Towards Data-driven Production: Analysis of Data Models Describing Machinery Jobs in OPC UA

Tonja Heinemann[a], Marwin Gihr, Oliver Riedel[b] and Armin Lechler[c]
University of Stuttgart, Institute for Control Engineering of Machine Tools and Manufacturing Units, Seidenstraße 36, Stuttgart, Germany

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Abstract: This work analyzes the Open Platform Communications Unified Architecture (OPC UA) specifications for flat glass, plastics and rubber, machine vision, ISA-95 and machine tools regarding their job descriptions. Common contents of job models in the domain of machinery are deducted. Using a structured qualitative content analysis, more than 70 functional elements used in OPC UA job models have been identified. While some of these functional elements are modeled similarly in multiple domains, major differences are identified for other functional elements. Especially those differences constitute impediments in the standardization of industrial communication. The results of this work harmonize the contents and the modeling techniques regarding machining jobs in OPC UA and provide a generally applicable method for the standardization of machine communication throughout different domains. With this method for standardization, this work contributes directly to the goal of OPC UA, to easily exchange data between platforms from multiple vendors.

1 INTRODUCTION

With the advent of Industry 4.0, cloud manufacturing and lot size 1 in production, the data transfer of machines between each other and between controlling systems like Manufacturing Execution Systems (MES) raises in importance. A popular standard to use for such communication today is Open Platform Communications Unified Architecture (OPC UA). OPC UA allows specifying data models for specific use cases and specific domains. This opportunity is used in the 36 Companion specifications (CS) published today as well as in the specifications being currently developed (OPC Foundation, 2022c).

An important part of data transmission in the machinery domain is a description of jobs. A job is considered the source of all activities, as well as data container for all information and efforts necessary for processing or originating from processing (Informationstechnik, 2016). Multiple of the existing CS define such jobs. These existing models have similar intentions and overlap in content, but are different by definition.

To solve such problems, especially for newly developed CS, but also in updates of the existing CS, harmonization groups have formed (OPC Foundation, 2022b; VDMA e.V., 2022). These groups need to know the contents of existing specifications to include all the functionality that is already provided. Such an overview is developed in this work.

This paper is structured as follows: In section 2, the examined CS in this work are introduced along with a brief description of the role of CS in OPC UA. The content analysis used for the overview is described in section 3. This method involves the definition of categories. These are introduced in section 4. The resulting overview is presented in section 5, section 6 gives context for the results. The last section 7 contains a discussion of the method used and the results generated.

2 OPC UA AND COMPANION SPECIFICATIONS

The ISO-Standard OPC UA composes multiple existing paradigms in data transport for use in industrial environments (IEC 62541-[1-14]:2020, 2020). These include transport protocols, data formats, communi-

[a] https://orcid.org/0000-0001-8601-7820
[b] https://orcid.org/0000-0002-1883-6813
[c] https://orcid.org/0000-0002-4073-1487

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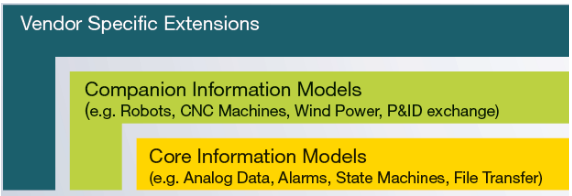

Figure 1: Hierarchy of Information Models in OPC UA (OPC Foundation, 2019).

cation paradigms such as server-client and publish-subscribe and means of secure communication like encryption algorithms. On top of this technological foundation of data transport, OPC UA defines rules for data representation and collaborating parties use these rules to define data representations for different domains (OPC Foundation, 2022c). These data representations are called information models and are hierarchically structured as shown in figure 1. The main goal of information models is to describe the structure of data and its intended usage on an OPC UA interface. The "Core Information Models" contain the most general aspects, intended to be reused in all subsequent information models. "Companion Information Models" are often defined by collaborating parties and contain data models for a specific use-case or domain. The models regarded in this work are all companion information models, described in so-called companion specifications (CS) (40501-1, 2020; 40083, 2021; 40077, 2020; 40301, 2022; 10030, 2013; 10031-4, 2021; 30260, 2020; 40100-1, 2019). For individual information models, often defined by a single company, there is the information model group of "Vendor Specific Extensions".

The CS are defined by a so-called joint working group consisting of OPC Foundation members of the respective domain. This working group defines the applications and use cases for the CS, develops the information model and edits the CS documentation. Resulting CS do include concepts, that are similar in principle, but handled differently in various CS. Such a concept is the representation of production jobs. Based on the description of all CS published by the OPC Foundation (OPC Foundation, 2022a), the CS for Machine Tools, Plastics and Rubber Machinery, Flat Glass, OPEN-SCS, ISA-95 and Machine Vision contain an information model describing jobs (40501-1, 2020; 40083, 2021; 40077, 2020; 40301, 2022; 10030, 2013; 10031-4, 2021; 30260, 2020; 40100-1, 2019).

In OPC 40501, the CS for machine tools, the job model focuses on times spent per program, part and job for a communication for systems like MES (Manufacturing Execution Systems). The individual entities, programs, parts and jobs, have key indicators like a unique identifier. However, more complex properties like identification of material lots used in parts or a detailed representation of subprogram structures is not included. The machine tools model is representing the job without providing an interface to control it. (40501-1, 2020)

Two of the specifications for plastics and rubber machinery contain information about jobs, namely OPC 40083 and OPC 40077. In combination, they provide a communication interface between machines and MES systems. The job description contains the planned jobs and related information as well as a management interface for production data like programs. Using this interface, some aspects of production like enabling and disabling automatic runs, can be controlled by an OPC UA client. (40083, 2021; 40077, 2020)

The model of OPC 40301 aims to provide a communication interface between MES or ERP (Enterprise Resource Planning) and glass processing machines. It represents jobs, instructions used for production and the material used in production. In addition to representing the state of jobs, the model also allows to manage jobs by e.g. adding, deleting, suspending and releasing jobs. (40301, 2022)

The specifications OPC 10030 and 10031-4 are mappings of the ISA-95 standard defined by the ISA (International Society of Automation) to communicate between MES and diverse manufacturing software systems. OPC 10030 contains models for management of material, personnel and components. In OPC 10031-4, these models are extended by means to control machine jobs. The jobs are connected to the related material, equipment, physical assets and personnel. In addition, the interface allows to control jobs. (10030, 2013; 10031-4, 2021)

The specification of OPC 30260, representing the Open Serialization Communication Standard (OPEN-SCS) in OPC UA, utilizes the ISA-95 standard and is thus implicitly represented in this work, but not explicitly analyzed (30260, 2020).

In OPC 40100-1, communication among machine vision systems and between vision systems and controllers or MES is specified. Machine vision systems are used e.g. to gain information about production quality and to identify products. In the OPC UA model, jobs are displayed as "recipes", and can be modified over the interface.

Even though the different models exist and are known to the specification groups, no comparison or comprehensive overview has been developed so far. With such a comparison, the individual concepts and aspects of each model can be compared and be used as groundwork for a harmonized model containing all

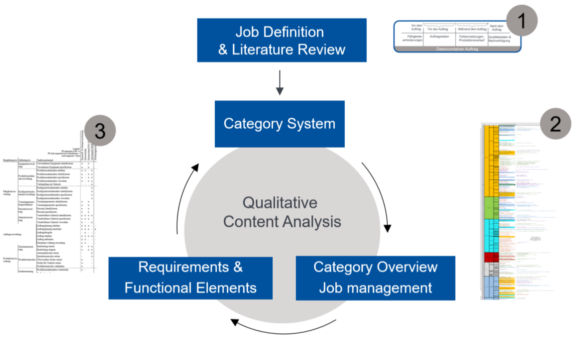

Figure 2: Qualitative Content Analysis for OPC UA CS.

aspects. For such a harmonized model, all information needed for production and thus also the information contained in the job model, needs to be included. In addition, the tasks in job management that are currently contained in the individual specifications need to be portrayed. The analysis shown in this work aims to find the information contained in job models as well as the tasks in job management necessary to transmit between communication partners as indicated by the existing OPC UA job models.

3 METHOD

To identify the information contained in existing OPC UA job models as well as the tasks in job management displayed in these OPC UA job models, a structured qualitative content analysis is performed.

This kind of analysis strives to generate a detailed understanding of the models in the specifications. For this analysis, first a set of main categories is defined. The first set of categories is defined a-priori by means of a literature review. In Figure 2 this is depicted as step 1. Individual elements of the OPC UA models are then categorized according to the category set; in the end all elements need to be included in a category. This is shown in step 2 in Figure 2. The category overview in the sketch contains all elements with their sources and additional information. By analyzing the elements in each category, finding similarities and differences, sub-categories can be deducted based on the evaluated contents. In figure 2 this is represented by step 3. The result is an overview of functional elements in CS, that can be used as requirements for the generation of new specifications or for harmonization of existing CS. In this step, the previous categories can be modified if needed. If so, the elements in the specification are assigned to the new categories again. For this reason, the process is drawn as a circle in figure 2. In the end, all delimitable elements are assigned to at least one category. (Kuckartz, 2012)

Table 1: Categories for Job Models Defined in OPC UA CS.

Main category	Sub category
Data for job preparation	Ensure capability
Data for job execution	-
Data during job execution	Production state
	Production mode
	Execution information
	Parameter monitoring
Data after job execution	-
Resource capability description	Equipment description
	Production data set description
	Configuration data set description
	Variant parameter description
	Personnel description
	Material description
Job management	-
Production management	Machine control
	Production mode
	Device control
	Production parameters
Result management	-
Safety	Functional reliability
Security	Authenticity
	Availability

4 CATEGORY SYSTEM FOR EXAMINED JOB MODELS

Table 1 shows the categories for the information and task management elements contained in a job. The data for job preparation concerns checking the capabilities and capacities of machines needed in advance to schedule and start production activities. As soon as a job is scheduled, the information required by machines to execute the job is sent to the machine.

During job execution, the machine transmits information for systems to monitor the production.

This category is subdivided in information about the state and the operation mode of the machine, as well as in information about the job execution itself and the monitoring of job-related parameters.

After job execution, results and information for product tracing are transmitted.

The capabilities of machines are not only needed in advance to start a job but also to manage it during execution. Furthermore, they need to be adapted independent of jobs, like information about tools available on the machine. For this reason, a category for resource capability description is considered. Subcategories include the description of equipment used in production, like tools and fixtures, personnel required for the job, and material used in production. The production data set description contains programs and instructions for production. The description of configuration data sets concerns settings that can be made on machines and production equipment. And the variant parameter description contains all information that changes in different variants of similar products.

The category job management contains elements, e.g. used to add or delete jobs on machines.

All information concerning functions like starting or stopping the job is gathered in the category production management. The respective subcategories further specify if actions concern the machine control, change the production mode, control additional devices apart from the machine itself or changes of parameters like controller settings or tolerances.

If the communication partner can control how and how long results are available, especially independent of active jobs, the respective elements are categorized as result management.

For the operation of manufacturing equipment, safety plays a crucial role. As to communication partners, ensuring the functional reliability by informing about errors and invalid system states is identified in the OPC UA specifications.

In terms of security, OPC UA itself provides options for authentication of communication partners, as well as methods to encrypt the data transfer. For this reason, these aspects don't need to be handled explicitly in companion specifications. Nevertheless, in the examined specifications, aspects related to authenticity and availability and thus to security are included.

5 RESULTS

Within the categories and sub-categories, the elements are evaluated and grouped using the following common functional elements. More than 70 functional elements for job models are found. The categories and the functional elements therein are shown in table 2. In the rightmost five columns, the existence of a functional element in the specifications is shown with an "x". The following text will use the abbreviations for the specifications used in the table.

In the category "Data for job preparation", PAR, G and V are represented. The models provide lists of configurations and available job data like machine programs.

Concerning the category "Data for job execution", MT is the only specification without elements in this category. All other specifications' models contain most of the functional elements identified. For the functional element "Production data set", different modeling approaches are used to link a data set to a job. PAR, I95 and V transmit the data set ID to link to the job, while G requires to transmit the data set along with the job. In similar fashion, material data is referenced by ID in PAR, I95 and V while for G all types of material are provided wile creating a job. I95 only makes a difference between resources and resource classes. A resource class represents the material properties in an abstract fashion (e.g. size) while resources are directly linked to real material (e.g. with lot number).

The functional elements in "Data during job execution" are apparent in all specifications. They follow similar OPC UA modeling principles in all specifications. The same can be said for the three specifications implementing "Data after job execution".

Each specification contains functional elements of the category "Resource capability description". However, MT and G only implement few functional elements while PAR, I95 and V implement the majority. Concerning similarities and differences in modeling, one sub category is taken as an example. As a sub category, the material description occurs in all specifications but MT. In I95, the material is represented in an array structure containing material IDs. In PAR and V, a list containing entries that directly represent the material is used. G, on the other hand, uses an array containing references to the OPC UA representation of the material.

The category "Job management" again is present in all specifications. The MT specification however only implements one functional element, "Display job plans". Concerning job plans, the representations differ: MT and G use a list, while I95 and PAR contain the priority and intended start time of jobs. While the list in MT and G represents the production order of jobs, I95 uses an array for this information while PAR displays the current and the upcoming job. For the functional element "Receive job", however, PAR, G, I95 and V use OPC UA methods, and thus similar modeling concepts.

Table 2: Overview of functional elements and their occurrence in CS.

PAR: OPC 40083 and OPC 40077 (Plastics and Rubber)
G: OPC 40301 (Flat Glass)
I95: OPC 10030 and OPC 10031-4 (ISA-95)
V: OPC 40100-1 (Machine Vision)
MT: OPC 40501 (Machine Tools)

Main category	Sub category	Functional element	PAR	G	I95	V	MT
Data for job preparation	Ensure capability	Filter and transmit capabilities	x			x	
		Prerequisites		x			
		Add capabilities	x			x	
		Request capabilities	x				
Data for job execution		Job identification	x	x	x	x	
		Job description	x		x		
		Production data set	x	x	x	x	
		Variant parameters	x		x	x	
		Job meta data	x	x	x		
		Material data	x	x	x	x	
		Equipment data	x	x			
		Personnel data			x		
		Instructions	x				
Data during job execution	Production state	Informative	x	x	x	x	x
		Interaction needed (Server)	x	x	x	x	x
		Interaction needed (Client)	x				
	Production mode	Informative	x			x	x
	Execution information	Job identification			x		x
		Job description			x		
		Process duration	x	x	x		x
		Products	x		x		x
		Resources used			x		x
	Parameter monitoring		x	x			x
Data after job execution		Product data	x			x	x
Resource capability description	Equipment description	Identify usable equipment	x		x		x
		Specify usable equipment	x		x		x
		Show inactive equipment	x				
	Production data set description	Receive production data sets	x			x	
		Identify production data sets	x		x	x	
		Specify production data sets	x		x	x	
		Manage production data sets	x			x	
		Material relation				x	
		Show inactive data sets				x	
	Configuration data set description	Receive configuration data sets				x	
		Identify configuration data sets				x	
		Specify configuration data sets				x	

Table 2: Overview of functional elements and their occurrence in CS (cont.).

PAR: OPC 40083 and OPC 40077 (Plastics and Rubber)
G: OPC 40301 (Flat Glass)
I95: OPC 10030 and OPC 10031-4 (ISA-95)
V: OPC 40100-1 (Machine Vision)
MT: OPC 40501 (Machine Tools)

Main category	Sub category	Functional element	PAR	G	I95	V	MT
		Manage configuration data sets				x	
		Show inactive data sets				x	
	Variant parameter description	Identify variant parameters	x		x		
		Specify variant parameters	x		x		
	Personnel description	Identify personnel	x	x	x		
		Specify personnel	x	x	x		
		Inform about inactive personnel	x				
	Material description	Identify material	x	x	x	x	
		Specify material	x		x		
		Manage material	x			x	
Job management		Receive job plans	x	x	x		
		Display job plans	x	x	x		x
		Release job		x			
		Receive job	x	x	x	x	
		Request job	x	x			
		Job management meta data		x			
Production management	Machine control	Start processing	x		x	x	
		Stop processing	x		x	x	
		Request sample product	x				
	Production mode	Set automatic mode				x	
		Set simulation mode				x	
		Set supervised mode	x				
		Prevent production mode	x				
	Device control	Forward production data sets	x				
		Inform about devices	x	x			
		Control device	x				
	Production parameters	Production settings	x				
		Supervision settings	x				
Result management		Provide results				x	
		Identify results				x	
		Specify results				x	
		Manage results				x	
Safety	Functional reliability	Information				x	
		Prevent undefined system states		x			
		Lock processing	x	x			
Security	Authenticity	Server settings	x		x		x
	Availability	Limit number of clients	x	x			
		Optimize computing resources				x	

Category "Production management" contains multiple diverse functional elements that are largely supported by PAR and V, G and I95 support individual functional elements. They are largely similar in design if multiple specifications support a functional element, the only exception is the sub category "Production mode". While V models the machine state using the concept of a state machine (displaying states and possible transitions between them), PAR only displays possible states using an enumeration.

The category "Result management" is only included in V.

The categories safety and security show sparse occurrence in the specifications. In the safety category, the functional elements contain model elements reporting safety relevant system states, preventing undefined system states and locking operations on the interface. The G specification allows locking the production of a job, while PAR provides the ability to prohibit changes in data sets. Concerning security, the specifications contain diverse measures, like requiring a specific minimum strength of encryption algorithms for data transmission, limiting the number of simultaneous service users and providing the option to delete unused data and thus optimize computer resource usage.

6 ANALYSIS

When looking at the functional elements contained in the different specifications in table 2, the PAR specification clearly contains the most functional elements. Compared to G, MT and V, the PAR specification is older, with its first release in 2016 and updates to the specification since. In addition, both PAR and I95 are based on previous existing standards while G, MT and V have developed the model initially for OPC UA.

The V specification stands out, being the only specification including configuration data set description and result management while including fewer of the functional elements in data during job execution and job management than the other specifications. This might be attributed to the difference in the type of device: While the injection molding machines of PAR, the glass processing machines and the machine tools all generally use input materials to produce output materials or parts, the vision systems don't touch the items they are processing. Moreover, a process on a vision device is often much shorter and involves fewer individual steps, e.g. a program for a milling machine. In addition, parameters like temperature and forces, that are often monitored during different production processes, do not occur in the same context for machine vision.

The G, I95 and MT specifications cover many of the same functional elements, with the MT specification implementing the fewest functional elements. One reason for this is the MT specification not defining interaction possibilities on the OPC UA interface - neither can jobs be managed (added, deleted, edited etc.) nor can the production be managed (start, stop, set modes, ...).

Especially in the categories "Data for job execution", "Data during Job Execution" and "Job management", all specifications show similarities. Both in the functional elements they implement, but largely also in the way, these functional elements are implemented. In cases where the specifications handle functional elements differently, the same information is conveyed, be it the style of reference between job and production data set or the order of execution, if multiple jobs are present.

Major differences between the specifications arise in "Data for job preparation", "Resource capability description", "Production Management" and "Result Management". In "Data for job preparation", V focuses on recipes, on descriptions of process steps. PAR focuses on production data sets. G informs about prerequisites like the allowed file format accepted in file transfer. As the examples are this sparse, this category seems to be less focused on than the categories more closely related with job execution.

The whole sub category "Configuration data set description" only appears in V. This might be due to the different domain of vision systems and subsequently to the greater significance of configuration data. However, configuration data may still be of value for the other domains. Similar assumptions are true for the category "Result management". For the V specification, the process results are the main process outcome, as the product is in the other four specification domains. And the "Products" functional element (Data during job execution), the "Product data" functional element (Data after job execution) and the "Material description" subcategory (Resource capability description) are implemented widely among the specifications.

When regarding safety and security, neither CS contains comprehensive measures. This seems odd given the importance of those two domains in machinery and industry 4.0. However, the safety in machinery is usually ensured at controller level. So regardless if a start/stop command originates from the machine panel or the OPC UA interface, the controller checks if that command can be safely executed. For this reason, the safety functions themselves don't need to be included in the interface.

In case of security, the CS contain few and diverse measures. This aspect is to be regarded with the architecture of OPC UA in mind. Most CS don't specify the security algorithms to be used, similar to them not specifying the transmission protocols to be used. This leaves all possible security algorithms described in OPC UA Part 2 as possible choices for implementation along with the CS model (OPC, 2018). Similarly, the number of maximum clients usually depends on the hardware resources of OPC UA server products. The handling of server resources is therefore often not part of the CS.

7 DISCUSSION

Using a structured qualitative content analysis on OPC UA CS yields a more profound understanding of functional elements focused on in the group of CS. This kind of understanding achieves the goal set in this work: to identify the information contained in existing OPC UA job models as well as the tasks in job management displayed in these models. However, such a structured content analysis may produce different results based on the initial chosen set of categories. A different set of categories used in this case would have led to a different structure in the resulting overview. However, it is likely that the goal of this work would still have been achieved.

As this work only regarded existing specifications, the job model may not be complete, including all aspects possible. The result also does not take job models in other representations than OPC UA into account. Still, some models are not OPC UA specific, but rather implementations of previously existing standards in OPC UA (40083, 2021; 40077, 2020; 10030, 2013; 10031-4, 2021). The benefit of limiting the analysis to OPC UA models is a higher comparability of modeling techniques, as all models regarded in this work have to follow the same rules.

As a result of the content analysis, the overview presented in table 2 has been created. This overview can now be used as a basis in extending or harmonizing the above models. The category system developed in the analysis could even be used itself to structure data on OPC UA interfaces. Additionally, the category system serves as a basis to identify the elements that are important to model. This prevents working groups from overlooking aspects, that other specifications already contain. The additional documents generated in the analysis also serve as a guideline how these elements may be modeled.

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