MACHINE OPERATION RESEARCH - PRODUCT AND MACHINE DATA INTEGRATION

Dipl.-Ing. Dipl.-Kfm.(FH) Arndt S. G., Dipl.-Ing. Klement S., Dr.-Ing. Saske, B., Prof. Dr.-Ing. habil. Stelzer R. H.
Faculty of Mechanical Science and Engineering – Technische Universität Dresden, Germany
stephan.arndt@tu-dresden.de

Abstract: *Data from machine operation is an important source for product-relevant quality aspects. The integration of machine data into the digital product life cycle processes enables the improvement of products, systems and processes. In product development in particular, future machine generations can be engineered being more adapted to the requirements for operation issues during use phase, enabled by product and machine data inspection and analysis. In this paper, we propose a comprehensive and generic reference data model called Field Data Model (FDM), organising well-structured product and machine data. The FDM is part of Product Lifecylce Management (PLM), enabling data integration from heterogeneous data sources like PDM, machine control systems and machine-related sensors. The FDM is part of a Field Data Management System (FDMS) that is used to automatically set up and organize Field Objects (FO), representing – real or virtual – machines or machine components of special interest to machine manufacturers or machine operators.*

Keywords: Product Lifecycle Management, Data Integration, Lifecycle Engineering

1 Introduction

Information on machine status and behavior just as from operation processes during use phase – encoded by machine data – are sources of innovation. In product development, machine data can be used to improve future machine generations that are more reliable and better meet the requirements for operation issues. Even the value of current machine generations can be sustained or increased by machine data [1, 2]. In the use phase, product data can be utilized for machine reconfiguration [3]. Product data can also be used to eliminate or prevent machine errors [4]. In this way, there is a growing demand for an intensive cross-exchange of data between the operating and development phase. Hence, machine manufacturers in particular have great interest in gathering and analyzing machine data to extract valuable information. Only a limited amount of machine data is currently used yet.

Machines are increasingly equipped with sensors, computer systems and modern communication interfaces that provide the required machine data. Satisfying the demand for machine data also needs to face organizational deficits with respect to company-wide data and process management. The fact of different machine models, configurations and generations coming from different machine manufacturers and being used by different machine operators results to a wide spectrum of possible combination. The inherent complexity currently can only be managed with considerable effort.

Product and machine data need to be integrated consistently to get valuable gain of information as described by the so-called Closed-loop PLM concept [2]. Approaches for product and machine data integration only implement one-sided storage using the machine manufacturer's Product Data Management (PDM) [5, 6]. Concerning this, data is beyond the control of the machine operators whose interest, however, is to protect their data and not to pass it unregulated to the outside world. Machine manufacturers are also aware of their data. The protection of expertise prohibits the unwarranted transfer of product data to the machine operators. Binding regulations and contracts are necessary to overcome the implied organizational deficits. Furthermore, the development of fundamental concepts and models for product and machine data integration needs to be taken forward.

2 Related Work

2.1 Product Lifecycle Management

PLM is a strategic and integral management approach for process and data integration relating to the product life cycle that is a core process of industrial companies. It starts with product development, production and ends up with product use and recycling phase. Product development comprises the planning of products, associated equipment, resources as well as manufacturing processes [7]. PLM specific processes, methods and tools enable the availability and provision of product information at the right time, in the right quality and order as well at the right place. PLM ensures a consistent and persistent information storage using PDM as data backbone.

PLM is well established in product development and production. Otherwise, the integration of use phase specific resources and systems with PLM is insufficiently solved [8, 9]. Data provided by machines is often incomplete and not available in the required quality for product development objectives. Management systems increasingly face the challenge of managing and leveraging information from the use phase efficiently, using specific data and process models. Therefore, PLM will be used increasingly in the operational phase in the future [10].

2.2 Product Data

Modern Product Development is characterized by a holistic and systemic product view that has led to changes in the way products are developed. Digital tools for product design, simulation and production planning are omnipresent. The intensive use of these development tools causes an increased volume of product specific and life cycle relevant data [7]. This data is part of the product model, the result of product development [11, 12]. Finally, any machine is an instance of a specific product model configuration.

Domain-specific engineering models describe each functional, physical, organizational and geometric aspect of a prospective machine. All these product aspects are encrypted by data that is heterogeneous in type and rely on various data models respecting domain- and modelling tool-specific particularities. Such structured data is usually stored in files. Files contain metadata, considering information for description and administration.

Product data is managed by PDM in a consistent and structured way. PDM ensures the unambiguous reproducibility of any product configuration. Figure 1 shows the PDM Basic Data Model. As a core concept of PDM, file-based engineering models are organized using documents. Thus, in the Entity Relationship Diagram the entity type *Document* is related to *File* – a *File* again is stored in a *Vault*. *Part* entity type represents all components that are necessary to produce a configuration-right machine.

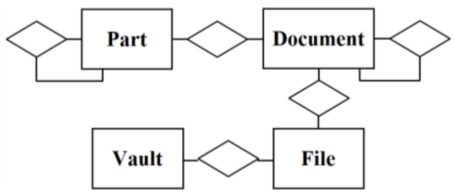


Fig. 1 *The PDM Basic Data Model*

In the PDM context, all entity types have well-defined semantics. It can be assumed, most PDM applications are built on the PDM Basic Data Model. Thus, each entity type can theoretically be used for data integration purposes but from a strategic perspective, *Part* entity type is most appropriate. The top part of the hierarchical organized part structure corresponds to the machine or a machine component configuration to be manufactured.

2.3 Machine Data

Machines are increasingly equipped with sensors that collect various operating data regarding machine state and operation processes. Such data is primary used for automation purposes, ensuring trouble-free machine operation. Because of the advancing digitization and networking of machines, the total volume of operating data, generated by sensors and information-processing devices, has increased worldwide – from 2010 to 2015 by a factor of 10.000 – up to 10 Zettabyte [13]. By 2020 and beyond an exponential growth of this data volume is predicted. In 2025, 160 Zettabyte of new data is expected to be generated [14].

Machine data is part of the technology related operating data (Table 1). It is assigned to specific machines or machine components. Machine data can also be interpreted as field data that results out of the interaction between user and machine during operation phase.

Table 1: *Types of Operating Data [15]*

Operating Data			
Organisation related Data		Technology related Data	
Job Data	Personal Data	Machine Data	Process Data
job status, number of manufactured pieces etc.	attendance and working hours, labour costs etc.	error messages, consumption of resources, sensor readings etc.	quality, adjustment, process parameters etc.

Field data provide quality-relevant information about machine usage [16]. It can also be assigned right to specific machines or machine components. Thus, machine data is an integral part of PLM. It can be interpreted as an intersection of operating and field data (Figure 2).

Fig. 2 *Machine data as an intersection of operating and field data*

Depending on data sources and communication requirements, machine data can be structured or semi-structured. Structured data is commonly found in database management systems. Semi-structured data is typical for spreadsheets or flat files [17]. In this context, communication technologies like OPC UA have become de facto industry standard protocols for data exchange and integration purposes e.g. in the promising field of Industrial Internet of Things. Such protocols are based on very own data models that are adapted for storing device information, error protocols or communication data.

Different data models deriving from various data sources like standardized communication protocols can be traced back to a general structure and more generic view on machine data as shown in Figure 3. The entity type *Information Object* represents any kind of physical, information relevant thing like a production plant, a machine or machine component. The entity type *Object Item* is kind of a wildcard and stands for any structured Information related to an Information Object. The Generic Machine Data Model can be used for historical data, stored in distributed and heterogeneous databases, as well as for machine live data. Regarding data analysis objectives, the Generic Machine Data Model can also be used to organize training datasets.

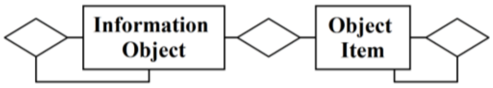


Fig. 3 *The Generic Machine Data Model*

3 Data Integration

3.1 Methodology

A profound understanding of the structures and semantics of product and machine data is essential for successful data integration. According to the IEC TC 65/290/DC, several harmonization levels are differentiated in order to establish compatibility of information systems. Each harmonization level refers to a specific object for integration. Data integration initially requires the integration of data models (IEC, 2002). In our case, the data models from product development and machine operation can either be integrated by bilateral conversion rules (loose coupling) or by a integration data model as reusable artefact (close coupling) [18]. In this paper, an integration data model called *Field Data Model* (FDM) is proposed that meets the following core requirements:

1. The integration data model realizes the consistent linking of product and machine data in a structured form.

2. The integration data model is usable for various purposes of data usage like data query, analysis and visualization across multiple domains.

A stringent methodology is required to meet the core requirements. In Design Science approved research methodologies exist, which can be used to support any artifact development (like data models) [19]. The basic prerequisite for a successful development outcome is a deep understanding about the contextual information background. Reference catalogues and suchlike can be used to fall back on verified basics [20].

3.2 Field Data Model

The FDM is a comprehensive and generic reference data model. It can be adapted to create individual data models for application cases as for machine tools, electronic devices or automobiles. FDM can be modified to meet the application-specific requirements and realize the consistent linking of product and machine data. Data sets based on the FDM can be used by different resources and users of PLM.

According to [21] the FDM is designed as a three-part model. The *Part Data Model of Product Development* – the lower of the FDM (see Figure 4) – is partially based on the PDM Basic Data Model (see subsection 2.2). Document, File and Vault entity types are used for the *Part Data Model of Machine Operation* – see the upper part of the FDM. This data model follows the generic view on machine data, as described in 2.3.

Both part models are linked by a single entity type called *Field Object* (FO) as key element for model integration. The FO is a virtual representation for exclusive machines as well as machine components that are of special interest to machine manufacturers or machine operators. Such machine components can have a mechanical, electrical, electronic or information processing background. The FO is related to the *Information Object* and *Part* entity types, considering any number cardinalities including zero. In other words, a FO can be related to no or any number of parts or information objects.

The inverse relations of FO result in a sub-data model called *Field Object Structure* (FS) (the broken line bordered area in Figure 4). A FO can be related to no or any number of FO. Such relations representatively describe – logical, mechanical, electrical or topological-related – couplings and interactions between machines or machine components. Thus, the FS represents relationships that do not exist in any engineering model. For instance, the closeness of

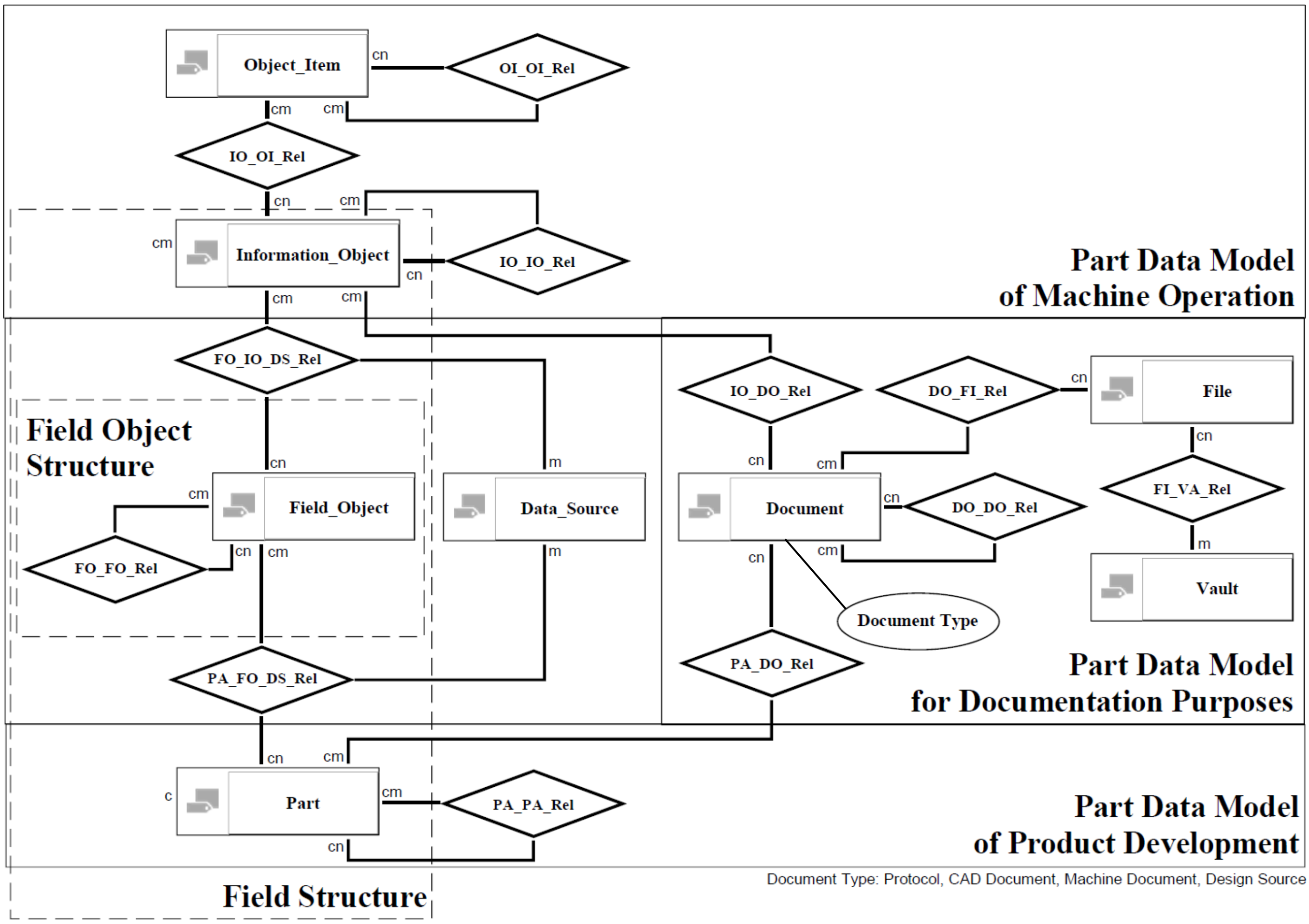


Fig. 4 The Field Data Model

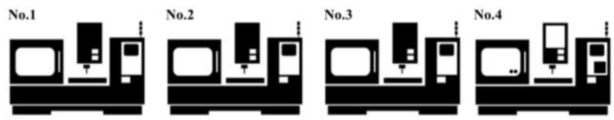
machine components belonging to different machines standing next to each other on the shop floor can be relevant for data analyses. For this reason, the information about the distance between these machine components and their mechanical coupling need to be part of a shared data set.

Structured FO can also be used to group several FO that logically fit together like from machines of the same configuration or type, for example. In this way, locally separated machines are linked from a data perspective, even if they are neither physically coupled nor connect by communication technologies. Thus, queries or analyses on product data and data from grouped machines are possible.

FDM adaption as well as FO creation and structuring need to be planned thoroughly for individual data utilization needs. Thus, successful data integration, using the FDM, requires manual intervention to a certain extent. FO for grouping purposes and for special analysis tasks in particular need to be manually added and linked. Such FOs, unlike those described above, cannot be derived from a hierarchically organized article structure

As use case, a machine configuration is manufactured three times (No. 1 to 3, see Figure 5). Thus, these machines share the same part (ID 1) but are represented by different information objects (ID 1 to 3). They are grouped and linked by one FO (ID 1). A second machine configuration is manufactured uniquely (No. 4, see Figure 5). In this case, only one part (ID 2) and information object (ID 4) exist that are also linked by one FO (ID 2). Both FO (ID 1 and 2) are also linked.

The result is an individual data model representative for data sets that is usable for data analyses. In this example, the sensor readings and events of all three machines (No 1 to 3) can be analyzed and evaluated simultaneously. This approach is used to identify similarities and differences in the machine operator's usage behaviors. They also have exclusive access to the latest development results stored in PDM. These are, for example, product documentations.



Part
ID
1
2

PA_FO_Rel	
ID_1	ID_2
1	1
2	2

Field Object
ID
1
2

FO_FO_Rel	
ID_1	ID_2
1	2

FO_IO_Rel	
ID_1	ID_2
1	1
1	2
1	3
2	4

Information Object	
ID	No.
1	1
2	2
3	3
4	4

Fig. 5 *Example for Field Object entities and relations*

Back to the FDM (see Figure 4), the *Part Data Model for Documentation Purposes* – right side of the FDM – is primarily used for file management issues. Each Document entity has a specific Document Type. Protocol type, for example, allows the management of protocol-specific files that log information about decision-making and work output relating to FS planning.

4 Discussion and Future Work

The proposed FDM realizes data integration via structured FO in an abstract way. The generic approach of a reference model remains solution independent. The implementation of diverse software tools for product and machine data integration and management is possible.

The Generic Machine Data Model in particular (see Figure 3), does not represent any standardized information models like from OPC UA. Each machine specific information model must be individually and dynamically adapted to fit the Generic Machine Data Model. This work includes the definition of reasonable, machine specific attributes that are necessary and applicable for data analysis purposes. Alternatively, it is more reasonable to define general attributes. For example, any sensor (Information Object) has Measured Value and Measurement Time as attributes related to the Object Item ‘Measurement’. This example indicates unequivocally, general data from operation phase like sensor readings is currently not sufficiently considered by the FDM. For that reason, we are planning to extend the reference data model by commonly used entity types. However, the final adaptation of the FDM requires the active involvement of machine manufacturers and machine operators. Individual requirements must be fulfilled to set up analyzable data sets based on the FDM.

A vast and growing amount of machine data is already available nowadays that need to be managed efficiently. In particular, the raw data provided by sensors cannot be integrated in product development processes without being processed. Thus, machine data integration is inefficient without data reduction and preparation. The utilization of the available machine data exceeds in particular the capacities and capabilities of small and medium-sized enterprises. Thus, a process model closely adapted to the FDM is required, which involves data preparation and reduction.

Creating and linking FO manually is time-consuming and at high risk of error. It is almost impossible to create a Field Structure of complex assemblies manually. For this, new digital tools are required. These tools can be part of different product life cycle processes. In product development, structured FO for example can be generated manually or automatically after design release. Another challenging problem to be solved is the consistent linking of FO and Information Objects. Such links must be fully established after production phase. Appropriate digital tools are also required for this purpose.

An information system for FO management is required to solve the problems being discussed. In [21] the architecture of such a management system called *Field Data Management System* (FDMS) is described. The FDM is an integral part of such a FDMS that has interfaces to databases of product development like PDM and machine operation. From a functional perspective, the FDMS fully implements the document-based management approach, which is already part of the FDM (see subsection 3.2). This approach meets the same administrative policies that are essential in PDM. FO-release and change processes are possible.

Further work about semantics is also necessary. Finally, no semantics is required for pure data integration but common and unified semantics is an essential requirement for successful data evaluation and interpretation.

5 Conclusion

In this paper, we proposed a comprehensive and generic reference data model called Field Data Model, organizing well-structured product and machine data and being a prerequisite for cross-domains data queries or analyses. The Field Data Model is part of the Product Lifecycle Management strategy, enabling data model integration from heterogeneous data sources from product development and machine operation. The data required for data integration are from the Product Data Management as well as from machine-related information objects like sensors or machine control systems. The Field Data Model is an integral part of an information system for Field Data Management that is in development. Machine demonstrators of different application cases confirm the validation of such a management system.

6 References

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