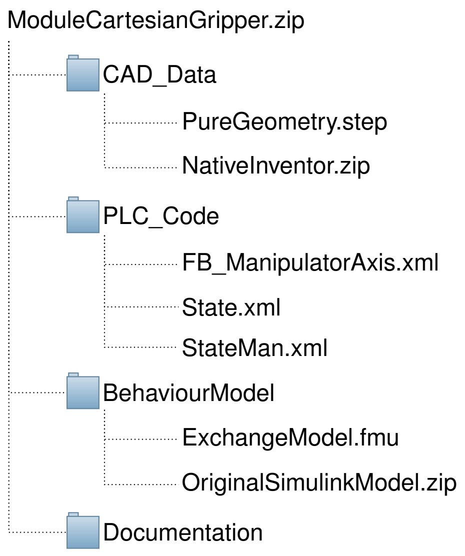


Figure 4.14.: Data structure of module Cartesian Gripper consisting of the pure geometry and included kinematization in a native format, PLC code and the behaviour model exported to a .fmu file and the original source files from Simulink. The folder of additional documentation is also empty in this module.

4.2.4. Module Load Cell

CAD Data

Since no kinematization is required for this module, no special steps are necessary in the construction of the CAD assembly. In addition, data exchange is simplified since a .step file can be used without losing any relevant information.

Behaviour Modelling

The generation of the behaviour model of this module is similarly simple, because the serial communication itself is not modeled but only the message as string-type for debugging purpose. With this behaviour model shown in Figure 4.15 a message can be created with a defined prefix and suffix and a desired measured value, which later has to be interpreted by the PLC.

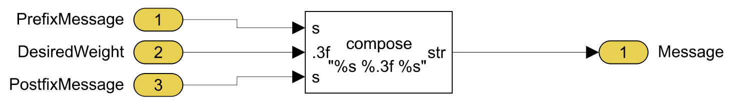


Figure 4.15.: Behaviour model of module Load Cell consisting of composing a serial message with the measured weight.

PLC Code

Here the manufacturer provides only the hardware and the documentation of the communication, but no code for the PLC.

Resulting File

Also in this module the last step consists of merging the data into the data structure. The resulting structure is shown in Figure 4.16 and consists of the CAD assembly, the behaviour model and additional documentation of the serial communication protocol.

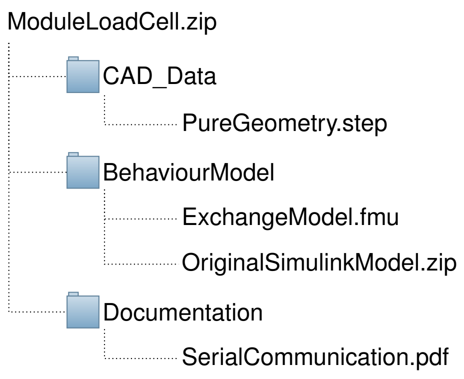


Figure 4.16.: Data structure of module Load Cell consisting of the pure geometry, the behaviour model as exported .fmu file and the original source in Simulink and documentation.

4.2.5. Module Thermal Processing

CAD Data

This module is also based on static components and therefore has no kinematization. This simplifies on the one hand the setup in the CAD software and on the other hand the export of the assembly. As a result, no special requirements for the CAD model are needed and the export can be performed in the .step format without the loss of relevant information.

Behaviour Modelling

However, the behaviour model is slightly more complex with the modelling of the temperature curve. Taking into account the room temperature as constant offset and the maximum reachable temperature of the cartridge heaters, the temperature of the containers is described with a transfer function. Finally, this temperature has to be converted into the corresponding signals of the sensors. The entire model in Simulink is shown in Figure 4.17.

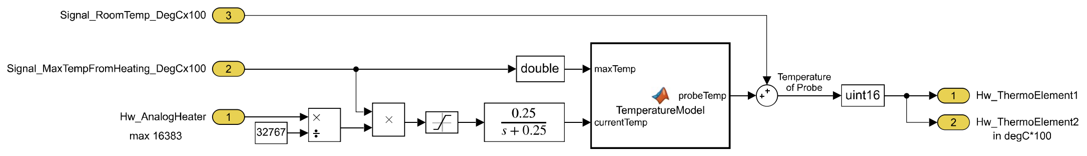


Figure 4.17.: Behaviour model of module Thermal Processing describing the temperature curve of a container with the influence of the used heating cartridges and the resulting sensor signals.

PLC Code

With this module the PLC code is again provided in the form of a function block. This block is listed in Source Code A.0.5 and enables the initialization and operation of the module. In the process, the containers are heated to a defined temperature and then held for a certain time.

Resulting File

Finally, the collected data is merged into the data structure. This structure is shown in Figure 4.18 and consists of CAD data, behaviour model and PLC code.

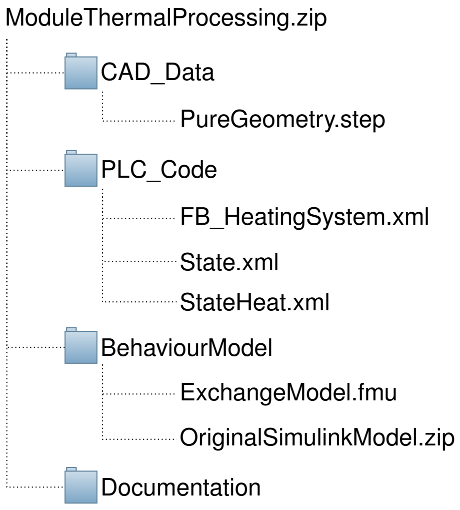


Figure 4.18.: Data structure of module Thermal Processing consisting of pure geometry, PLC code and the behaviour model as exported .fmu file and the original source from Simulink. Also in this module no further documentation is needed.

4.3. Implementation of the Data Structure - Workflow of a Customer

4.3.1. A Single Module

For the CAD data, as already mentioned, it is assumed that both sides use Inventor. This way the native format can be kept and in addition to the geometry also the kinematization is preserved. For purely static modules without kinematization, the .step format is used. The import of a .step file is done as described in [39]. Since in this example the customer uses a PLC from manufacturer Beckhoff, the behaviour model is integrated directly from the Simulink files into the PLC run-time. As said, the integration of .fmu files is not possible at this time due to ongoing development of the required product. The integration of the Simulink models into TwinCAT is done analog to [62]. The function blocks of the PLC control can be easily integrated and instantiated in an existing TwinCAT project. After assigning the interface variables, the code can be used.

4.3.2. Complete Factory - Combining the Modules

For the mechanical planning of the plant, the individual modules are combined and positioned in an assembly representing a standard activity for an average user of Inventor.
As already mentioned in Section 4.1.6, virtual commissioning takes place in a HIL system. Here, the PLC control and the behaviour models of the plant are executed on two different IPCs, which exchange the respective state via the real-time capable EAP interface. A publisher and subscriber are created on both IPCs and linked to the respective variables of the process image in order to establish communication.
On the IPC with the simulation of the plant first a new TwinCAT project is created and the TcCom objects of the individual modules are instantiated. These objects are then assigned to a task with $10\,\mathrm{ms}$. The outputs from this model are set as publish variables and the inputs as subscribe variables in the EAP communication. In addition to the individual modules, a higher-level program is created responsible for controlling the interfaces

between individual modules. For example, the position of used containers can be monitored and prepared in this higher-level program for a visualisation. The position can be determined either by means of sensors (module Separation) or by optional outputs in the behaviour models (modules Conveyor Belt and Cartesian Gripper). On the second IPC with the controlling software a new TwinCAT project is also created and the clock time is set to $10\,\mathrm{ms}$. In this project now the function blocks of the individual modules are imported and called cyclically in the MAIN program. Furthermore, in the MAIN program the higher-level control between the modules is created and linked to the inputs and outputs of the function blocks. For the used drives several NC axes must be added in TwinCAT and parameterized with the corresponding settings from the individual data sheets. To establish EAP communication with the simulation of the plant, the outputs of the controller (actuators) are set as publish variables and the inputs (sensors) as subscribe variables. Afterwards, they are linked to the according variables in the process image.
As soon as the two IPCs are configured, the run-time is started. From this point on, the plant is simulated on the first IPC and the control on the second IPC can be tested and finally, a virtual commissioning can be performed with this setup. The practical implementation of virtual commissioning would benefit from an optional visualization of the simulated plant. In this case, in addition to the position of the mechanical components of the plant, the position of the containers needs to be known. As already mentioned, this could be determined by the higher-level program of the first IPC (simulation) and further communicated to a visualization platform. The position of the remaining components is simple to determine via the sensors or the NC axes. For example, the visualization itself could be done in Unity or also Inventor (using TE1130 [16]).

4.4. Summary

In this chapter, the proposed data structure is used in a real-life application and tested for its practical usability. An exemplary plant is divided into several modules and a data structure is created for each module and prepared for exchange. For this purpose, the CAD data with and without kinematization are exported, the behaviour model is created and the control code for the PLC is written. In the second step, this information is then imported from that data structure and integrated into a setup for a virtual commissioning. The simulation of the plant is executed in a second IPC in parallel with the control PLC, with the necessary communication taking place in real-time via EAP.

5. Results and Evaluation

The result of this thesis is the proposed data structure shown in Chapter 3, bundling information from the CAD design, physical behaviour model, PLC source code and optional documentation. The structure is modular designed and data is stored in compatible formats. The practical use of the data structure is also investigated in this thesis using an example in Chapter 4. To evaluate the benefits of this data structure, this example is evaluated using the criteria from Section 2.3.
Through the evaluation it is stated that the data structure can basically be used in a SIL and HIL system, because no dependencies to the used hardware exists. The advantage in a HIL system is the additional computing power for the simulation of the plant with the disadvantage of additional communication. The data required for virtual commissioning, such as CAD assemblies, behaviour models, PLC code and documentation, can be represented in the data structure without problems. As shown in the example, individual modules of a plant can be reproduced with the data structure and finally integrated into a higher-level system. However, there is still room for development in the compatibility of the data formats, especially in the area of kinematized CAD data and in the integration of *.fmu* models in a PLC project. While the integration of behaviour models in the case of *Beckhoff* is only a matter of time, the exchange of kinematization in CAD data represents a bigger challenge. In this case, a practicable solution has not yet been established in the industry. In terms of the requirements for the additional know-how needed, no further skills are required in the case of the CAD data and the pure PLC code. When creating the behaviour models, basic knowledge of programming a PLC is an advantage but not absolutely necessary. However, the integration of the behaviour models into the PLC project requires additional knowledge, which can be acquired in a seminar, for example.
The result of this evaluation is summarized in Table 5.1. This evaluation is valid for the used software versions shown in Table 3.1, where upward compatibility is likely but downward compatibility is not guaranteed.

Table 5.1.: Evaluation of proposed data structure with respect to the shown example from bad (○○○) to good (●●●). Although the defined information is represented in the data structure, compatibility could be improved, especially for kinematized CAD data.

Criterion	Evaluation
Independent of hardware setup (HIL/SIL)	●●●
Represent all relevant data	●●●
Modular layout to represent components	●●●
High compatibility between different tools	●○○
Using standard formats	●●●
Low level of additional knowledge	●●○

In general, with this data structure, the difficulties of setting up a virtual commissioning can be reduced, which simplifies its implementation. This has the advantage of minimizing the time and cost of commissioning a new plant.

6. Summary and Outlook

6.1. Summary

In the scope of this master thesis, a data structure for the exchange of relevant information for a virtual commissioning is developed. This structure is focused on high compatibility between different tools and has a modular structure. The covered information of the data structure includes the mechanical design represented by the CAD data, physical behaviour models of different used components and source code for the control via a PLC. Additional information such as data sheets can be added to the data structure as required.
The presented data structure is evaluated on the basis of an example for its usability. The result of this evaluation shows potential for improvement, especially in the exchange of kinematized CAD assemblies. Besides the native formats there is no established solution available at the moment. Furthermore, the integration of .fmu models into a PLC run-time is also under development in the case of Beckhoff but suitable alternatives are found.

6.2. Outlook

The next possible steps of this thesis are on the one hand further research on the exchange of kinematized CAD assemblies based on a neutral data format and on the other hand further evaluation of the data structure with respect to bigger use cases and additional software for the integration of the behaviour models in the PLC. As part of these larger use cases, compatibility of different versions of the software used can also be further investigate.

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List of Figures

List of Tables

List of Code

List of Acronyms

CIP	Continual Improvement Process
COLLADA	Collaborative Design Activity
DUT	Device under Test
FMI	Functional Mockup Interface
FMU	Functional Mockup Unit
GUI	Graphical User Interface
HIL	Hardware in the Loop
HMI	Human-machine interface
HTML	Hypertext Markup Language
IGES	Initial Graphics Exchange Specification
MD	Markdown
PDF	Portable Document Format
SIL	Software in the Loop
STEP	Standard for the Exchange of Product model data

A. PLC Source Code

Source Code A.0.1: Code for module Separation as PLCopen-xml.

```
<?xml version="1.0" encoding="utf-8"?>
<project xmlns="http://www.plcopen.org/xml/tc6_0200">
  <fileHeader companyName="Beckhoff Automation GmbH" productName="TwinCAT PLC Control" productVersion="3.5.13.21"
      creationDateTime="2022-05-27T15:51:05.3586322" />
  <contentHeader name="main" modificationDateTime="2022-05-27T15:51:05.3606326">
    <coordinateInfo>
      <fbd>
        <scaling x="1" y="1" />
      </fbd>
      <ld>
        <scaling x="1" y="1" />
      </ld>
      <sfc>
        <scaling x="1" y="1" />
      </sfc>
    </coordinateInfo>
    <addData>
      <data name="http://www.3s-software.com/plcopenxml/projectinformation" handleUnknown="implementation">
        <ProjectInformation />
      </data>
    </addData>
  </contentHeader>
  <types>
    <dataTypes />
    <pous>
      <pou name="FB_Separator" pouType="functionBlock">
        <interface>
          <inputVars>
            <variable name="bEnable">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> start/stops the functionblock</xhtml>
              </documentation>
            </variable>
            <variable name="bExecute">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> Ejects 1 flask if true</xhtml>
              </documentation>
            </variable>
            <variable name="bErrorReset">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Reset Error </xhtml>
              </documentation>
            </variable>
            <variable name="bSensor1">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Hardware Sensor 1</xhtml>
              </documentation>
            </variable>
            <variable name="bSensor2">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Hardware Sensor 2</xhtml>
              </documentation>
            </variable>
            <variable name="bSensor3">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Hardware Sensor 3</xhtml>
              </documentation>
            </variable>
          </inputVars>
          <outputVars>
            <variable name="bR1AKT1">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Relais 1 Aktor 1 (Schieber oben)</xhtml>
              </documentation>
            </variable>
            <variable name="bR2AKT1">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Relais 2 Aktor 1</xhtml>
              </documentation>
            </variable>
            <variable name="bR1AKT2">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Relais 1 Aktor 2 (Schieber unten)</xhtml>
              </documentation>
            </variable>
            <variable name="bR2AKT2">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Relais 2 Aktor 2</xhtml>
              </documentation>
            </variable>
            <variable name="bNoBottle">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Keine Flasche vorhanden</xhtml>
              </documentation>
            </variable>
            <variable name="bWrongBottle">
              <type>
                <BOOL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Falsche oder gedrehte Flasche vorhanden</xhtml>
              </documentation>
            </variable>
            <variable name="eStatus">
              <type>
                <derived name="State" />
              </type>
              <initialValue>
                <simpleValue value="State.Off" />
              </initialValue>
            </variable>
          </outputVars>
          <localVars>
            <variable name="timer">
              <type>
                <derived name="TON" />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml">Timer to make sure, that the flask has cleared the slope</
      xhtml>
              </documentation>
            </variable>
            <variable name="eState">
              <type>
                <derived name="StateSeparator" />
              </type>
              <initialValue>
                <simpleValue value="StateSeparator.Off" />
              </initialValue>
            </variable>
          </localVars>
        </interface>
        <body>
          <ST>
            <xhtml xmlns="http://www.w3.org/1999/xhtml">CASE eState OF
  StateSeparator.Off:
    eStatus := State.Off;
    bR1AKT1 := TRUE;   //Eingefahren oben
    bR2AKT1 := FALSE;  //Eingefahren oben

    bR1AKT2 := FALSE;  //Eingefahren unten
    bR2AKT2 := TRUE;   //Eingefahren unten

    IF bEnable THEN
      eState := StateSeparator.Init;
    END_IF

```

```
StateSeparator.Init:

  eStatus := State.Busy; //Beschaeftigt Signallampe

  bR1AKT1 := FALSE; //Ausgefahren oben
  bR2AKT1 := TRUE;

  bR1AKT2 := FALSE; //Eingefahren unten
  bR2AKT2 := TRUE;


  IF bSensor1 THEN
    eState := StateSeparator.Init_Wait; //Zustandswechsel sobald Sensor Flasche zwischen Schiebern sieht
  END_IF

StateSeparator.Init_Wait:
  timer(IN := TRUE, PT := T#1000MS); //Timer wartet bis Flasche sicher zum Stehen kommt

  IF timer.Q THEN
    timer(IN := FALSE);
    eState := StateSeparator.Ready; //Zustand Ready nach Timer
  END_IF

StateSeparator.Ready:
  eStatus := State.Ready; //Zustand Ready Signallampe

  bR1AKT1 := TRUE;  //Eingefahren oben
  bR2AKT1 := FALSE; //Eingefahren oben

  bR1AKT2 := FALSE; //Eingefahren unten
  bR2AKT2 := TRUE;  //Eingefahren unten

  IF bExecute THEN
    eState := StateSeparator.Eject_Wait_1; //Auswerfen sobald Exceute TRUE
  END_IF

StateSeparator.Eject_Wait_1:  // Warten bis Schieber oben ganz geschlossen ist
    eStatus := State.Busy; //Zustand Busy Signallampe

    timer(IN := TRUE, PT := T#2500MS); //Timer auf 2,5 S eingestellt

  IF timer.Q THEN
    timer(IN := FALSE);
    eState := StateSeparator.Eject; //Zustand bereit nach Timer
  END_IF

StateSeparator.Eject: //Auswerfen der unteren Flasche
  bR1AKT2 := TRUE;  //L sst Flaschen auf Band ab durch  ffnen  des unteren Schiebers
  bR2AKT2 := FALSE;

  IF NOT bSensor1 THEN
    eState := StateSeparator.Eject_Wait_2;
  END_IF

StateSeparator.Eject_Wait_2:  // Warten bis Flasche durch F rderband weit genug von Schieber wegtransportiert
  eStatus := State.Done;
  timer(IN := TRUE, PT := T#4000MS); //Timer auf 4 S eingestellt

  IF timer.Q THEN
    timer(IN := FALSE);
    eState := StateSeparator.Done_Wait;
  END_IF

StateSeparator.Done_Wait: // Schlie en des unteren Schiebers und Warten bis komplettt geschlossen
  bR1AKT2 := FALSE; //Eingefahren unten
  bR2AKT2 := TRUE;  //Eingefahren unten

  timer(IN := TRUE, PT := T#3000MS); //Timer wartet bis Schieber geschlossen ist

  IF timer.Q THEN
    timer(IN := FALSE);
    eState := StateSeparator.Done;
  END_IF

StateSeparator.Done:  //Vereinzelungsvorgang abgeschlossen

  IF NOT bExecute THEN
    eState := StateSeparator.Init;
  END_IF

END_CASE</xhtml>
          </ST>
        </body>
        <addData>
          <data name="http://www.3s-software.com/plcopenxml/interfaceasplaintext" handleUnknown="implementation">
            <InterfaceAsPlainText>
              <xhtml xmlns="http://www.w3.org/1999/xhtml">FUNCTION_BLOCK FB_Separator
VAR_INPUT
  bEnable : BOOL;   // start/stops the functionblock
  bExecute: BOOL;   // Ejects 1 flask if true
  bErrorReset: BOOL;  //Reset Error

  bSensor1 : BOOL; //Hardware Sensor 1
  bSensor2 : BOOL; //Hardware Sensor 2
  bSensor3 : BOOL; //Hardware Sensor 3
END_VAR
VAR_OUTPUT
  bR1AKT1 : BOOL; //Relais 1 Aktor 1 (Schieber oben)
  bR2AKT1 : BOOL; //Relais 2 Aktor 1
  bR1AKT2 : BOOL; //Relais 1 Aktor 2 (Schieber unten)
  bR2AKT2 : BOOL; //Relais 2 Aktor 2

  bNoBottle    : BOOL;    //Keine Flasche vorhanden
  bWrongBottle  : BOOL; //Falsche oder gedrehte Flasche vorhanden

  eStatus : State := State.Off;
END_VAR
VAR
  timer : TON; //Timer to make sure, that the flask has cleared the slope
  eState : StateSeparator := StateSeparator.Off;
END_VAR
</xhtml>
            </InterfaceAsPlainText>
          </data>
          <data name="http://www.3s-software.com/plcopenxml/objectid" handleUnknown="discard">
            <ObjectId>91946f14-5ef9-4883-993a-962cda20c177</ObjectId>
          </data>
        </addData>
      </pou>
    </pous>
  </types>
  <instances>
    <configurations />
  </instances>
  <addData>
    <data name="http://www.3s-software.com/plcopenxml/projectstructure" handleUnknown="discard">
      <ProjectStructure>
        <Object Name="FB_Separator" ObjectId="91946f14-5ef9-4883-993a-962cda20c177" />
      </ProjectStructure>
    </data>
  </addData>
</project>
```

Source Code A.0.2: Code for module Conveyor Belt as PLCopen-xml.

```
<?xml version="1.0" encoding="utf-8"?>
<project xmlns="http://www.plcopen.org/xml/tc6_0200">
  <fileHeader companyName="Beckhoff Automation GmbH" productName="TwinCAT PLC Control" productVersion="3.5.13.21"
      creationDateTime="2022-08-13T15:46:57.5102704" />
  <contentHeader name="PlcMain" modificationDateTime="2022-08-13T15:46:57.5102704">
    <coordinateInfo>
      <fbd>
        <scaling x="1" y="1" />
      </fbd>
      <ld>
        <scaling x="1" y="1" />
      </ld>
      <sfc>
        <scaling x="1" y="1" />
      </sfc>
    </coordinateInfo>
    <addData>
      <data name="http://www.3s-software.com/plcopenxml/projectinformation" handleUnknown="implementation">
        <ProjectInformation />
      </data>
    </addData>
  </contentHeader>
  <types>
    <dataTypes />
    <pous>
      <pou name="FB_Conveyor" pouType="functionBlock">
        <interface>
          <inputVars>
            <variable name="bEnable">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bExecute">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="eDirection">
              <type>
                <derived name="MC_Direction" />
              </type>
              <initialValue>
                <simpleValue value="MC_Positive_Direction" />
              </initialValue>
            </variable>
            <variable name="nVel">
              <type>
                <INT />
              </type>
              <initialValue>
                <simpleValue value="25" />
              </initialValue>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> mm per s</xhtml>
              </documentation>
            </variable>
          </inputVars>
          <outputVars>
            <variable name="eStatus">
              <type>
                <derived name="State" />
              </type>
              <initialValue>
                <simpleValue value="State.Off" />
              </initialValue>
            </variable>
          </outputVars>
          <inOutVars>
            <variable name="ax">
              <type>
                <derived name="AXIS_REF" />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> axis reference</xhtml>
              </documentation>
            </variable>
          </inOutVars>
          <localVars>
            <variable name="fbReset">
              <type>
                <derived name="MC_Reset" />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> NC FBs</xhtml>
              </documentation>
            </variable>
            <variable name="fbPower">
              <type>
                <derived name="MC_Power" />
              </type>
            </variable>
            <variable name="fbMove">
              <type>
                <derived name="MC_MoveVelocity" />
              </type>
            </variable>
            <variable name="fbHalt">
              <type>
                <derived name="MC_Halt" />
              </type>
            </variable>
            <variable name="bAxPower">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bAxMove">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="eState">
              <type>
                <derived name="StateCnv" />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> state</xhtml>
              </documentation>
            </variable>
          </localVars>
        </interface>
        <body>
          <ST>
            <xhtml xmlns="http://www.w3.org/1999/xhtml">// update axis
ax.ReadStatus();

// call NC FBs
fbReset(
  Axis:= ax);
fbPower(
  Axis:= ax,
  Enable:= bAxPower,
  Enable_Positive:= bAxPower,
  Enable_Negative:= bAxPower,
  Override:= 100);
fbMove(
  Axis:= ax,
  Execute:=bAxMove,
  Velocity:= nVel,
  Direction:= eDirection);
fbHalt(
  Axis:= ax,
  Execute:= NOT bAxMove);

IF NOT bEnable THEN
  eState := StateCnv.Off;
END_IF

CASE eState OF
StateCnv.Off:
  eStatus := State.Off;
  bAxPower := FALSE;
  bAxMove := FALSE;

  IF bEnable THEN
    eState := StateCnv.Reset;
  END_IF
StateCnv.Reset:
  eStatus := State.Busy;
  fbReset.Execute := TRUE;

  IF fbReset.Done THEN
    eState := StateCnv.Power;
  END_IF
StateCnv.Power:
  eStatus := State.Busy;
  bAxPower := TRUE;

  IF fbPower.Status THEN
    eState := StateCnv.Ready;
  END_IF
StateCnv.Ready:
  eStatus := State.Ready;
  bAxMove := FALSE;

  IF bExecute THEN
    eState := StateCnv.Moving;
  END_IF
StateCnv.Moving:
  eStatus := State.Busy;
  bAxMove := TRUE;

  IF NOT bExecute THEN
    eState := StateCnv.Ready;
  END_IF
END_CASE</xhtml>
          </ST>
        </body>
        <addData>
          <data name="http://www.3s-software.com/plcopenxml/interfaceasplaintext" handleUnknown="implementation">
            <InterfaceAsPlainText>
              <xhtml xmlns="http://www.w3.org/1999/xhtml">FUNCTION_BLOCK FB_Conveyor
VAR_INPUT
  bEnable : BOOL;
  bExecute: BOOL;
  eDirection : MC_Direction := MC_Positive_Direction;
  nVel  : INT := 25; // mm per s
END_VAR
VAR_OUTPUT
  eStatus : State := State.Off;
END_VAR
VAR_IN_OUT
  ax : AXIS_REF; // axis reference
END_VAR
VAR
  // NC FBs
  fbReset : MC_Reset;
  fbPower : MC_Power;
  fbMove  : MC_MoveVelocity;
  fbHalt  : MC_Halt;

  bAxPower : BOOL;
  bAxMove : BOOL;

  // state
  eState : StateCnv;
END_VAR
</xhtml>
            </InterfaceAsPlainText>
          </data>
          <data name="http://www.3s-software.com/plcopenxml/objectid" handleUnknown="discard">
            <ObjectId>fbe14543-a9c7-41a4-8387-253afb962875</ObjectId>
          </data>
        </addData>
      </pou>
    </pous>
  </types>
  <instances>
    <configurations />
  </instances>
  <addData>
    <data name="http://www.3s-software.com/plcopenxml/projectstructure" handleUnknown="discard">
      <ProjectStructure>
        <Object Name="FB_Conveyor" ObjectId="fbe14543-a9c7-41a4-8387-253afb962875" />
      </ProjectStructure>
    </data>
  </addData>
</project>
```

Source Code A.0.3: Code for module Dosing Unit as PLCopen-xml.

```
<?xml version="1.0" encoding="utf-8"?>
<project xmlns="http://www.plcopen.org/xml/tc6_0200">
  <fileHeader companyName="Beckhoff Automation GmbH" productName="TwinCAT PLC Control" productVersion="3.5.13.21"
      creationDateTime="2022-08-13T15:46:51.4562744" />
  <contentHeader name="PlcMain" modificationDateTime="2022-08-13T15:46:51.4582743">
    <coordinateInfo>
      <fbd>
        <scaling x="1" y="1" />
      </fbd>
      <ld>
        <scaling x="1" y="1" />
      </ld>
      <sfc>
        <scaling x="1" y="1" />
      </sfc>
    </coordinateInfo>
    <addData>
      <data name="http://www.3s-software.com/plcopenxml/projectinformation" handleUnknown="implementation">
        <ProjectInformation />
      </data>
    </addData>
  </contentHeader>
  <types>
    <dataTypes />
    <pous>
      <pou name="FB_Dispenser" pouType="functionBlock">
        <interface>
          <inputVars>
            <variable name="bEnable">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bExecute">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="nDispenseGrams">
              <type>
                <INT />
              </type>
              <initialValue>
                <simpleValue value="1" />
              </initialValue>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> Gewunschte Menge in Gramm</xhtml>
              </documentation>
            </variable>
          </inputVars>
          <outputVars>
            <variable name="eStatus">
              <type>
                <derived name="State" />
              </type>
              <initialValue>
                <simpleValue value="State.Off" />
              </initialValue>
            </variable>
          </outputVars>
          <inOutVars>
            <variable name="ax">
              <type>
                <derived name="AXIS_REF" />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> Referenz auf die NC-Achse</xhtml>
              </documentation>
            </variable>
          </inOutVars>
          <localVars>
            <variable name="fbReset">
              <type>
                <derived name="MC_Reset" />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> Fur NC-Achse notig</xhtml>
              </documentation>
            </variable>
            <variable name="fbPower">
              <type>
                <derived name="MC_Power" />
              </type>
            </variable>
            <variable name="fbMove">
              <type>
                <derived name="MC_MoveRelative" />
              </type>
            </variable>
            <variable name="nVelocity">
              <type>
                <INT />
              </type>
              <initialValue>
                <simpleValue value="720" />
              </initialValue>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> Grad pro Sekunde</xhtml>
              </documentation>
            </variable>
            <variable name="fGramPerRev">
              <type>
                <REAL />
              </type>
              <initialValue>
                <simpleValue value="0.245" />
              </initialValue>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> Skalierung auf Gramm pro ganzer Umdrehung (360 Grad)</xhtml>
              </documentation>
            </variable>
            <variable name="eState">
              <type>
                <derived name="StateDisp" />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> Status der Zustandsmaschine</xhtml>
              </documentation>
            </variable>
            <variable name="bAxPower">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bAxMove">
              <type>
                <BOOL />
              </type>
            </variable>
          </localVars>
          <documentation>
            <xhtml xmlns="http://www.w3.org/1999/xhtml"> Das ist die Musterlosung zur Steuerung einer Dosiereinheit.
 Library TC2_MC2 ist notig.</xhtml>
          </documentation>
        </interface>
        <body>
          <ST>
            <xhtml xmlns="http://www.w3.org/1999/xhtml">
// update axis
ax.ReadStatus();

// call NC FBs
fbReset(
  Axis:= ax);
fbPower(
  Axis:= ax,
  Enable:= bAxPower,
  Enable_Positive:= bAxPower,
  Enable_Negative:= bAxPower,
  Override:= 100);
fbMove(
  Axis:=ax,
  Execute:=bAxMove,
  Velocity:=nVelocity,
  Distance:= nDispenseGrams *360 / fGramPerRev);



IF NOT bEnable THEN
  eState := StateDisp.Off;
END_IF

CASE eState OF
StateDisp.Off:
  eStatus := State.Off;
  bAxMove := FALSE;
  bAxPower := FALSE;

  IF bEnable THEN
    eState := StateDisp.Reset;
  END_IF
StateDisp.Reset:
  eStatus := State.Busy;
  fbReset.Execute := TRUE;
  IF fbReset.Done THEN
    fbReset.Execute := FALSE;
    eState := StateDisp.PowerUp;
  END_IF
StateDisp.PowerUp:
  eStatus := State.Busy;
  bAxPower := TRUE;
  IF fbPower.Status THEN
    eState := StateDisp.Idle;
  END_IF
StateDisp.Idle:
  eStatus := State.Ready;
  bAxMove := FALSE;

  IF bExecute THEN
    eState := StateDisp.Dispensing;
  END_IF
StateDisp.Dispensing:
  eStatus := State.Busy;
  bAxMove := TRUE;

  IF fbMove.Done THEN
    eState := StateDisp.Done;
  END_IF
StateDisp.Done:
  eStatus := State.Done;
  bAxMove := FALSE;

  IF NOT bExecute THEN
    eState := StateDisp.Idle;
  END_IF
END_CASE</xhtml>
          </ST>
        </body>
        <addData>
          <data name="http://www.3s-software.com/plcopenxml/interfaceasplaintext" handleUnknown="implementation">
            <InterfaceAsPlainText>
              <xhtml xmlns="http://www.w3.org/1999/xhtml">// Das ist die Musterlosung zur Steuerung einer Dosiereinheit.
// Library TC2_MC2 ist notig.

FUNCTION_BLOCK FB_Dispenser
  VAR_INPUT
    bEnable          : BOOL;
    bExecute         : BOOL;
    nDispenseGrams       : INT := 1;    // Gewunschte Menge in Gramm
  END_VAR

  VAR_OUTPUT
    eStatus : State := State.Off;
  END_VAR

  VAR_IN_OUT
    ax    : AXIS_REF;        // Referenz auf die NC-Achse
  END_VAR

  VAR
    // Fur NC-Achse notig
    fbReset      : MC_Reset;
    fbPower      : MC_Power;
    fbMove       : MC_MoveRelative;

    // Parameter
    nVelocity      : INT := 720;    // Grad pro Sekunde
    fGramPerRev      : REAL := 0.245;     // Skalierung auf Gramm pro ganzer Umdrehung (360 Grad)

    // Working variables
    eState         : StateDisp;     // Status der Zustandsmaschine
    bAxPower       : BOOL;
    bAxMove        : BOOL;
END_VAR

// ----- Ende der Definition. Hier folgt der Code ------



</xhtml>
            </InterfaceAsPlainText>
          </data>
          <data name="http://www.3s-software.com/plcopenxml/objectid" handleUnknown="discard">
            <ObjectId>45b31251-7302-454e-ad8b-8a17ba762004</ObjectId>
          </data>
        </addData>
      </pou>
    </pous>
  </types>
  <instances>
    <configurations />
  </instances>
  <addData>
    <data name="http://www.3s-software.com/plcopenxml/projectstructure" handleUnknown="discard">
      <ProjectStructure>
        <Object Name="FB_Dispenser" ObjectId="45b31251-7302-454e-ad8b-8a17ba762004" />
      </ProjectStructure>
    </data>
  </addData>
</project>
```

Source Code A.0.4: Code for module Cartesian Gripper as PLCopen-xml.

```
<?xml version="1.0" encoding="utf-8"?>
<project xmlns="http://www.plcopen.org/xml/tc6_0200">
  <fileHeader companyName="Beckhoff Automation GmbH" productName="TwinCAT PLC Control" productVersion="3.5.13.21"
      creationDateTime="2022-08-12T11:34:54.3732365" />
  <contentHeader name="PlcMain" modificationDateTime="2022-08-12T11:34:54.3752427">
    <coordinateInfo>
      <fbd>
        <scaling x="1" y="1" />
      </fbd>
      <ld>
        <scaling x="1" y="1" />
      </ld>
      <sfc>
        <scaling x="1" y="1" />
      </sfc>
    </coordinateInfo>
    <addData>
      <data name="http://www.3s-software.com/plcopenxml/projectinformation" handleUnknown="implementation">
        <ProjectInformation />
      </data>
    </addData>
  </contentHeader>
  <types>
    <dataTypes />
    <pous>
      <pou name="FB_ManipulatorAxis" pouType="functionBlock">
        <interface>
          <inputVars>
            <variable name="bEnable">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bExecute">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bEndschalterMin">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bEndSchalterMax">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="fPosition">
              <type>
                <LREAL />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> gewunschte Postition der Achse</xhtml>
              </documentation>
            </variable>
            <variable name="fVelocity">
              <type>
                <LREAL />
              </type>
            </variable>
            <variable name="Direction">
              <type>
                <derived name="MC_Direction" />
              </type>
            </variable>
          </inputVars>
          <outputVars>
            <variable name="eOutState">
              <type>
                <derived name="State" />
              </type>
              <initialValue>
                <simpleValue value="State.Off" />
              </initialValue>
            </variable>
            <variable name="fActPos">
              <type>
                <LREAL />
              </type>
            </variable>
          </outputVars>
          <inOutVars>
            <variable name="aAchse">
              <type>
                <derived name="AXIS_REF" />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> NC–Achse</xhtml>
              </documentation>
            </variable>
          </inOutVars>
          <localVars>
            <variable name="Reset_Achse">
              <type>
                <derived name="MC_Reset" />
              </type>
              <documentation>
                <xhtml xmlns="http://www.w3.org/1999/xhtml"> Fur NC–Achse notig</xhtml>
              </documentation>
            </variable>
            <variable name="Power_Achse">
              <type>
                <derived name="MC_Power" />
              </type>
            </variable>
            <variable name="Move_Achse">
              <type>
                <derived name="MC_MoveAbsolute" />
              </type>
            </variable>
            <variable name="Move_Vel">
              <type>
                <derived name="MC_MoveVelocity" />
              </type>
            </variable>
            <variable name="Home_Achse">
              <type>
                <derived name="MC_Home" />
              </type>
            </variable>
            <variable name="Halt_Achse">
              <type>
                <derived name="MC_Halt" />
              </type>
            </variable>
            <variable name="Position_Achse">
              <type>
                <derived name="MC_ReadActualPosition" />
              </type>
            </variable>
            <variable name="bAchsePower">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bAchseMove">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="eState">
              <type>
                <derived name="StateMan" />
              </type>
            </variable>
          </localVars>
        </interface>
        <body>
          <ST>
            <xhtml xmlns="http://www.w3.org/1999/xhtml">// Einstellungen der Achse
aAchse.ReadStatus();
Reset_Achse(Axis:=aAchse);
Power_Achse(Axis:=aAchse, Override := 100, Enable := bAchsePower, Enable_Negative := bAchsePower, Enable_Positive :=
      bAchsePower);
Move_Achse(Axis:=aAchse);
Home_Achse(Axis:= aAchse, bCalibrationCam := NOT bEndschalterMin, Position := 0);
Move_Vel(Axis:=aAchse);
Halt_Achse(Axis:=aAchse);

CASE eState OF
StateMan.Off:
  eOutState := State.Off;
  bAchseMove := FALSE;
  bAchsePower := FALSE;

  IF bEnable THEN
    eState := StateMan.Reset;
  END_IF
StateMan.Reset:
  eOutState := State.Busy;
  Reset_Achse.Execute := TRUE;

  IF Reset_Achse.Done THEN
    Reset_Achse.Execute := FALSE;
    eState := StateMan.PowerUp;
  END_IF
StateMan.PowerUp:
  eOutState := State.Busy;
  bAchsePower := TRUE;

  IF Power_Achse.Status THEN
    eState := StateMan.Homing;
  END_IF
StateMan.Homing:
  eOutState := State.Busy;
  Home_Achse.Execute := TRUE;

  IF Home_Achse.Done THEN
    Home_Achse.Execute := FALSE;
    eState := StateMan.Ready;
  END_IF
StateMan.Ready:
    eOutState := State.Ready;
    Move_Achse.Execute := FALSE;
  IF bExecute THEN
    eState := StateMan.Moving;
  END_IF
StateMan.Moving:
  eOutState := State.Busy;
  Move_Achse.Velocity := fVelocity;

  Move_Achse.Position := fPosition;
  Move_Achse.Execute := TRUE;

  IF Move_Achse.Done OR ( NOT bEndschalterMin  AND (Move_Achse.Position &lt; Position_Achse.Position)) OR (NOT
      bEndschalterMax AND (Move_Achse.Position &gt; Position_Achse.Position)) THEN

    IF NOT(bEndschalterMax) OR NOT(bEndschalterMin) THEN
        Halt_Achse.Execute := TRUE;
    END_IF

    eState := StateMan.Done;
  END_IF
StateMan.Done:
  eOutState := State.Done;
  Move_Achse.Execute := FALSE;

  IF NOT bExecute THEN
    eState := StateMan.Ready;
  END_IF
END_CASE</xhtml>
          </ST>
        </body>
        <addData>
          <data name="http://www.3s-software.com/plcopenxml/interfaceasplaintext" handleUnknown="implementation">
            <InterfaceAsPlainText>
              <xhtml xmlns="http://www.w3.org/1999/xhtml">FUNCTION_BLOCK FB_ManipulatorAxis
  VAR_INPUT
    bEnable       : BOOL;
    bExecute      : BOOL;
    bEndschalterMin  : BOOL;
    bEndSchalterMax  : BOOL;
    fPosition     : LREAL;        // gewunschte Postition der Achse
    fVelocity        : LREAL;
    Direction     : MC_Direction;
  END_VAR

  VAR_OUTPUT
    eOutState          : State:=State.Off;
    fActPos            : LREAL;
  END_VAR

  VAR_IN_OUT
    aAchse        : AXIS_REF;     // NC-Achse
  END_VAR

  VAR
    // Fur NC-Achse notig
    Reset_Achse        : MC_Reset;
    Power_Achse        : MC_Power;
    Move_Achse         : MC_MoveAbsolute;
    Move_Vel         : MC_MoveVelocity;
    Home_Achse         : MC_Home;
    Halt_Achse         : MC_Halt;
    Position_Achse      : MC_ReadActualPosition;
    bAchsePower        : BOOL;
    bAchseMove         : BOOL;

    eState        : StateMan;
  END_VAR</xhtml>
            </InterfaceAsPlainText>
          </data>
          <data name="http://www.3s-software.com/plcopenxml/objectid" handleUnknown="discard">
            <ObjectId>e010b4d0-16a4-42c7-b4be-1acb68c0d19a</ObjectId>
          </data>
        </addData>
      </pou>
    </pous>
  </types>
  <instances>
    <configurations />
```

```xml
  </instances>
  <addData>
    <data name="http://www.3s-software.com/plcopenxml/projectstructure" handleUnknown="discard">
      <ProjectStructure>
        <Object Name="FB_ManipulatorAxis" ObjectId="e010b4d0-16a4-42c7-b4be-1acb68c0d19a" />
      </ProjectStructure>
    </data>
  </addData>
</project>
```

Source Code A.0.5: Code for module Thermal Processing as PLCopen-xml.

```xml
<?xml version="1.0" encoding="utf-8"?>
<project xmlns="http://www.plcopen.org/xml/tc6_0200">
  <fileHeader companyName="Beckhoff Automation GmbH" productName="TwinCAT PLC Control" productVersion="3.5.13.21"
      creationDateTime="2022-08-12T17:36:56.3108408" />
  <contentHeader name="PlcMain" modificationDateTime="2022-08-12T17:36:56.3128405">
    <coordinateInfo>
      <fbd>
        <scaling x="1" y="1" />
      </fbd>
      <ld>
        <scaling x="1" y="1" />
      </ld>
      <sfc>
        <scaling x="1" y="1" />
      </sfc>
    </coordinateInfo>
    <addData>
      <data name="http://www.3s-software.com/plcopenxml/projectinformation" handleUnknown="implementation">
        <ProjectInformation />
      </data>
    </addData>
  </contentHeader>
  <types>
    <dataTypes />
    <pous>
      <pou name="FB_HeatingSystem" pouType="functionBlock">
        <interface>
          <inputVars>
            <variable name="bEnable">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bExecute">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="nMaxTemp">
              <type>
                <UINT />
              </type>
            </variable>
            <variable name="nTemp">
              <type>
                <UINT />
              </type>
            </variable>
          </inputVars>
          <outputVars>
            <variable name="bVentilator1">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bVentilator2">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="bVentilator3">
              <type>
                <BOOL />
              </type>
            </variable>
            <variable name="nHeizpatrone">
              <type>
                <UINT />
              </type>
              <initialValue>
                <simpleValue value="0" />
              </initialValue>
            </variable>
            <variable name="eStatus">
              <type>
                <derived name="State" />
              </type>
              <initialValue>
                <simpleValue value="State.Off" />
              </initialValue>
            </variable>
          </outputVars>
          <localVars>
            <variable name="nHeat">
              <type>
                <REAL />
              </type>
              <initialValue>
                <simpleValue value="0" />
              </initialValue>
            </variable>
            <variable name="timer">
              <type>
                <derived name="TON" />
              </type>
            </variable>
            <variable name="timer1">
              <type>
                <derived name="TON" />
              </type>
            </variable>
            <variable name="eState">
              <type>
                <derived name="StateHeat" />
              </type>
              <initialValue>
                <simpleValue value="StateHeat.Off" />
              </initialValue>
            </variable>
          </localVars>
        </interface>
        <body>
          <ST>
            <xhtml xmlns="http://www.w3.org/1999/xhtml">nHeizpatrone := TO_UINT(F_map(nHeat, 0, 5, 0, 16383));

IF NOT bEnable THEN
  eState:= StateHeat.Off;
END_IF

CASE eState OF
StateHeat.Off:
  eStatus := State.Off;

  bVentilator1 := FALSE;
  bVentilator2 := FALSE;
  bVentilator3 := FALSE;
  nHeat := 0;

  IF bEnable THEN
    eState := StateHeat.Init;
  END_IF

StateHeat.Init:
  eStatus := State.Busy;
  bVentilator1 := TRUE;
  bVentilator2 := TRUE;
  bVentilator3 := TRUE;

  IF nTemp &lt;= nMaxTemp THEN
    eState := StateHeat.Ready;
  END_IF

StateHeat.Ready:
  eStatus := State.Ready;

  nHeat := 0;

  IF bExecute THEN
    eState := StateHeat.Heat;
  END_IF

StateHeat.Heat:
  eStatus := State.Busy;

  nHeat := 5;

  IF nTemp &gt;= 3000 THEN
    nHeat := 0;
    eState := StateHeat.Hold;
  END_IF

StateHeat.Hold:
  eStatus := State.Busy;

  timer(IN := TRUE, PT := T#30S);

  IF nTemp &gt;= 3700 THEN
    nHeat := 0;
  ELSIF nTemp &lt;= 3500 THEN
    timer1(IN := TRUE, PT:= T#500MS);
    IF timer1.Q THEN
      timer1(IN := FALSE);
      nHeat := nHeat + 0.05;
      IF nHeat &gt;= 5 THEN
        nHeat := 5;
      END_IF
    END_IF

  END_IF

  IF timer.Q THEN
    timer(IN := FALSE);
    nHeat := 0;
    eState := StateHeat.Done;
  END_IF

StateHeat.Done:
  eStatus := State.Done;

  nHeat := 0;

  IF NOT bExecute THEN
    eState := StateHeat.Init;
  END_IF

END_CASE</xhtml>
          </ST>
        </body>
        <addData>
          <data name="http://www.3s-software.com/plcopenxml/interfaceasplaintext" handleUnknown="implementation">
            <InterfaceAsPlainText>
              <xhtml xmlns="http://www.w3.org/1999/xhtml">FUNCTION_BLOCK FB_HeatingSystem
VAR_INPUT
  bEnable : BOOL;
  bExecute : BOOL;

  nMaxTemp : UINT;
  nTemp : UINT;
END_VAR
VAR_OUTPUT
  bVentilator1 : BOOL;
  bVentilator2 : BOOL;
  bVentilator3 : BOOL;
  nHeizpatrone : UINT := 0;

  eStatus : State := State.Off;
END_VAR
VAR
  nHeat : REAL := 0;
  timer : TON;
  timer1 : TON;
  eState : StateHeat := StateHeat.Off;
END_VAR
</xhtml>
            </InterfaceAsPlainText>
          </data>
          <data name="http://www.3s-software.com/plcopenxml/objectid" handleUnknown="discard">
            <ObjectId>7c7b126e-8b79-4d92-8382-02f37357639c</ObjectId>
          </data>
        </addData>
      </pou>
    </pous>
  </types>
  <instances>
    <configurations />
  </instances>
  <addData>
    <data name="http://www.3s-software.com/plcopenxml/projectstructure" handleUnknown="discard">
      <ProjectStructure>
        <Object Name="FB_HeatingSystem" ObjectId="7c7b126e-8b79-4d92-8382-02f37357639c" />
      </ProjectStructure>
    </data>
  </addData>
</project>
```