Informatics

Smart Manufacturing Systems: Model-Driven Integration of ERP and MOM

DISSERTATION

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to Anna, Emil, and Arthur

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Our family would not be complete without my parents, who have always supported me in every way they could. Thank you so much for this—I am taking a leaf out of your book!

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Abstract

Automated production systems are following a general technological trend: increasingly complex products, combined with drastically reduced lot-sizes per product variant, as well as shorter response and production times are being demanded. In order to be able to meet these expectations, modern IT systems at all levels of the automation hierarchy are required: from business related software at the corporate management level, down to the programmable logic controllers at the field level. For a well-designed coupling of systems that are located at different levels, it is necessary to find, define, and implement clear data conversion mechanisms—this endeavor is also known as *vertical integration*. At the same time, it is necessary to automate the inter-organizational data exchange—an aspect of *horizontal integration*.

If integration succeeds, and decisive systems are flexible enough with respect to their software and hardware components, we can speak of so called *smart manufacturing systems* that are able to adapt to new situations spontaneously. This flexibility can be related to different elements of a production system:

Products: modern production systems should be able to produce diverse and variable products. This includes products that have not been conceived when the production system has been engineered and commissioned.

Processes: the capabilities that are offered by a production system can evolve over time as well. New production processes can emerge, for instance, through new or re-arranged resources, as well as through novel requirements of certain products.

Resources: are also volatile in various aspects. They can be defect, need to be maintained, are procured, retired, and replaced. Some of them are mobile and can be continuously re-arranged, etc.

Model-driven engineering, leveraging concepts from model-driven software engineering, provides a rich set of techniques, tools and methods for the formalization of domain models as well as for the loose or close coupling of them. Focusing on conceptual models and their instances enables the precise definition of knowledge that can be later on used formally, such as for data validation. Concepts, such as model transformations facilitate the conversion of design time and runtime information between different domains.

In this cumulative thesis, we are recapitulating a selection of own contributions; with respect to the conceptual models we have been employing established industrial standards, in order to facilitate industrial application. By doing so, we have focused on the upper levels of the automation hierarchy, yet we have also partially considered the lower levels. Our approaches and implementations have been successfully evaluated by a number of experiments and case studies and are therefore a contribution towards model-driven smart manufacturing systems. Our research shows that the application of model-driven engineering techniques and tools can be useful within the following scenarios:

Vertical Integration: by providing mapping and transformation rules for elements of different conceptual models, such as those representing information technology systems of the the enterprise resource planning or manufacturing operations management levels.

Declarative Manifestations: creating explicit and structured artifacts of static (models) and dynamic (transformations) nature. In our work, we are applying thereupon transformations, validations, and code generators in order to convert between domains or doublecheck data consistency.

Knowledge Inference: transforming declarative information into logical expressions for the efficient computation of new knowledge that can be fed back into models or other data structures for further usage. We have been using this approach for the spontaneous computation of production plans from production system models.

Kurzfassung

Die Welt der automatisierten Produktionssysteme ist im Umbruch: immer komplexere Produkte, kombiniert mit drastisch reduzierten Stückzahlen pro Produktvariation sowie kürzeren Antwort- und Produktionszeiten, werden gefordert. Um diesen Anforderungen gerecht zu werden, bedarf es der Unterstützung moderner IT-Systeme auf allen Ebenen der produzierenden Betriebe; von den Geschäftsanwendungen der Unternehmensleitebene bin hinunter zu den speicherprogrammierbaren Steuerungen der Feldebene. Um unternehmensintern die Systeme unterschiedlicher Ebenen bestmöglich zu verknüpfen, müssen klare Datenkonversionsmechanismen gefunden, definiert und implementiert werden – man spricht von *vertikaler Integration*. Gleichzeitig ist es notwendig, den inter-organisationalen Datenaustausch automatisiert umzusetzen – ein Aspekt der *horizontalen Integration*.

Wenn diese Integration gelingt, und die entsprechenden Systeme sowohl Software- als auch Hardware-seitig ausreichend flexibel ausgestaltet sind, spricht man von *intelligenten Produktionssystemen*, die sich spontan auf jeweils aktuelle Gegebenheiten einstellen können. Diese Flexibilität kann folglich unterschiedliche Elemente eines Produktionssystems betreffen:

Produkte: Moderne Produktionssysteme sollen in der Lage sein, unterschiedliche oder variable Produkte zu fertigen. Dazu gehören auch Produkte, die bei der Planung und Inbetriebnahme der Produktionsanlage noch nicht bekannt waren.

Prozesse: Die Fähigkeiten, die ein Produktionssystem anbietet können ebenso einem Wandel unterzogen sein. Neue Produktionsprozesse können sich etwa durch neue oder neu angeordnete Ressourcen sowie durch neuartige Anforderungen von Produkten ergeben.

Ressourcen: Auch die einzelnen Ressourcen einer Produktionsanlage sind volatil in vielerlei Hinsicht. Sie können kurzfristig ausfallen, werden regelmäßig gewartet, werden angeschafft, ausgemustert und ersetzt, können sich bewegen und entsprechend neu arrangieren, etc.

Modellgetriebener Entwurf, mit Anleihen aus dem modellgetriebenen Software-Engineering, bietet eine Vielzahl an Techniken, Werkzeugen und Methoden an, die eine Formalisierung der Domänenmodelle und in weiterer Folge deren lose oder enge Kopplung ermöglichen. Die Fokussierung auf konzeptuelle Modelle sowie deren Instanzierungen ermöglicht es, domänenspezifische Sachverhalte möglichst klar zu definieren und in weite-

rer Folge formal, etwa für Datenvalidierungen, zu nutzen. Konzepte wie etwa Modelltransformationen erleichtern die Konvertierung von Design- und Laufzeitinformationen zwischen unterschiedlichen Domänen.

In dieser kumulativen Dissertation fassen wir eine Auswahl eigener Arbeiten auf diesem Gebiet zusammen; dabei setzen wir bezüglich der konzeptuellen Modelle auf etablierte Industrienormen, um die industrielle Umsetzung zu erleichtern. Unser Fokus liegt auf den höheren Ebenen der „Automatisierungspyramide“, wobei wir auch die unteren Ebenen nicht außer Acht gelassen haben. Unsere Ansätze und Umsetzungen haben wir in einer Vielzahl von Experimenten und Fallstudien erfolgreich evaluiert und damit einen Beitrag zur Umsetzung modellgetriebener intelligenter Produktionssysteme geleistet. Unsere Forschungsarbeiten zeigen, dass die Methoden und Werkzeuge des modellgetriebenen Entwurfs in folgenden Szenarien von Nutzen sein können:

Vertikale Integration: Durch die Definition von Abbildungs- und Transformationsregeln für Elemente unterschiedlicher konzeptueller Modelle, in den in dieser Arbeit vorgestellten Ansätzen vor allem hinsichtlich der Unternehmensleitebene und der Betriebsleitebene.

Deklarative Manifestationen: Die Umsetzung expliziter und strukturierter Artefakte sowohl statischer (Modelle) als auch dynamischer (Transformationen) Natur. In userer Arbeit wenden wir darauf aufbauend Transformationen, Validierungen und Code-Generatoren an, um etwa Daten zwischen Domänen zu konvertieren oder die Datenkonsistenz zu prüfen.

Wissensinferenz: Die Transformation deklarativer Informationen in logische Ausdrücke, um effizient neues Wissen zu berechnen, das wiederum in Modelle oder andere Datenstrukturen zur weiteren Verwendung rückgeführt werden kann. Wir haben diesen Ansatz für die spontane Berechnung von Produktionsplänen verwendet, basierend auf einem Modell des Produktionssystems.

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Chapter 1

Introduction

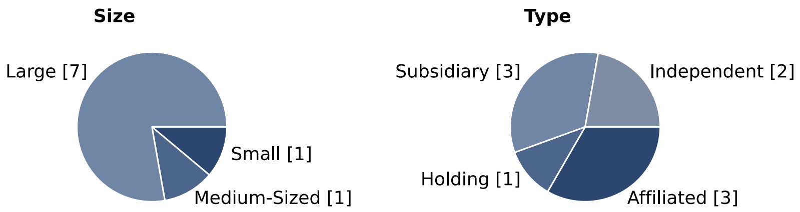
Automated production systems (APSs) are currently undergoing a fundamental transformation from behaviorally static entities to adaptive systems of systems (SsoS). This change process is also known as the fourth industrial revolution, Industry 4.0 (I4.0), and is further referred to by the terms smart manufacturing [Kan+16], industrial internet of things (IIoT) [Boy+18], and cyber-physical production systems (CPPSs) [BGL17]. In our work, we interchangeably use the terms I4.0 and smart manufacturing as umbrella concepts for the application of decentralized networks in order to enable smart computation nodes in production environments to spontaneously exchange data, react to contextual changes, and connect the physical world—through sensors and actuators—with the cyber world.

Smart manufacturing environments require high flexibility in multiple dimensions, such as the resources that make up the production system itself, the products that are to be produced, the material flow throughout the factory, the procedural capabilitites of the shop floor, etc. [Sch12; SOM14]. According to the principles of smart manufacturing, products and their recipes are not required to be known at design time, product variants may be edited at runtime, and production planning and scheduling are to be invoked on-the-fly, when a new production order appears.

This agility is driven by the need for an *adaptive organization* [Dav+12], and it can be achieved by establishing well-integrated information technology (IT) systems [And14]. This integration will have to be implemented by internal IT systems, but also in accordance with external partners; it can be supported by providing *models* for the data to be exchanged. These models are further of importance for many other aspects that are prominent in I4.0 scenarios, such as simulation, optimization and data analytics [Kus18] as well as the *digital twin* [Tao+18]. Such models can be implicitly computed from operations data, or they can be explicitly modeled in a traditional top-down fashion. Either way, as we will show in this thesis, many concepts established in the software engineering community in the field of model-driven software engineering (MDSE) [Ken02] can be beneficial in the context of smart manufacturing, such as metamodeling, queries, views, and model transformations [Sch06].

Integration can be established in horizontal or vertical direction; within a single company and among different enterprises [Sch12]. Vertical integration of neighboring IT systems, e.g., enterprise resource planning (ERP) and manufacturing operations management (MOM), is already a taunting task that materializes a lot of issues that are waiting to be solved [Ehr+19]. While ad-hoc solutions for the integration of two or more specific software tools are an intuitive way to establish data convergence, they are also fostering vendor lock-in, i.e., the cost of changing an IT system for another one from a different vendor are considered to be relatively high [OST16].

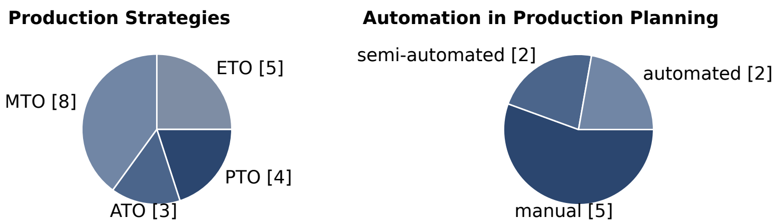
In an initial exploratory study, as part of the InteGra 4.0 (horizontal and vertical interface integration 4.0) project, we have conducted in-depth face-to-face interviews with nine manufacturing enterprises and three software and service providers. The production companies we have interviewed were one small, one medium-sized and seven large enterprises, with varying economical dependencies (cf. Fig. 1).



(a) Sizes of the companies. (b) Types of the companies.

Figure 1: Classification of participating companies.

From this study we have learnt that especially in small or medium sized enterprises the gap between the business level and the production level is filled to some extent with manual work. The larger share of the participants are involved in an engineer to order (ETO) production strategy, and of these, most plan their production manually (cf. Fig. 2), which usually comes with media breaks. With tighter integration of participating IT systems, this information barrier could be eased or even removed.



(a) Production strategies. (b) Automation in production planning.

Figure 2: Selected results from an initial exploratory study.

This integration can be reached by implementing adapters for the corresponding sub-systems, or it can be reached conceptually, by providing conversion rules for abstract models of the underlying systems. The latter approach is the one that we follow in this thesis, and we believe that it is of use for system integrators dealing with specific pieces of software, in terms of providing guidance based on industry standards.

1.1 Problem Statement

In this thesis, we explore the role of model-driven engineering (MDE) in smart manufacturing systems, with a focus on the higher levels of the functional automation hierarchy. Currently, it is common sense to provide a virtual representation of the production system (i) in a level of detail that is required by, (ii) using the expressiveness that is provided by the corresponding IT systems that drive particular sub-systems, such as those for ERP or MOM [Wes99; FWW16].

While larger system vendors provide solutions that span both of these levels, there exist many software solutions that only support one or the other. In order to integrate these systems, data exchange adapters for both directions need to be implemented, and the core structural or procedural model needs to defined in both systems separately. This leads to long-lasting integration projects (e.g., in case of a system change) and potential integrity problems, when information is inadvertently modeled ambiguously or divergently [Dre+05].

Proprietary data stores and formats fragment the knowledge space of enterprises to an extent, where the big picture is unknown in terms of fully integrated systems. ERP systems, manufacturing execution systems (MESs), simulation tools, material flow planners, plant layout designers, etc.—they all use their own knowledge representation format, and not all of them provide import or export interfaces. This leads to a situation where specific knowledge is only available inside certain tools, but any insights gained in these tools need to be manually introduced to other information systems (ISs) or engineering tools [RDU19; GF20].

In real-world production systems, the actual production system is under continuous change [And+18]. Such changes include switching the input/output (I/O) ports of actuators, refining the position or orientation of sensors, or updates to the program code of programmable logic controllers (PLCs). While it is already hard to feedback these changes to at least some of the involved engineering tools, it is even harder to make sure that all involved tools are notified. Heterogeneous and disconnected data sources make this request even harder to fulfill. For this reason, information integration, based on international standards, is among the key enablers for convergent engineering data states throughout (i) heterogeneous tool landscapes and (ii) different lifecycles.

Our approach stipulates the usage of existing international standards for the modeling of level-specific information and defines mappings between these standards in order to make them applicable cooperatively. It fosters the design of either ERP or MOM information and then use transformation rules to convert this information into the respective other system and thus (i) reduce initial modeling effort and (ii) streamline information integration of runtime data.

A stringent investigation of the standards' landscape in smart manufacturing systems [LMF16], in conjunction with a concrete proposal for the interleaved use of exemplary standards is an academic niche that is progressively, and in parts, being tackled by this cumulative thesis.

1.2 Goals

We are testing the versatility of MDE in the context of smart manufacturing. Specifically, we investigate the interface between business and production systems, as well as the utilization of statically defined production systems for the generation of procedural information, such as production plans. We are grounding our work on standardized and internationally accepted conceptual models and use knowledge inference techniques to automatically enrich corresponding model instances. By the term conceptual model, we understand domain-specific terms and definitions, including information about entities' relationships, without formal specification, i.e., without concrete syntax or precisely specified relationships. Reaching the knowledge expansion goal is driven by general purpose logic solvers, relying on widely used and proven language constructs.

With our research we want to show the feasibility of MDE for I4.0 applications, with a focus on vertical integration, business domain independent modeling, and knowledge inference. We do so by targeting the following goals:

G1 Establish vertical integration by providing model mappings between established conceptual models (such as standardized domain-specific languages). These mappings should be generic, so that they can be used by a broad range of industries.

G2 Provide concrete metamodels for selected industrial standards so that they can be used to model a variety of aspects present in APS engineering.

G3 Implement prototypical applications, including concrete model transformations, as proof-of-concepts for the developed model mappings and metamodels.

G4 Show successful knowledge inference for smart manufacturing systems by experiments and case studies that are backed by real production systems.

1.3 Methodology

The applied methodology follows the *design science* approach, as described in [Hev+04]. In short, it embeds IS research in a larger framework comprising the environment (the business domain) it is related to, and the knowledge base it is founded upon (cf. Fig. 3). The environment defines the relevance of the problems tackled by the own research, while the knowledge base specifies the rigor to be applied to one's research. Conversely, research results lead to an extension of the knowledge base and to changes in the environment if they are applied accordingly. Developed artifacts are justified by meaningful evaluations, and these evaluations may in turn lead to refinements in future revisions of the artifacts. Ultimately, this framework defines a multi-circular model that fosters iterative approaches.

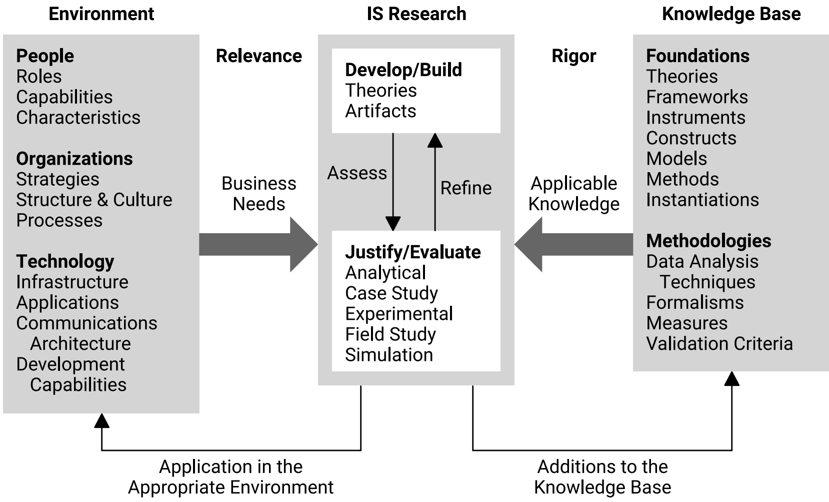


Figure 3: The original design science research framework for IS research (cf. [Hev+04]).

The concrete manifestation of the design science approach, as it has been applied in the context of this thesis, is visualized in Fig. 4. We have been working on issues related to ERP and MOM in the context of the digitization of manufacturing systems, I4.0, and utilized a set of established tools and methods to create concrete artifacts that have been evaluated (i) analytically, (ii) in case studies, (iii) and/or in experiments. Our contributions include metamodels, reference model instances, model mappings, and model transformations that have been published in meaningful publication outlets. More specifically, we are applying the guidelines and methodological paradigms as laid out in the following clauses:

Design as an Artifact

> "Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation."
> [Hev+04]

We are developing a series of artifacts, including conceptual models together with model mappings and model transformations, as well as executable software. The main artifacts are listed below, along with the corresponding papers where they have been presented:

A1 Concrete metamodel for ISO/IEC 15944-4. This standard is conceptually defined, but leaves out certain semantics. With our concrete metamodel, developed over several iterations, we provide a versatile, proven, widely applicable instantiation of the Resource-Event-Agent (REA) business ontology [Wal+14a; WH14b; Wal+15b; Wal+15a].

A2 Concrete metamodel for IEC 62264. While this standard is defined relatively detailed, by making use of Unified Modeling Language (UML)

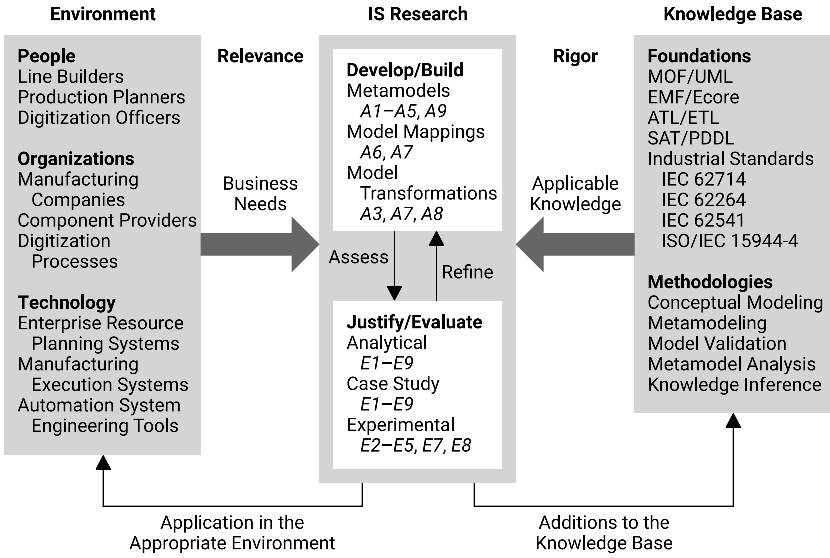


Figure 4: Application of the design science research framework in the context of this thesis (following [Hev+04]).

class diagrams, certain implementation aspects are left to the user. In our metamodel we follow the standard as closely as possible, while providing certain umbrella elements in order to converge unrelated sub-models [WHM17b; WHM17a].

A3 Concrete metamodel and model-to-text transformation for the planning domain definition language (PDDL). PDDL is strictly defined by means of the Backus-Naur-Form (BNF); a concrete metamodel following a Meta Object Facility (MOF) methodology had not been readily available [Wal+19a; Wal+19c].

A4 Concrete metamodel for IEC 62714. This standard is defined on top of IEC 62424, which in turn is specified using Extensible Markup Language (XML) Schema. With our metamodel we enable tighter coupling of entities in conjunction with extended validation capabilities inherent to formally defined metamodels, as compared to the XML based approach [WHM17b].

A5 Concrete metamodel and codified implementation for feature models (FMs). FMs are a thoroughly investigated topic, yet there is no consensus on a versatile metamodel for defining such FMs. With our OPC Unified Architecture (OPC UA) information model we provide a concrete, flexible schema for the specification of FMs in industrial contexts [Wal+18b; Wal+19d].

A6 Mapping rules between ISO/IEC 15944-4 and IEC 62264. While the former standard targets ERP related information, the latter standard goes deeper down the automation hierarchy. With our mapping we provide a blueprint for ERP to MOM data alignment [WHM17a].

A7 Mapping rules and model transformations between IEC 62714 and IEC 62264. Used for compliant modeling of IEC 62264 information in Automation Markup Language (AutomationML) contexts [Wal18a]. Based on *A2* and *A4* we have implemented concrete model transformations using the ATL Transformation Language (ATL) [Wal+19b].

A8 Model transformations between IEC 62264 and PDDL. Establishing a link from standards-based MOM information models to knowledge inference methodologies and reactive production planning [Wal+19a; Wal+19c].

A9 OPC UA information model for explicitly linking heterogeneous data originating from different source domains. This information model enables engineers to relate corresponding elements in a non-invasive way, i.e., without altering the structure or properties of existing nodes. Subsequent engineering or knowledge inference tools can exploit this information for model refinement or similar efforts [Wal+18c].

Problem Relevance

> "The objective of design-science research is to develop technology-based solutions to important and relevant business problems."
> [Hev+04]

Smart manufacturing systems are an ongoing trend in multi-discipline research and engineering [Ger18; Qu+19; Mit+19; Yao+19]. While the topic itself, along with intermediate developments, is quite old [Wes99], many issues are yet not broadly solved—and new computing paradigms require constant adaptations. In order to ease future research and development, international standards play an important role; not only do they streamline multi-lateral approaches, they also foster technology integration and cross-system compatibility [LMF16].

One of the more recent widely accepted contributions is the reference architecture model Industry 4.0 (RAMI4.0). It has been developed as part of the German initiative for the digitization of manufacturing systems, "Industry 4.0" [DIN16b]. This phrase aggregates what is otherwise often referred to as CPPS, IIoT, smart factories, etc. It defines a three dimensional framework for the classification of I4.0 applications and their sub-systems. Among the three prominently placed international standards is IEC 62264, which is a central element in this thesis. While its initial version stems from the early 2000s [ANS00], it has gained new momentum through RAMI4.0 and related activities. The work presented in this thesis covers parts of the RAMI4.0, especially with respect to the inter-standard integration. Also, it investigates metamodels for case-independent application and reference models for specific use cases that could be used as guidelines for own developments or blueprints for similar implementations.

Design Evaluation

> "The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods."
> [Hev+04]

The variety of research artifacts are evaluated using a broad spectrum of evaluation methods, including analytical measures, case studies, and experimental settings. Specifically, we have applied the following evaluation methods to the beforementioned artifacts (E1 evaluates A1, etc.):

E1 *Concrete metamodel for ISO/IEC 15944-4:* Rigorous domain and application analysis, followed by multiple real-life case studies. The latest metamodel revision is a refined iteration of a well tested metamodel version that was used in a full-fledged cloud-enabled application prototype developed for an industrial partner [Wal+14b; WH14a; Wal+15b; Wal+15a].

E2 *Concrete metamodel for IEC 62264:* Conceptual model analysis for the creation of a concrete metamodel. This metamodel has in turn been analyzed and used successfully in several model transformations, case studies, and experiments in later iterations within this work [WHM17d; WHM17c; Wal+17; Wal+19b].

E3 *Concrete metamodel and model-to-text transformation for PDDL:* Thorough domain analysis, that led to a sound metamodel, which was in turn successfully utilized in numerous case studies and experiments, some of which were executed in the context of an I4.0 testbed situated at the Czech Technical University (CTU) in Prague [Wal+19a; Wal+19c].

E4 *Concrete metamodel for IEC 62714:* In-depth domain analysis, successful usage of the developed metamodel in experiments and a use case. The developed metamodel provides a semantically enriched revision of the XML Schema based original definition of the Computer Aided Engineering Exchange (CAEX) format, and in turn of AutomationML [WHM17b; Wal+19b].

E5 *Informational and concrete metamodel for FMs:* Exhaustive domain analysis and application in use cases and thereupon further application analyses [MWM15]. Several materializations of the conceptual FM model have been realized, including an OPC UA information model and a Java implementation, for experiments and actual computations [Wal+18b; Wal+19d].

E6 *Mapping rules between ISO/IEC 15944-4 and IEC 62264:* Detailed cross-domain and mapping rule analysis accompanied by a use case. The use case was defined around an actual production process from the furniture industry [WHM17a].

E7 *Mapping rules and transformations between IEC 62714 and IEC 62264:* Analysis of cross-domain information utilization and overlap, application in several use cases of varying complexity. Experimental evaluation and concluding mapping analysis was realized through formal, bi-directional model transformations [Wal+19b].

E8 *Model transformations between IEC 62264 and PDDL:* Analysis of domains and application scenarios, as well as of the resulting model transformations, further tested in several experiments and case studies. The evaluation setting for the experiments, as well as the blueprint for most of the more complex case studies, was again within the context of CTU's I4.0 testbed [Wal+19a; Wal+19c].

E9 *OPC UA information model for explicitly linking of heterogeneous data:* Analysis of related approaches for different target technologies. Application in a specific use case as a proof-of-concept. [Wal+18c].

Research Contributions

> "Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies."
> [Hev+04]

The contributions of the research presented in this thesis are manifold and listed in detail in Sec. 1.5. The following list highlights the main contributions in brief:

C1 (Relates to *A1*) Reference model and application prototype for defining business information in the context of retail information systems (RISs) within the realms of REA ontologies. This work exemplifies and proofs the capability of REA to be able to handle complex business scenarios and it proofs, on a prototypical level, the applicability of REA towards real-life applications [Wal+15b; Wal+15a].

C2 (Relates to *A5*) Reference model for defining variability of arbitrary information using FMs in the context of OPC UA. This work is a low-complexity, universally applicable information model for the definition of feature models for OPC UA data, such as factory equipment and material/products [Wal+18b; Wal+19d].

C3 (Relates to *A9*) Reference model for explicating data heterogeneity in engineering artifacts, to be applied in the context of OPC UA. Using this model, it is possible to create non-destructive, semantically meaningful inter-domain links between nodes that represent corresponding or dependent pieces of information [Wal+18c].

C4 (Relates to *A6*) Conceptual mapping of REA and IEC 62264 information for the purpose of data reuse, cross-domain model-validation, and runtime artifact conversion. With this mapping it is possible to streamline data integration within the higher levels of the automation hierarchy. It is a reference mapping of IEC 62264 information to ERP system granularity [WHM17a; Wal+18a].

C5 (Relates to *A2*, *A4*, and *A7*) Conceptual mapping and concrete transformation rules for the modeling of IEC 62264 information within, or in parallel with, AutomationML. This work enables standards integration with clear syntax and semantics along with optional modeling rules for the creation of structured AutomationML models [Wal+18a; Wal+19b].

C6 (Relates to *A2*, *A4*, and *A7*) Application note for the combined utilization of IEC 62264 and AutomationML information. Numerous modeling examples of varying complexity are given in full detail and enable the quick application in custom engineering efforts. Further, concrete model transformations have been implemented and they show conceptual maturity by successfully executing loss-less round-trip transformations [Wal18a].

C7 (Relates to *A3* and *A8*) Application note for the utilization of PDDL in the context of smart manufacturing by leveraging IEC 62264 models. It is shown (i) how IEC 62264 information can be non-ambigously converted into PDDL data, (ii) how PDDL can be used to create production plans from IEC 62264 data, and (iii) how IEC 62264 models can be enriched by information gathered by planning solvers [Wal+19a; Wal+19c].

Research Rigor

> "Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact."
> [Hev+04]

For creation of conceptual models, metamodels, model mappings, and model transformations we have been applying tools and methods established in the MDSE research community. All our findings and artifacts are grounded in corresponding foundational resarch bodies that are referenced in the underlying publications accordingly. Equipped with a bias towards computer science and business informatics, we have followed best-practice approaches with respect to MDE and business-oriented ISs. We acknowledge that our concrete implementations might not be directly usable by domain experts, but the conceptual work that has realized provides a sound reference body of work to be used by professional engineers. Since it was the main theme throughout our research to stick to international standards, where applicable, we believe that two important properties are established: (i) the *relevance* of our research is undergirded by utilization of relevant and modern industrial standards, and (ii) the *applicability* of our research results, artifacts, and conclusions is facilitated.

Design as a Search Process

> "The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment."
> [Hev+04]

The contributions that have been cumulated in this thesis have inherently followed an iterative approach, where certain aspects of sub-systems have been highlighted, investigated, and improved over time, while the implementation work of larger systems that utilize these ever evolving subsystems has been carried out. An approximated view on the genesis of the publications is provided in Fig. 5: the findings of a certain piece of research are iterated over and reused in other contributions. In some cases, the work could be reused directly, in others, refinements, fixes, or other enhancements have been introduced to the previous work, thus stabilizing the overall approach.

Communication of Research

> "Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences."
> [Hev+04]

Since [Hev+04] is focused on design science with respect to business information systems, it argues that research contributions must not be kept within the IT-affine community, but need to be actively carried to the domain experts, namely the "management-oriented audiences". In our case, the domain experts are represented by the automation systems engineering community, comprising both academic and industrial representatives. Examples for associations representing these domain experts include the AutomationML association, the Association of German Engineers (VDI), and the International Academy for Production Engineering (CIRP).

The communication strategy that has accompanied this thesis included several complementary aspects. First, the publication of research findings at scientific conferences, symposiums, and workshops provided the grounding for vocalized presentation in interactive, face-to-face settings. The typical international conference allows for the seeding of ideas and findings in large audiences using visual and auditive aids. While the "official" feedback with respect to one's own work is limited to a few questions, most of the fruitful, in-depth discussions are situated in private settings, for which the conference provides a valuable framework. Second, the placing of research contributions in renowned journals and collections supports wide-spread availability and enables to put one's contributions into broader contexts so that it can be accessed by a larger user base. Third, the active contribution in academic and industrial consortia provides plentiful opportunities to discuss certain findings and issues with experts from diverse fields. The committees that were personally attended by the authors included both technology- and management-oriented participants. Fourth, informal and unplanned knowledge exchange has led to the latest publications and proved to be a valuable source of innovative ideas.

The majority of publication outlets are venues hosted or supported by renowned engineering organizations, such as the Association for Computing Machinery (ACM), the Institute of Electrical and Electronics Engineers (IEEE), and CIRP. A minor share of publications has been realized in the context of industrial associations and venues, such as the AutomationML association or at AUTOMATION, the World Congress of Measurement and Automatic Control, which is organized by VDI, or in the context of scientific or industrial workshops and symposiums.

As this thesis is situated on the borderline between computer science and production engineering, (i) some publications have been placed in conferences related to computer science, such as the IEEE International Conference on Business Informatics (CBI), (ii) others have appeared in production engineering related conferences and journals, such as the IEEE Robotics and Automation Letters (RA-L), and (iii) some have been published in venues where both disciplines are represented in conjunction, such as the IEEE International Conference on Industrial Informatics (INDIN). All of these venues share an important property: submissions have undergone rigorous peer-review by scientists and/or industrial experts.

1.4 Synopsis of Publications

In this section, we are describing the publications that make up this cumulative thesis and show how they are related with each other. In order to make it easier to identify these publications in the text, they are **printed in bold**, when cited. This also applies to own "supplemental" publications that where contributed inbetween the core publications. In order to foster the understanding about the core publications' interdependencies, Fig. 5 shows a "dependency" graph, visualizing the publications' genesis.

In our scientific contributions we have analyzed, discussed, and proposed various technologies, methods, and modeling approaches along the *automation hierarchy*. Since there exist multiple definitions for this term [Ebe05; GMA13; FE14], we want to clarify that we are using it in the sense as it is presented in the IEC 62264 standard [IEC13a] (cf. Fig. 6). Consequently, in this work the levels of the hierarchy are defined as follows (extended with comments for better subsumption, taken from further definitions which have been collected in [MPM17]):

Level 4: ERP functions are accumulated here. This level usually incorporates all kinds of management information system (MIS), which support various business operations.

Level 3: activities related to MOM are subsumed here. This includes information about product recipies, production workflows, detailed production scheduling, etc.

Level 2: supervisory control and data acquisition (SCADA) functions are captured at this level. It represents aggregated monitoring and con-

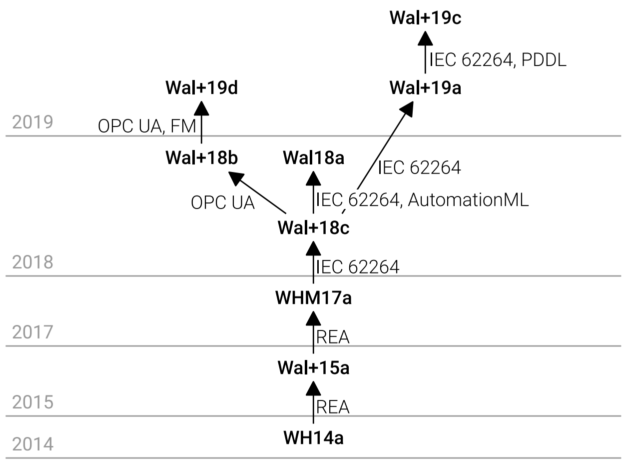


Figure 5: Genesis of the publications that form the backbone of this cumulative thesis. Dependency annotations highlight the main themes that have influenced a subsequent publication. External influences have been left out.

trol activities, which enable manual and automated control of the production process.

Level 1: PLC tasks as well as I/O handling are represented at this level, including sensors, actuators, and processing units, which are required to control certain subsystems or modules of an automated production system.

Level 0: represents the actual physical production process. It can be understood as the "ground truth" that is to be controled and monitored by the IT systems of the upper levels.

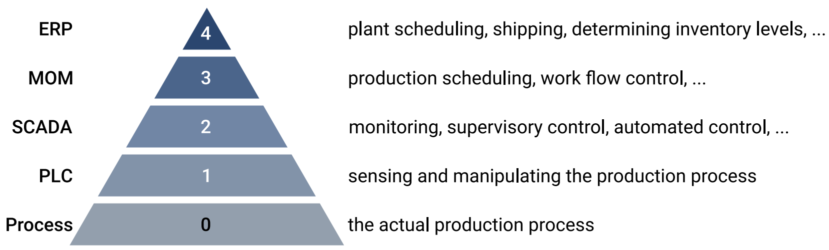


Figure 6: Functional automation hierarchy (taken from [IEC13a], visually adapted according to representations given in, e.g., [Wag03; Sau05]).

In this thesis, we are focusing on the upper two levels of the automation hierarchy, investigate dependencies and mappings between these layers, formalize conceptual models, and utilize them in computations for the purpose of knowledge expansion.

1.4.1 Enterprise Resource Planning

Our initial focus has been on the creation of a generic modeling and software infrastructure that are flexible enough to be configured and extended at runtime **[Wal+14a]**. The underlying conceptual model we have been relying on was the REA business ontology [McC82], which has been standardized as ISO/IEC 15944-4 [II07]. We have proposed an implementation concept for a domain-agnostic software system that has extended REA with "fragments", which are customizeable pieces of structured data, such as a shipping address or a Global Positioning System (GPS) coordinate. These fragments could be used to augment REA concepts with complex and reusable attributes.

This concept has been further detailed in **[WH14b]**. Not only have the core design decisions been clarified, but also some additions have been made, such as a dedicated submodel dealing with units and relations. With these extensions it is possible to establish a semantically rich business model.

This work has been additionally enriched by **[Wal+14b]**, where the injection of business rules is described. With that, users are being empowered to add certain behavior to the data-driven REA model. The foundation for this approach has been the clarification of possible lifecycle changes that could occur in such a system. Each lifecycle change would represent an "anchor point" that could hold zero or more business rules. This allows users, e.g., to prevent the persistance of incomplete data or to trigger a purchase order of supplies in case the local stock has decreased below a certain threshold level.

In **[WH14a]** a concrete data model, designed for relational glspldb, has been presented that incorporates the previously defined concepts. For the informal definition of business rules the graphical syntax of Decision Model and Notation (DMN) has been used, which has been published only months before that work has materialized [OMG14]. The usability and expressiveness of DMN have been assessed as being very intuitive to use and very good, respectively; especially when it comes to reading and interpreting information that is encoded by DMN's Decision Requirements Diagrams (DRDs) or boxed expressions.

Consequently, a RIS, named "REAlist", has been developed, which combines a robust REA core database (DB) and application programming interface (API) with a RIS specific application layer and provides a web application on top that allows the comfortable handling of REA information **[Wal+15b; Wal+15a]**. With this work we have shown that it is possible to build an extensive RIS with an intuitive web-based graphical user interface (GUI) by solely relying on core REA concepts. The basis for this is an unambigous mapping of different business functions that are defined in the *Retail-H*, such as *contracting*, *order management*, and *accounts payable* [BS04; BS07] to REA constellations.

1.4.2 Manufacturing Operations Management

Manufacturing operations management handles the production control of an enterprise and incorporates all necessary information and activities that are required for smooth operations. Initial studies on the combined use of ERP and MOM information have been presented in [MH15b; MH15a], where IEC 62264-2 information is mapped to REA by extending the REA metamodel. Additionally, in [MH15b], the operations definition submodel of IEC 62264-2 has been proposed as the basis for a task execution layer for REA, since this layer of REA is not formally defined. This approach has been later refined in **[WHM17d]**, where it is shown that many concepts of IEC 62264-2 have direct correspondences to concepts of REA, which essentially means that they capture similar information at a similar level of granularity. Consequently, for the task execution layer more detailed pieces of information are to be used, such as the ones that are defined in part 4 of the IEC 62264 standard, e.g., workflow specifications, work schedules, and work performances.

The alignment of REA and IEC 62264 part 2 has been discussed in more detail in **[WHM17a]** by the example of an office furniture manufacturer. It has been shown that most concepts of IEC 62264-2 can be mapped to metamodel elements of REA, the main exceptions being (i) *operations capabilities* and *process segment capabilities* as well as (ii) *test specifications* and *test results*. The former are not directly stored using REA concepts, but could be computed when required; the latter do not have semantically corresponding entities. In the reverse direction, from REA to IEC 62264-2, the most prominent missing mapping is that of events. While being a core entity in REA, this level of detail is not provided in IEC 62264-2. Instead, the event level is skipped and all information is aggregated at the level of dualities and converted to IEC 62264-2 elements. Another important concept of REA that is missing in IEC 62264-2 is the claim, for which there exists no dedicated corresponding element.

Data exchange between the plethora of engineering tools that are engaged in the design and commissioning of APSs is a complex matter [GK16]. One promising approach to resolve some of the issues related with that scenario has been materialized in terms of the standard series IEC 62714, representing AutomationML [BSS16]. AutomationML itself is based on IEC 62424, which defines an XML dialect for data exchange within the realms of piping and instrumentation diagrams (P&IDs), called CAEX. AutomationML targets the representation of the equipment hierarchy of a production site, but can also be used to model additional concepts, such as products and processes [SD09].

This is very similar to the capabilitites of IEC 62264-2 and therefore, in **[WHM17c]** we have had an initial look at the encoding of IEC 62264-2 information within the context of AutomationML documents. The main contributions in that work have been (i) the conceptual mapping of IEC 62264 elements to AutomationML elements and (ii) the creation and usage of an AutomationML role class library. While details of the mapping and the role class library have evolved over time, the approach and initial implementation have proven useful.

The application of AutomationML on higher levels of the automation hierarchy has been further elaborated in **[Wal+17]**, where a number of application scenarios have been discussed. Some of them dealing with engineering information, others dealing with runtime information, which could be exploited using AutomationML. Also, the interplay of AutomationML with OPC UA, as defined in [DIN16a] has been briefly discussed. The representation of engineering information within OPC UA information models is picked up in later work, when it comes to the identification of identical or similar information originating from different tooling environments.

The synchronization of information available in different domains is then discussed in **[WHM17b]**. Three separate views on the same system are kept in sync by employing model transformations as well as model validations. We have had a look at the ERP level (represented by REA), the MES level (represented by IEC 62264) and the lower levels (represented by AutomationML). By the example of a company producing glued-laminated timber (Glulam), we have carved out the benefit of applying methods and tools from MDE.

The potential ambiguity of engineering information has been further discussed in **[Wal+18c]**. There, the issue of multiple representations of equal or similar information has been elaborated. The high number of engineering tools engaged in the design and runtime of APSs, together with the increasing number of *companion specifications* for OPC UA, might well lead to a situation where, for instance, information about a certain machine is represented manifold (e.g., stemming from IEC 62264, AutomationML, and MTConnect [MTC18]). In order to resolve some of the irritation and fuzziness of such a setting, we have introduced an OPC UA information model comprising four *reference types* that allow the explication of relations between engineering artifacts.

The integrated use of IEC 62264 and AutomationML, as it has advanced from the state described in **[WHM17c]**, has been explained in **[Wal+18a]**. The general approach as well as, e.g., the application of interface classes has been described in more detail, together with the combined use of AutomationML, IEC 62264-2, and the Business To Manufacturing Markup Language (B2MML).

A complete and detailed guide for the utilization of IEC 62264-2 information within the context of AutomationML documents has been published in **[Wal18a]**, in terms of an official AutomationML application recommendation (AR). This AR provides an extensive role class library together with an interface class library for the representation of IEC 62264-2 information, as well as an additional role class library comprising a single role class for the referencing of external B2MML information. In one section the issue of ambigous information in the context of OPC UA is explained; accompanied by an OPC UA reference type to be used for annotating the relationship between IEC 62264-2 and AutomationML nodes.

A workflow for the combined use of IEC 62264 and AutomationML has been presented in **[Wal+19b]**: supported by a graphical domain specific language (DSL), implemented in a tool called “ISA-95 Designer”, it is possible to model IEC 62264 data, which can in turn be transformed into AutomationML information by applying two chained model transformations. Vice-versa, IEC 62264 information encoded in AutomationML documents can be extracted using another set of two model transformations and visualized by the ISA-95 Designer. The term "ISA-95", apparent in this tool's name, is the name of the root standard that IEC 62264 is based upon [ANS00].

Since IEC 62264 provides a conceptual model for the representation of MOM information, we have explored how this information could be exploited for the automated generation of production plans. For this purpose, we have targeted PDDL as the concrete encoding format [Kov11]. PDDL provides a standardized and object oriented way of specifying planning domains and concrete planning problems—it has looked like a good fit for our endeavors.

The rationale behind this approach is that IEC 62264 can be used to model (i) the machinery of a production system (the equipment), (ii) the material that is being consumed and produced, (iii) the production processes that are available (the process segments), as well as (iv) the relations that arbitrary resources can have with each other. The idea is to establish a conversion rule from IEC 62264 information to PDDL information, as explained in **[Wal+19a]**. In essence, the IEC 62264 process segments are translated into PDDL actions that could be applied by a planning solver in order to progress from an initial state to a goal state. In our initial example, it has been required to compute the sequence of actions that would be necessary to prepare just-in-time-delivery of raw material for a production process that is to be executed later, by ordering a sequence of shuttles in a monorail intra-logistic transportation system. We could successfully proof (i) *that* the production system that has been designed is capable of re-sorting the transportation shuttles from any sequence into any other sequence and (ii) *how exactly* the re-sorting can be accomplished, in terms of step-by-step directions.

Consequently, we have then increased the complexity of this approach in two ways: (i) by creating a more complex scenario, including assembly tasks with industrial robots and (ii) by utilizing *durative actions* [FL03b] as a more capable planning approach **[Wal+19c]**. Traditional PDDL solvers compute sequential plans, i.e., plans where each step follows another. This is however not very efficient when it comes to plans to be applied in manufacturing contexts, as multiple production steps can be accomplished in parallel, e.g., by increasing the amount of machinery. The results that we have gained from the experiments following this approach have revealed that (i) while meaningful plans for manufacturing products can be found, (ii) the computational cost are vast. It might thus prove more feasible to compute only sequential plans and then try to parallelize some of the steps of the resulting plan in a post-processing step, by applying certain knowledge about the underlying APS. The impact of such an approach depends on factors such as the interwovenness of the production steps and could be significant or neglectable.

A high-level compilation of ideas and findings in the fields of automation systems engineering and I4.0 has been published in **[Maz+20]**, as an iteration of the work presented in [Maz+15]. The focus has been on integrating industrial standards that operate on different levels of the automation hierarchy—such as ISO/IEC 15944 (REA), IEC 62264, IEC 62714 (AutomationML), IEC 62424 (CAEX), IEC 62541 (OPC UA), and IEC 61499—into a common framework for providing an approach for vertical and horizontal integration.

1.4.3 Variability Engineering

Variability engineering in the context of smart manufacturing is a term that is used to describe technical systems that can be assembled in different variations, based on a set of variation points. Among the most prominent examples are cars, as they are offered by most manufacturers: one can select the kind of lighting, color, wheels, etc. Such variation points (or their potential implementations) are called *features*, following the seminal work published in [Kan+90]. Over the years this initial approach has been extended into what is nowadays known as FMs [LKL02; CHE05; Bat05].

Variability engineering and feature modeling can be a powerful method to describe and structure both products [GFd98; Ola+12; You+17] and production systems [Sch10; Vog+15d; Deu+18] likewise—however, especially FMs have often been applied for describing families of products. As such, complementary to the pure business models that have been discussed earlier, a closer look at integrating the user's view into the configuration of products that are to be offered to consumers has been taken. For this, a specific kind of quality function deployment (QFD) method has been chosen, the House of Quality (HoQ). It allows the capturing of consumers' requirements and mapping them against the offered features of a certain product family. Soon, we discovered that the "roof" of the HoQ, which is traditionally described by a matrix, could be realized by a FM. This approach has been presented along with a case study in **[MWM15]**.

Later, we have applied FMs in the context of smart manufacturing by defining an OPC UA information model for defining variability regardless of its application domain **[Wal+18b]**. OPC UA was chosen because of its use in manufacturing operations—this is where production systems and products (or the parts a product is made up of) meet. With this information model it is possible to define FMs within OPC UA servers, and to target production system nodes and product-related nodes in equal measure. Exemplarily, we have used this information model to describe allowed configurations in gas station deployments.

In **[Wal+19d]** we have extended the previously crafted information model by adding means to explicitly annotate OPC UA nodes as being part of a specific configuration of a configurable technical system. This enables more detailed analyses by making variability-related information more explicit. In case a FM has evolved, a system that should conform to this FM can be checked for conformance rather easily—even features that, e.g., have been allowed in previous versions of a specific FM but are no longer supported by a newer revision can be detected by this approach.

1.5 Scientific Contribution

The scientific impact of our work can be differentiated by the kind of artifact that has been created: (i) reference models, which showcase a specific implementation approach, (ii) conceptual mappings, which provide links between metamodels, and (iii) application notes, which introduce a technique to an application area. In the following sections we will outline the main contributions in each of these fields.

1.5.1 Reference Models

Reference models, as we mean them in this thesis, are domain-specific sample implementations that are generic enough to be used in a multitude of application scenarios, because they implement the core functionality for certain service instances. From this viewpoint, our main contributions fall into the realms of REA and OPC UA as the metamodel frameworks they are embedded in.

1.5.1.1 Resource-Event-Agent

For REA, we have developed an extensive reference model **[Wal+15a]**—and successfully implemented a DB backend and web application on top of it **[Wal+15b]**—that resembles the core parts of the *Retail-H* [BS04; BS07]. With that we have shown that it is possible and feasible to build RISs that are solely based on REA concepts as the core data source. The system architecture of our solution is presented in Fig. 7: based on a REA-specific DB an API is defined that allows the manipulation of this data in a consistent way. Access to this API for users is granted twofold: (i) through a web frontend that allows direct manipulation of REA concepts, and (ii) through a web frontend targeting the "REAlist" API, which is a RIS abstraction of REA, targeting the *Retail-H* reference model [BS07].

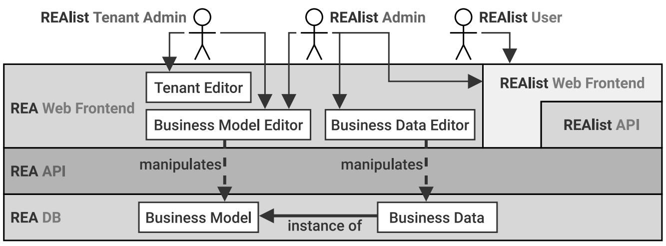


Figure 7: Software stack of our REA-driven multi-tenant cloud application (from **[Wal+15a]**).

More precisely, we have created detailed REA models for the business functions that make up the *H* of the Retail-H: contracting, order management, goods receipt, invoice auditing, accounts payable, warehousing, marketing, selling, goods issue, billing, and accounts receivable [BS07]. Additionally, we have developed a web application that leverages these models and abstracts them in a web-based GUI in order to allow authorized personnel (expressed via REA *agent type* roles) to write and read information on the level of typical RISs.

1.5.1.2 OPC Unified Architecture

In the context of OPC UA we have developed and showcased an information model for the implementation of FMs **[Wal+18b]** and the manifestation of selected FM configurations **[Wal+19d]**. This information model supports cardinality-based FMs, as they are described in [CHE05] and thus enables complex applications. The OPC UA visualization of this information model is depicted in Fig. 8: the main object type is named "Feature" and is used to create feature nodes. These nodes are interconnected by "HasSubFeature" references in order to span a tree-shaped feature model. Cross-tree constraints can be expressed via references of type "Excludes" or "Requires" between the feature nodes. Cardinality information is introduced by the properties of the feature nodes: the mandatory "min" and "max" properties are used to describe how often the current feature node may be included in a configuration, while the optional "groupMin" and "groupMax" properties can be used to describe how many child features may be selected in a single configuration.

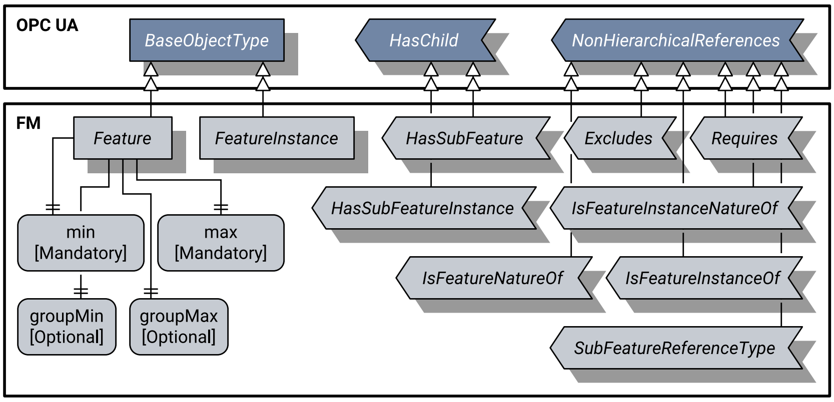


Figure 8: OPC UA information model for feature-based variability engineering **[Wal+18b; Wal+19d]**.

A feature model that is created with this approach is a self-contained piece of information that does not interfere with existing information models. However, it can (and should, in order to be of use) be related to already existing information that is stored in an OPC UA server. For instance, the typical setup of a production system might have initially been modeled by a set of interrelated "production system" object types—with the help of our information model, it is possible to link feature nodes to production system nodes via "IsFeatureNatureOf" references. With this non-intrusive, additional information it is possible to provide feature model related information, in a declarative way.

For the explication of heterogeneous information, we have created another information model that provides an extensible set of reference types:

RepresentsDifferentView, *HasRefinement*, *HasVerification*, and *HasImplementation* **[Wal+18c]**, which are depicted in Fig. 9: (i) *RepresentsDifferentView* is the most generic reference type that is used to relate two OPC UA nodes that depict the same entity, but that have been introduced to the OPC UA server from distinct engineering tools or domain models, (ii) *HasRefinement* is a more explicit reference type that additionally indicates that one node is a more refined view on another node, (iii) *HasVerification* relates two nodes, where one describes the verification of another one, and (iv) *HasImplementation* is used to relate two nodes, where one is the implementation of another one, which might, e.g., be representing requirements.

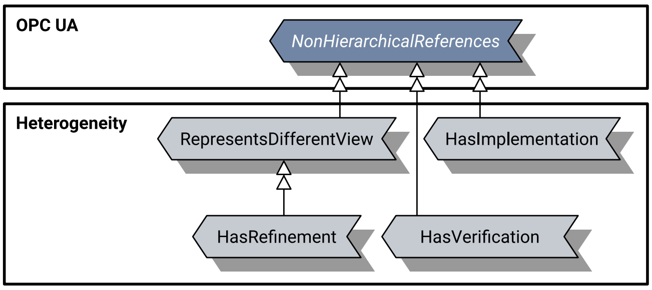


Figure 9: OPC UA information model for making explicit heterogeneity statements about related engineering artifacts **[Wal+18c]**.

Instances of these reference types are meant to be used between OPC UA nodes of different domains, however they can also be applied in the context of a single domain, if this domain does not provide corresponding reference types that might be of value. These reference types can be subclassed to describe more specialized inter-model relations, if required.

1.5.2 Conceptual Mappings

With the term "conceptual mapping" we describe the alignment of two or more different domains in the context of this thesis. This can include both mappings on the metamodel level or on the model level, or across levels. The realized mappings presented in this work are centered around vertical integration, respecting the ERP level standard ISO/IEC 15944-4, as well as the lower level standards IEC 62264 and AutomationML.

1.5.2.1 Resource-Event-Agent and IEC 62264

Since part 2 of IEC 62264 is meant as an object model for information exchange between the ERP and the MES level, it shares some of the concepts that are defined in the REA business model language, which can be seen as an abstraction for ERP systems. And while the original focus of REA has been on the *transfer* of economic resources between trading partners [McC82], it is also capable of describing manufacturing processes through *transformations* [GM97; GM00]. As such, REA can be viewed as a translational tool between the inter-organizational aspect of horizontal integration and vertical integration.

In **[WHM17a]** we have established a mapping between IEC 62264-2 and REA and we could show that there is a high level of semantic correspondence. Also, we could identify which elements of REA are *not* available in IEC 62264 and vice versa. We are providing a use case that depicts how a production system that is abstracted using IEC 62264-2 can be interfaced cleanly with an ERP system defined using REA concepts.

An excerpt of the mapping is depicted in Fig. 10: to the left some prominent elements of REA are depicted, and to the right the corresponding IEC 62264 concepts. Correspondence is visualized by gray connectors; it is allowed that an element of one side has multiple matches on the other side. The latter aspect is typical in cases where two distinct domain models are mapped against each other, because if all mappings would be 1 : 1, the two domain models would essentially provide the same level of informational granularity.

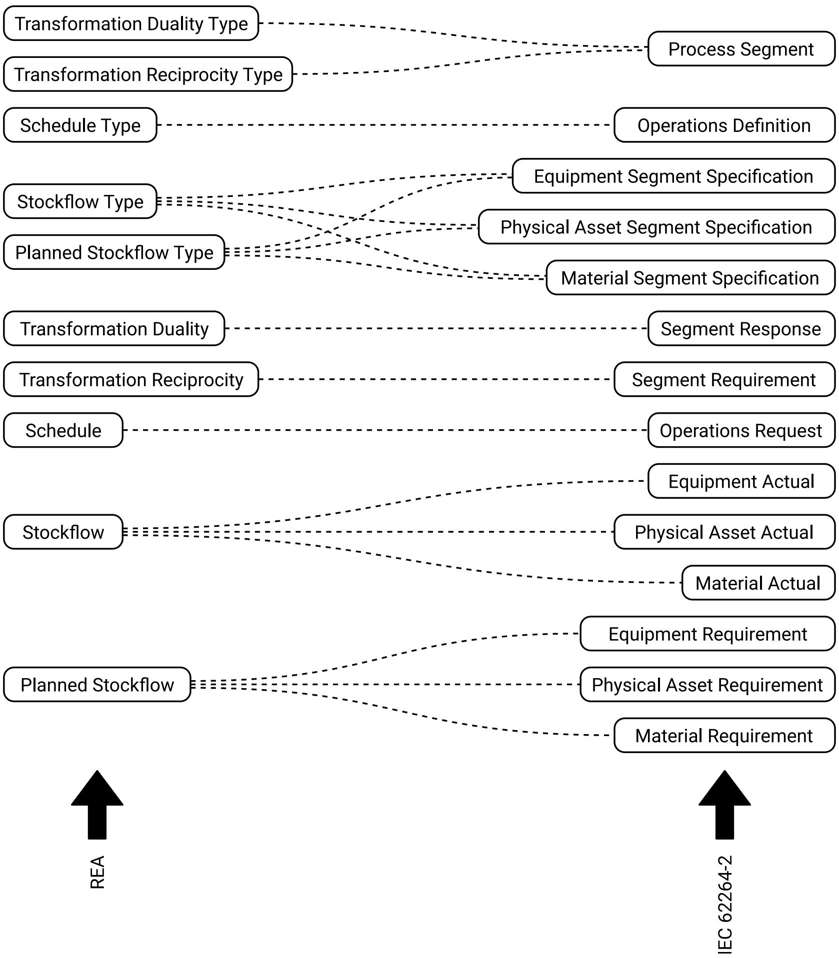


Figure 10: Excerpt of the conceptual mapping of the REA (left) and IEC 62264-2 (right) metamodels **[WHM17a]**.

We argue that, e.g., a REA *schedule type* corresponds to an IEC 62264 *operations definition*: a *schedule type* can be seen as a blueprint for future *schedule* instances, which is also true for *operations definitions*, which describe a blueprint for *operations requests*, to be issued at runtime. The *planned stockflows* (or resource reservations) that are specified within the reciprocities of REA *schedules* correspond to *equipment*, *physical asset*, or *material requirements* of *segment requirements* of IEC 62264.

In **[WHM17d]**, we have further argued that part 4 of IEC 62264 would be a good fit for REA for describing production processes on a more detailed level, in a way that would normally not be captured using REA core concepts—this more detailed level is usually referred to as the “task level” [GM97; GM99]—instead, some constructs of IEC 62264-4 could be used for that purpose.

1.5.2.2 IEC 62264 and AutomationML

IEC 62264 defines an abstract model for pieces of information (i) that are to be exchanged between the ERP and the MOM level of the automation hierarchy and (ii) that describe MOM activities, functions, and objects. With the extensive work that has been presented in an AR **[Wal18a]**, a detailed manual is provided on how to model AutomationML and IEC 62264 (i) in parallel or even (ii) in an integrated way. The application recommendation takes into account B2MML [MES13] and defines (i) an interface for aligning separately stored AutomationML and B2MML documents and (ii) a role class library and an interface class library for the modeling of IEC 62264 information in a self-contained AutomationML document.

Fig. 11 depicts an excerpt of the mapping, which has been realized twofold: (i) to the left it is shown with which metamodel concept the element instances are represented, (ii) to the left the semantic alignment of the created role class library with existing role classes of AutomationML is depicted. For instance, it is made clear, that IEC 62264 elements of type *equipment class* are modeled in terms of AutomationML *role classes*. At the same time, the role class library’s entry *EquipmentClass* is specified as a subclass of AutomationML’s base role class library entry *Resource*. By that dual alignment, we implement a rudimentary backwards-compatibility. AutomationML tools that do not know the discussed AR can treat entities of type *equipment class* as the well-known type *Resource*, which is a semantically related role class.

1.5.3 Application Notes

In this section we highlight specific examples of where conceptual work has been applied in specific use cases, and where research artifacts are studied in case studies in order to proof their adequacy and correctness. We elaborate (i) on the utilization of IEC 62264 information in the context of AutomationML and (ii) on the combined usage of IEC 62264 and PDDL.

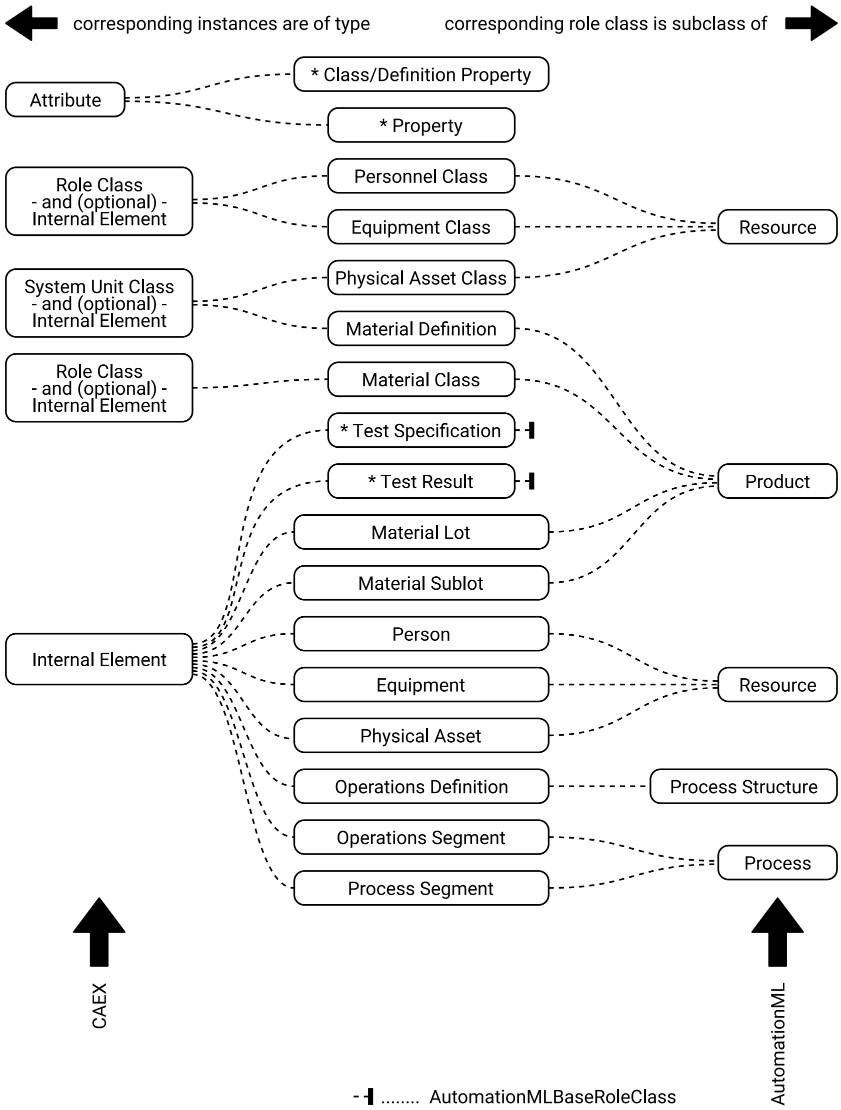


Figure 11: Excerpt of the conceptual mapping of IEC 62264-2 and AutomationML elements **[Wal18a]**.

1.5.3.1 IEC 62264 and AutomationML

As part of the AR for the alignment of the ERP and MOM levels in AutomationML environments **[Wal18a]**, we have provided detailed usage examples of how the various role and interface classes are to be used in combination with each other. The current AR state integrates all of the IEC 62264-2 conceptual models and also respects the availability of two complementary mapping documents: (i) modeling IEC 62264-2 information in OPC UA [Ono+13] and (ii) modeling AutomationML information in OPC UA [DIN16a]. In order to support the resolving of ambiguous data, a dedicated OPC UA reference type is provided as part of the AR that helps explicitly marking duplicate information stemming from different source domains within a single OPC UA server. While this does not itself *resolve* the ambiguity, these markings can be used as an intermediate step.

Further, we have outlined a general approach on how to structure AutomationML documents, by applying the main information models of IEC 62264 to AutomationML. This supports newcomers to AutomationML to model their diverse production system aspects in AutomationML in a modular and guided fashion (cf. Fig. 12). Different concerns, such as equipment, material, and processes, are separated from each other in dedicated sub-trees of the instance hierarchy and connected to each other using well-defined external interfaces and links among them. Engineering tools that are only interested in a certain sub-tree could therefore rather quickly extract relevant information. Evidence shows that this kind of structuring is suitable and useful for the modeling of highly automated production systems, such as in the automotive sector [BRS18].

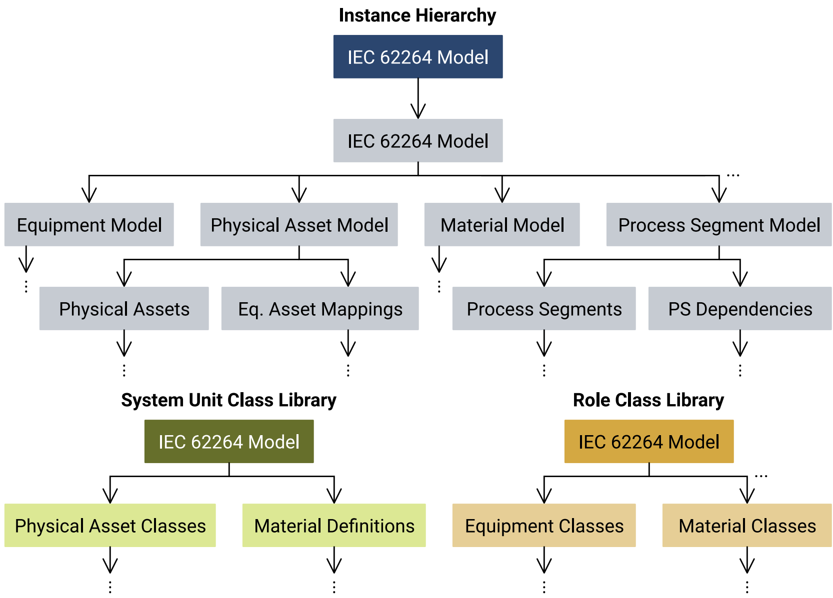


Figure 12: AutomationML document structure, when applying IEC 62264 vocabulary and relations (excerpt) **[Wal+19b]**.

We have also exemplified how ATL can be used to create AutomationML documents from IEC 62264 information—and vice-versa, if the role and interface classes, as defined in the AR, have been used **[Wal+19b]**. This is specifically useful in situations where IEC 62264 is already available and needs to be rendered within an AutomationML document. An exemplary Business Process Model and Notation (BPMN) workflow for manipulating a single model repeatedly between an AutomationML-based and an IEC 62264-based tool is depicted in Fig. 13. Note that in this case we have two different metamodels of AutomationML in use: one (dubbed "XML") directly representing the XML syntax based on the CAEX schema, the other one (dubbed "Graph") being a strictly object-oriented version thereof. Two additional ATL transformations (one back and one forth) are required to convert between these two serialization formats.

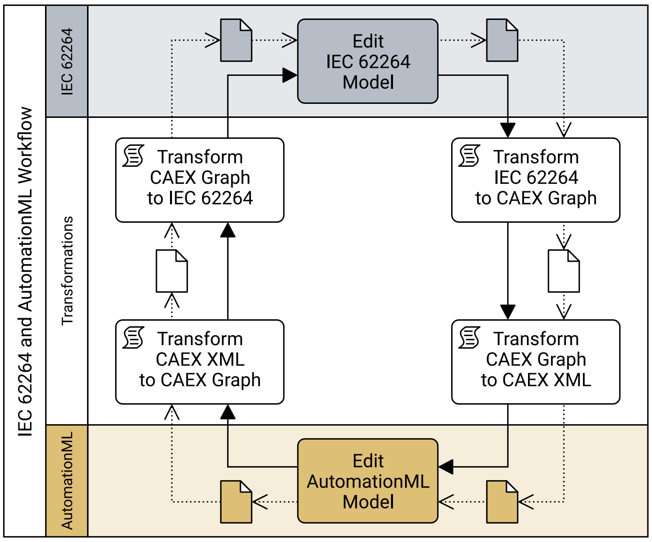


Figure 13: Workflow for editing a single model in two distinct engineering tools, one based on IEC 62264 information, the other one based on AutomationML data [**Wal+19b**].

1.5.3.2 IEC 62264 and PDDL

IEC 62264 is capable of providing rich data for the description of static properties of a production system, but also for the specification of complex, and even nested, production processes. As such, we have successfully tested the alignment of IEC 62264 with the grammar of several off-the-shelf PDDL planning solvers in order to find possible production plans for specific products in certain manufacturing environments. By coupling the production system model with the planning solver using model-driven techniques, we enable a reactive production system, where relevant changes in the IEC 62264 model can trigger replanning tasks and provide new production plans in a fully automated way [**Wal+19a; Wal+19c**].

We have applied our concepts on the basis of a real production system that is set up at CTU's Czech Institute of Informatics, Robotics and Cybernetics (CIIRC): the Industry 4.0 testbed (cf. Fig. 14). It comprises four robot cells that are connected by a monorail-based intra-logistics system featuring shuttles that may drive along the track and carry material to and from the cells.

The general workflow of our approach is depicted in Fig. 15: starting with the creation of a production system model comprising an initial state description and the formulation of an envisioned goal state (both expressed using IEC 62264), a set of PDDL artifacts is generated: one domain file and one to many problem files, corresponding to the number of provided goal

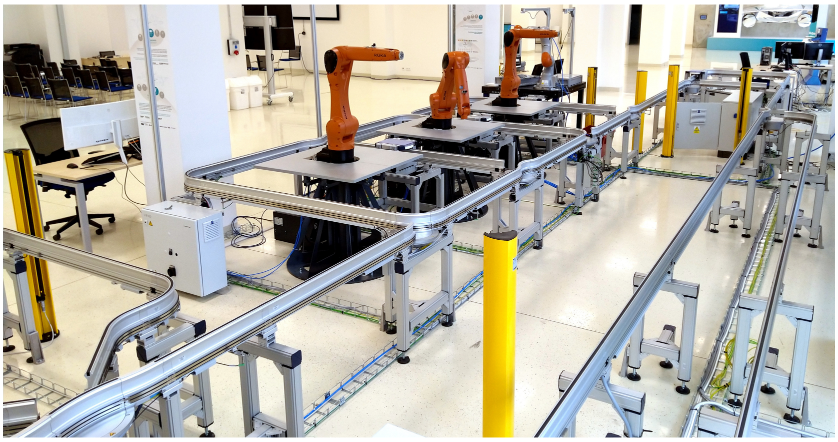


Figure 14: Industry 4.0 testbed, installed at CTU's CIIRC.

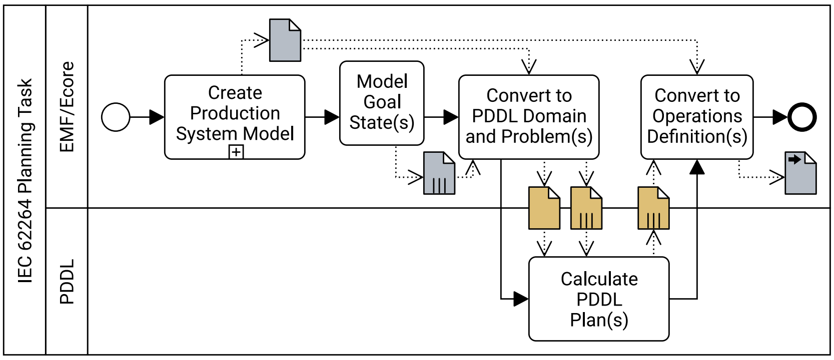


Figure 15: Workflow for generating PDDL artifacts from IEC 62264 information, as well as inferring and feeding back knowledge [**Wal+19c**].

state models. These files are handed over to an off-the-shelf PDDL solver that tries to find a production plan for each of the production goals, i.e., a sequence of actions that lead from the initial state to the goal state. In our examples, we assemble toy trucks from a few sub-components.

The main contribution is the transformation of IEC 62264 information into a valid PDDL representation. Fig. 16 depicts the transformation of pure IEC 62264 metamodel information into PDDL domain description fragments by the example of equipment information: (i) metamodel classes are made available as PDDL types, metamodel relations are transformed into PDDL predicates with a corresponding name, and properly typed parameters. The PDDL elements generated in such a way serve as the backbone for the remaining elements that are inferred from IEC 62264 model information. For instance, (i) all classes, e.g., *equipment classes* are converted into *constants*, (ii) *process segments* are converted into *actions* and their *segment requirements* are added thereto as *parameters*, or (iii) all kinds of instances, e.g., *equipment* are converted into *objects* of a corresponding problem definition file.

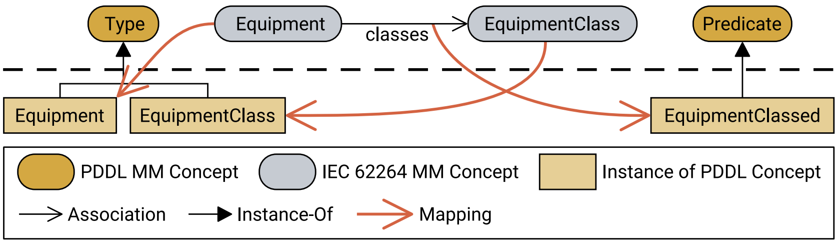


Figure 16: Converting IEC 62264 information into a PDDL representation (as it was used in [Wal+19c].

The computed production plan is then written back into the production system model in terms of an operations definition, where each PDDL action call is converted into an operations segment. If no plan could be found, no such operations definition is created—instead, the user is notified that no plan could be found for the given production problem. The corresponding engineer is then able to explore whether the product is faulty, or the production system is simply not capable of producing the selected kind of product.

1.6 Research Projects

Some of the publications underlying this thesis have been realized in the context of the following research projects:

REAlist: Funded by the Austrian Research Promotion Agency (FFG) as a "BRIDGE" project, this project has investigated the usage of REA as the foundation of a prototypical ERP system. Among the issues that have had to be solved has been the integration of a business rule engine, and the theoretical framework for this has been presented in [WH14a]. The underlying system architecture as well as the domain-specific REA model instances have been described in [Wal+15a].

CDL-MINT: The Christian Doppler Laboratory (CDL) for Model-Integrated Smart Production has represented the hosting environment for the remaining publications. We have investigated the application of methods and techniques of MDE in the context of smart manufacturing. One important aspect has been the exploration of vertical integration across levels of the automation hierarchy, which resulted in [WHM17a] and [Wal18a], as well as the declaration of heterogeneous data stemming from diverse sources within a single technical space [Wal+18c]. Another aspect has been the expression of variability in production processes, which could benefit from our previous research [MWM15]. Variability information models have been presented in [Wal+18b] and extended in [Wal+19d]. A third aspect has dealt with the combination of structural and behavioral models for the ad-hoc creation of production plans, which has been initially presented in [Wal+19a] and has been extended with temporal information and more complex use cases in [Wal+19c].

Chapter 2

Publications

The following peer-reviewed publications, grouped by publication medium, have directly contributed to this cumulative thesis. Detailed information about each of these publications is given in corresponding sections after the listing—sorted by publication date, in ascending order. Each section prints the publication's abstract as well as all cited works. Further, a "contribution" clause depicts the tasks that were carried out by the author of this thesis with relative majority, i.e., where he was contributing more substance and effort than any of his co-authors.

Journal Articles

[Wal+19a] **Bernhard Wally**, Jiří Vyskočil, Petr Novák, Christian Huemer, Radek Šindelár, Petr Kadera, Alexandra Mazak, Manuel Wimmer. "Flexible Production Systems: Automated Generation of Operations Plans based on ISA-95 and PDDL". In: Robotics and Automation Letters 4.4 (Oct. 2019), pp. 4062–4069. ISSN: 2377-3766. DOI: 10.1109/LRA.2019.2929991.

Whitepapers

[Wal18a] **Bernhard Wally**. Provisioning for MES and ERP. Support for IEC 62264 and B2MML. Application Recommendation. AR_MES_ERP 1.1.0. Nov. 2018.

Conference Proceedings

[Wal+19c] **Bernhard Wally**, Jiří Vyskočil, Petr Novák, Christian Huemer, Radek Šindelár, Petr Kadera, Alexandra Mazak, Manuel Wimmer. "Production Planning with IEC 62264 and PDDL". In: Proceedings of the 17th IEEE International Conference on Industrial Informatics (INDIN). July 2019, pp. 492–499. ISBN: 978-1-7281-2928-0. DOI: 10.1109/INDIN41052.2019.8972050.

[Wal+19d] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer, Radek Šindelár. "Modeling Variability and Persisting Configurations in OPC UA". In: Procedia CIRP. Vol. 81: Proceedings of the 52nd CIRP Conference on Manufacturing Systems (CMS). Ed. by Peter Butala, Edvard Govekar, and Rok Vrabič. June 2019, pp. 13–18. DOI: 10.1016/j.procir.2019.03.003.

[Wal+18b] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "A Variability Information Model for OPC UA". In: Proceedings of the 23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). Sept. 2018. ISBN: 978-1-5386-7109-2. DOI: 10.1109/ETFA.2018.8502502.

[Wal+18c] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "AutomationML, ISA-95 and Others: Rendezvous in the OPC UA Universe". In: Proceedings of the 14th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2018, pp. 1381–1387. ISBN: 978-1-5386-3594-0. DOI: 10.1109/COASE.2018.8560600.

[WHM17a] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "Aligning Business Services with Production Services: The Case of REA and ISA-95". In: Proceedings of the 10th IEEE International Conference on Service Oriented Computing and Applications (SOCA). Nov. 2017, pp. 9–17. ISBN: 978-1-5386-1327-6. DOI: 10.1109/SOCA.2017.10.

[Wal+15a] **Bernhard Wally**, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer. "Model-Driven Retail Information System based on REA Business Ontology and Retail-H". In: Proceedings of the 17th IEEE Conference on Business Informatics (CBI). Vol. 1. July 2015, pp. 116–124. ISBN: 978-1-4673-7340-1. DOI: 10.1109/CBI.2015.49.

Workshop Proceedings

[WH14a] **Bernhard Wally**, Christian Huemer. "Defining Business Rules for REA Business Models". In: Proceedings of the 16th IEEE International Conference on Business Informatics (CBI). Vol. 2 – Workshop Papers. 1st Workshop on Enterprise Engineering Theories and Methods (WEETM). July 2014. ISBN: 978-1-4799-5779-8. DOI: 10.1109/CBI.2014.52.

2.1 Defining Business Rules for REA Business Models

Citation

Bernhard Wally, Christian Huemer. "Defining Business Rules for REA Business Models". In: Proceedings of the 16th IEEE International Conference on Business Informatics (CBI). Vol. 2 – Workshop Papers. 1st Workshop on Enterprise Engineering Theories and Methods (WEETM). July 2014. ISBN: 978-1-4799-5779-8. DOI: 10.1109/CBI.2014.52.

Contribution

Conceptualization, Methodology, Investigation, Implementation, Writing

Abstract

The REA business model language is an established vehicle (i) to model businesses in terms of domain specific value chains and their key concepts and (ii) to capture business data in terms of accounting artefacts. REA has evolved into a specification that could drive web shops, enterprise/trading information systems, enterprise resource planning systems, etc. Such systems require support for sophisticated business rules in order to decouple business logic from application logic. In this work we present a framework for structural integration of business rules into REA business models.

Cited Works

[WH14] **Bernhard Wally**, Christian Huemer. "Towards a Generic Data Model for REA based Applications". In: Proceedings of the 4th International Symposium on Business Modeling and Software Design (BMSD). June 2014, pp. 153–158. ISBN: 978-989-758-032-1. DOI: 10.5220/0005425401530158.

[Wal+14] **Bernhard Wally**, Alexandra Mazak, Dieter Mayrhofer, Christian Huemer. "Defining Business Rules for REA based on Fragments and Declarations". In: Proceedings of the 8th International Workshop on Value Modeling and Business Ontology (VMBO). Mar. 2014.

[OMG14] Object Management Group. Decision Model and Notation. Specification. OMG DMN 1.0 Beta 1. 2014.

[Gai13] Frederik Gailly. "Transforming Enterprise Ontologies into SBVR formalizations". In: Proceedings of the CAiSE Forum at the 25th International Conference on Advanced Information Systems Engineering (CAiSE). Ed. by Rébecca Deneckère and Henderik A. Proper. 2013.

[GG13] Frederik Gailly, Guido L. Geerts. "Formal Definition of Business Rules Using REA Business Modeling Language". eng. In: Proceedings of the 7th International Workshop on Value Modeling and Business Ontology (VMBO). Delft, The Netherlands, 2013.

[OMG13] Object Management Group. OMG Meta Object Facility (MOF) Core Specification. Specification. OMG MOF 2.4.1. 2013.

[The13] The JBoss Drools Team. Drools Documentation. JBoss Community. 2013. URL: http://docs.jboss.org/drools/release/6.0.1.Final/drools-docs/pdf/drools-docs.pdf.

[GG12] Frederik Gailly, Guido L. Geerts. "Ontology-Driven Business Rule Specification". In: Proceedings of the 6th International Workshop on Value Modeling and Business Ontology (VMBO). 2012.

[GW10] Giancarlo Guizzardi, Gerd Wagner. "Using the unified foundational ontology (UFO) as a foundation for general conceptual modeling languages". In: Theory and Applications of Ontology: Computer Applications. Springer, 2010, pp. 175–196.

[OMG08] Object Management Group. Semantics of Business Vocabulary and Business Rules (SBVR). Specification. 2008.

[GM06] Guido L. Geerts, William E. McCarthy. "Policy-Level Specifications in REA Enterprise Information Systems". In: Journal of Information Systems 20.2 (2006), pp. 37–63.

[HKS06] Pavel Hrubỳ, Jesper Kiehn, Christian Vibe Scheller. Model-Driven Design using Business Patterns. Springer, 2006.

[RD05] Florian Rosenberg, Schahram Dustdar. "Business Rules Integration in BPEL – A Service-Oriented Approach". In: Proceedings of the 7th IEEE International Conference on E-Commerce Technology (CEC). 2005.

[DHo04] Maja D'Hondt. "Hybrid Aspects for Integrating Rule-Based Knowledge and Object-Oriented Functionality". PhD Thesis. Vrije Universiteit Brussel, Faculteit Wetenschappen, Vakgroep Informatica, System and Software Engineering Lab, 2004.

[And+03] Tony Andrews, Francisco Curbera, Hitesh Dholakia, Yaron Goland, Johannes Klein, Frank Leymann, Kevin Liu, Dieter Roller, Doug Smith, Ivana Trickovic, Sanjiva Weerawarana. Business Process Execution Language for Web Services. Specification. 2003.

[GM02] Guido L. Geerts, William E. McCarthy. "An ontological analysis of the economic primitives of the extended-REA enterprise information architecture". In: International Journal of Accounting Information Systems 3.1 (2002), pp. 1–16. ISSN: 1467-0895. DOI: 10.1016/S1467-0895(01)00020-3.

[GM00] Guido L. Geerts, William E. McCarthy. “The Ontological Foundation of REA Enterprise Information Systems”. In: Annual Meeting of the American Accounting Association, Philadelphia, PA. Vol. 362. 2000, pp. 127–150.

[San00] Oliver Sandtner. “Business Rules”. MA thesis. Universität Karlsruhe, Institut für Angewandte Informatik und Formale Beschreibungsverfahren, 2000.

[NJ98] Hiroaki Nakamura, Ralph E. Johnson. “Adaptive Framework for the REA Accounting Model”. In: OOPSLA’98 Workshop on Business Object Design and Implementation IV. 1998.

[Hay85] Frederick Hayes-Roth. “Rule-Based Systems”. In: Communications of the ACM 28.9 (1985), pp. 921–932.

[DS83] Richard O. Duda, Edward H. Shortliffe. “Expert Systems Research”. In: Science 220.4594 (1983), pp. 261–268.

[McC82] William E. McCarthy. “The REA Accounting Model: A Generalized Framework for Accounting Systems in a Shared Data Environment”. In: The Accounting Review 57.3 (1982), pp. 554–578.

2.2 Model-Driven Retail Information System based on REA Business Ontology and Retail-H

Citation

Bernhard Wally, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer. "Model-Driven Retail Information System based on REA Business Ontology and Retail-H". In: Proceedings of the 17th IEEE Conference on Business Informatics (CBI). Vol. 1. July 2015, pp. 116–124. ISBN: 978-1-4673-7340-1. DOI: 10.1109/CBI.2015.49.

Contribution

Investigation, Writing

Award

Nominated for the Best Paper Award of the 17th IEEE Conference on Business Informatics (CBI) 2015.

Abstract

Enterprise resource planning (ERP) systems are often cumbersome to customize to a client's needs. Model-driven approaches promise to simplify these attempts. In this work we present an ERP prototype based on the *Resource-Event-Agent* (REA) business ontology that follows a "model-at-runtime" approach: one may customize the ERP system during runtime by changing the underlying REA models. We are using *Retail-H* as the reference framework for building a retail information system (RIS). Our main contribution is the prototypical implementation of a domain agnostic REA engine that can be loaded at runtime with domain specific business models—these models can further be manipulated at runtime. On that basis we have exemplarily modeled main concepts of Retail-H in REA. Validation of the implemented components is realized by applying real business activities and requirements received from our partner, a business software solution provider.

Cited Works

[Wal+15] **Bernhard Wally**, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer, Peter Regatschnig, Dieter Mayrhofer. "REAlist – A Tool Demo". In: Proceedings of the 9th International Workshop on Value Modeling and Business Ontology (VMBO). Feb. 2015.

[SA13] Walter S. A. Schwaiger, Michael Abmayer. “Accounting and Management Information Systems: A Semantic Integration”. In: Proceedings of International Conference on Information Integration and Web-based Applications & Services (IIWAS). 2013, pp. 346–352. ISBN: 978-1-4503-2113-6. DOI: 10.1145/2539150.2539214.

[Al-12] Mohannad M. Al-Jallad. “REA Business Modeling Language: Toward a REA based Domain Specific Visual Language”. Student thesis. KTH Royal Institute of Technology, 2012.

[May12] Dieter Mayrhofer. “REA-DSL: Business Model Driven Data Engineering”. PhD Dissertation. Vienna University of Technology, 2012.

[Mei11] Vera Meister. Grundlagen betrieblicher Anwendungssysteme – Integrative Lösungsansätze für die betriebliche Praxis. Kontakt & Studium 703. expert Verlag, 2011. ISBN: 978-3816930587.

[Gro10] Norbert Gronau. Enterprise Resource Planning. Architektur, Funktionen und Management von ERP-Systemen. 2nd ed. Oldenbourg Wissenschaftsverlag, 2010. ISBN: 978-3486590500.

[BS07] Jörg Becker, Reinhard Schütte. “Reference Modeling for Business Systems Analysis”. In: ed. by Peter Fettke and Peter Loos. Idea Group, 2007. Chap. Reference Model for Retail Enterprises, pp. 182–205.

[II07] International Organization for Standardization, International Electrotechnical Commission. Business Transaction Scenarios – Accounting and Economic Ontology. ISO/IEC 15944-4:2007(E). 2007.

[DG06] Philippe Dugerdil, Gil Gaillard. “Model-Driven ERP Implementation”. In: Proceedings of the 2nd International Workshop on Model-Driven Enterprise Information Systems (MDEIS), in conjunction with the 8th International Conference on Enterprise Information Systems (ICEIS). 2006.

[GM06] Guido L. Geerts, William E. McCarthy. “Policy-Level Specifications in REA Enterprise Information Systems”. In: Journal of Information Systems 20.2 (2006), pp. 37–63.

[HKS06] Pavel Hrubỳ, Jesper Kiehn, Christian Vibe Scheller. Model-Driven Design using Business Patterns. Springer, 2006.

[Dre+05] Alexander Dreiling, Michael Rosemann, Wil M. P. van der Aalst, Wasim Sadiq, Sana Khan. “Model-Driven Process Configuration of Enterprise Systems”. In: Proceedings der 7. Internationalen Tagung Wirtschaftsinformatik (WI). Ed. by Otto K. Ferstl, Elmar J. Sinz, Sven Eckert, and Tilman Isselhorst. Physica-Verlag, 2005, pp. 687–706. ISBN: 978-3-7908-1574-0. DOI: 10.1007/3-7908-1624-8_36.

[BS04] Jörg Becker, Reinhard Schütte. Handelsinformationssysteme. 2nd ed. MI Wirtschaftsbuch, 2004.

[GM02] Guido L. Geerts, William E. McCarthy. “An ontological analysis of the economic primitives of the extended-REA enterprise information architecture”. In: International Journal of Accounting Information Systems 3.1 (2002), pp. 1–16. ISSN: 1467-0895. DOI: 10.1016/S1467-0895(01)00020-3.

[GB02] Jon Atle Gulla, Terje Brasethvik. “A Model-driven ERP Environment with Search Facilities”. In: Data & Knowledge Engineering 42.3 (2002), pp. 327–341. ISSN: 0169-023X. DOI: 10.1016/S0169-023X(02)00051-4.

[GM00] Guido L. Geerts, William E. McCarthy. “The Ontological Foundation of REA Enterprise Information Systems”. In: Annual Meeting of the American Accounting Association, Philadelphia, PA. Vol. 362. 2000, pp. 127–150.

[HM00] Rolf Haugen, William E. McCarthy. “REA: A semantic model for internet supply chain collaboration”. In: Proceedings of the 6th International Workshop on Business Object Component Design and Implementation. 2000.

[GM99] Guido L. Geerts, William E. McCarthy. “An accounting object infrastructure for knowledge-based enterprise models”. In: IEEE Intelligent Systems 14.4 (1999), pp. 89–94.

[JW97] Ralph Johnson, Bobby Woolf. “Type Object”. In: Pattern Languages of Program Design 3. Ed. by Robert C. Martin, Dirk Riehle, and Frank Buschmann. Addison-Wesley Longman Publishing, 1997, pp. 47–65. ISBN: 0-201-31011-2.

[McC82] William E. McCarthy. “The REA Accounting Model: A Generalized Framework for Accounting Systems in a Shared Data Environment”. In: The Accounting Review 57.3 (1982), pp. 554–578.

2.3 Aligning Business Services with Production Services: The Case of REA and ISA-95

Citation

Bernhard Wally, Christian Huemer, Alexandra Mazak. "Aligning Business Services with Production Services: The Case of REA and ISA-95". In: Proceedings of the 10th IEEE International Conference on Service Oriented Computing and Applications (SOCA). Nov. 2017, pp. 9–17. ISBN: 978-1-5386-1327-6. DOI: 10.1109/SOCA.2017.10.

Contribution

Conceptualization, Methodology, Investigation, Implementation, Writing

Abstract

"Industrie 4.0" aims at flexible production networks that require horizontal integration across companies. Evidently, any production related information exchanged in the network must be vertically forwarded to the corresponding service endpoints of the local production system. Accordingly, there is a need to align information that flows between companies and within each company. The Resource-Event-Agent (REA) business ontology describes a metamodel for internal business activities (e.g., production) and for inter-organizational exchange constellations on the enterprise resource planning (ERP) level. ISA-95 is a series of standards targeting the integration of enterprise control systems on the interface between ERP systems and manufacturing execution systems. Consequently, we align elements of REA and ISA-95 and define conversion rules for the transformation of elements from one system to the other. By interleaving the semantics of both standards, we formally strengthen the links between the services of the business level and the production level, and support multi-system adaptation in flexible production environments.

Cited Works

[WHM17a] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "A View on Model-Driven Vertical Integration: Alignment of Production Facility Models and Business Models". In: Proceedings of the 13th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2017. ISBN: 978-1-5090-6782-4. DOI: 10.1109/COASE.2017.8256235.

[Wal+17] **Bernhard Wally**, Miriam Schleipen, Nicole Schmidt, Nikolai D'Agostino, Robert Henßen, Yingbing Hua. "AutomationML auf höheren Automatisierungsebenen. Eine Auswahl relevanter Anwendungsfälle". In: Proceedings of AUTOMATION 2017. Technology networks Processes. 18. Leitkongress der Mess- und Automatisierungstechnik. VDI-Berichte 2293. VDI-Verlag, June 2017. ISBN: 978-3-18-092293-5.

[WHM17b] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "Entwining Plant Engineering Data and ERP Information: Vertical Integration with AutomationML and ISA-95". In: Proceedings of the 3rd IEEE International Conference on Control, Automation and Robotics (ICCAR). Apr. 2017. ISBN: 978-1-5090-6089-4. DOI: 10.1109/ICCAR.2017.7942718.

[WHM17c] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "ISA-95 based Task Specification Layer for REA in Production Environments". In: Proceedings of the 11th International Workshop on Value Modeling and Business Ontologies (VMBO). Mar. 2017.

[Ber+16] Luca Berardinelli, Stefan Biffl, Arndt Lüder, Emanuel Mätzler, Tanja Mayerhofer, Manuel Wimmer, Sabine Wolny. "Cross-disciplinary engineering with AutomationML and SysML". In: at – Automatisierungstechnik 64.4 (2016), pp. 253–269. DOI: 10.1515/auto-2015-0076.

[Fel+16] Stefan Feldmann, Manuel Wimmer, Konstantin Kernschmidt, Birgit Vogel-Heuser. "A comprehensive approach for managing inter-model inconsistencies in automated production systems engineering". In: Proceedings of the 12th IEEE International Conference on Automation Science and Engineering (CASE). 2016, pp. 1120–1127. DOI: 10.1109/COASE.2016.7743530.

[HW16] Heinz Nixdorf Institut der Universität Paderborn, Werkzeugmaschinenlabor WZL der Rheinisch-Westfälischen Technischen Hochschule Aachen. Industrie 4.0. Internationaler Benchmark, Zukunftsoptionen und Handlungsempfehlungen für die Produktionsforschung. Technical Report. 2016. 84 pp.

[MGG16] William E. McCarthy, Guido L. Geerts, Graham Gal. "The Economic Structures of Exchanges vs. Conversions in the REA Enterprise Ontology". Presented at the 10th International Workshop on Value Modeling and Business Ontology (VMBO). 2016.

[The+16] Alfred Theorin, Kristofer Bengtsson, Julien Provost, Michael Lieder, Charlotta Johnsson, Thomas Lundholm, Bengt Lennartson. "An event-driven manufacturing information system architecture for Industry 4.0". In: International Journal of Production Research (2016). to appear. DOI: 10.1080/00207543.2016.1201604.

[Wal+15] **Bernhard Wally**, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer. "Model-Driven Retail Information System based on REA Business Ontology and Retail-H". In: Proceedings of the 17th IEEE Conference on Business Informatics (CBI). Vol. 1. July 2015, pp. 116–124. ISBN: 978-1-4673-7340-1. DOI: 10.1109/CBI.2015.49.

[IEC15a] International Electrotechnical Commission. Enterprise–control system integration – Part 4: Object model attributes for manufacturing operations management integration. International Standard. IEC 62264-4:2015. 2015.

[IEC15b] International Electrotechnical Commission. Engineering data exchange format for use in industrial automation systems engineering – Automation markup language – Part 2: Role class libraries. International Standard. IEC 62714-2:2015. 2015.

[MH15a] Alexandra Mazak, Christian Huemer. "HoVer: A modeling framework for horizontal and vertical integration". In: Proceedings of the 13th IEEE International Conference on Industrial Informatics (INDIN). IEEE, 2015, pp. 1642–1647. DOI: 10.1109/INDIN.2015.7281980.

[MH15b] Alexandra Mazak, Christian Huemer. "From Business Functions to Control Functions: Transforming REA to ISA-95". In: Proceedings of the 17th IEEE Conference on Business Informatics (CBI). Vol. 1. IEEE, 2015, pp. 33–42. DOI: 10.1109/CBI.2015.50.

[OMG15] Object Management Group. OMG Unified Modeling Language (OMG UML). Specification. 2015.

[Pos+15] Jorge Posada, Carlos Toro, Iñigo Barandiaran, David Oyarzun, Didier Stricker, Raffaele Amicis, Eduardo B. Pinto, Peter Eisert, Jürgen Döllner, Ivan Vallarino. "Visual computing as a key enabling technology for industrie 4.0 and industrial internet". In: IEEE Computer Graphics and Applications 35.2 (2015), pp. 26–40.

[The+15] Alfred Theorin, Kristofer Bengtsson, Julien Provost, Michael Lieder, Charlotta Johnsson, Thomas Lundholm, Bengt Lennartson. "An Event-Driven Manufacturing Information System Architecture". In: Proceedings of the 15th IFAC Symposium on Information Control Problems in Manufacturing. 2015, pp. 547–554. DOI: http://dx.doi.org/10.1016/j.ifacol.2015.06.138.

[Vog+15] Birgit Vogel-Heuser, Stefan Feldmann, Jens Folmer, Jan Ladiges, Alexander Fay, Sascha Lity, Matthias Tichy, Matthias Kowal, Ina Schaefer, Christopher Haubeck, Winfried Lamersdorf, Timo Kehrer, Sinem Getir, Mattias Ulbrich, Vladimir Klebanov, Bernhard Beckert. "Selected Challenges of Software Evolution for Automated Production Systems". In: Proceedings of the 13th IEEE International Conference on Industrial Informatics (INDIN). 2015, pp. 314–321. DOI: 10.1109/INDIN.2015.7281753.

[Bre+14] Malte Brettel, Niklas Friederichsen, Michael Keller, Marius Rosenberg. "How virtualization, decentralization and network building change the manufacturing landscape: an industry 4.0 perspective". In: International Journal of Mechanical, Industrial Science and Engineering 8.1 (2014), pp. 37–44.

[IEC14] International Electrotechnical Commission. Engineering data exchange format for use in industrial automation systems engineering – Automation markup language – Part 1: Architecture and general requirements. International Standard. IEC 62714-1:2014. 2014.

[ISO14] International Organization for Standardization. Automation systems and integration – Key performance indicators (KPIs) for manufacturing operations management – Part 2: Definitions and descriptions. International Standard. ISO 22400-2:2014. 2014.

[IJ13] Jahanzaib Imtiaz, Jürgen Jasperneite. "Scalability of OPC-UA down to the chip level enables "Internet of Things"". In: Proceedings of 11th IEEE International Conference on Industrial Informatics (INDIN). 2013, pp. 500–505.

[IEC13a] International Electrotechnical Commission. Enterprise–control system integration – Part 1: Models and terminology. International Standard. IEC 62264-1:2013. 2013.

[IEC13b] International Electrotechnical Commission. Enterprise–control system integration – Part 2: Objects and attributes for enterprise–control system integration. International Standard. IEC 62264-2:2013. 2013.

[Ono+13] Toshio Ono, Shahzad Ali, Paul Hunkar, Dennis Brandl. OPC Unified Architecture for ISA-95 Common Object Model. Companion Specification. 2013.

[Unv13] Hakki Ozgur Unver. "An ISA-95-based manufacturing intelligence system in support of lean initiatives". In: International Journal of Advanced Manufacturing Technology 65.5 (2013), pp. 853–866. ISSN: 1433-3015. DOI: 10.1007/s00170-012-4223-z.

[Wit13] Maria Witsch. "Funktionale Spezifikation von Manufacturing Execution Systems im Spannungsfeld zwischen IT, Geschäftsprozess und Produktion". German. PhD thesis. Fakultät für Wirtschaftswissenschaften, Technische Universität München, 2013. ISBN: 978-3-86844-597-8.

[Sch12] Miriam Schleipen. "Adaptivität und semantische Interoperabilität von Manufacturing Execution Systemen (MES)". German. PhD Thesis. Karlsruher Institut für Technologie (KIT), 2012. 388 pp. ISBN: 978-3-86644-955-8. DOI: 10.5445/KSP/1000031462.

[WV12] Maria Witsch, Birgit Vogel-Heuser. “Towards a Formal Specification Framework for Manufacturing Execution Systems”. In: IEEE Transactions on Industrial Informatics 8.2 (2012), pp. 311–320. DOI: 10.1109/TII.2012.2186585.

[Wim+10] Manuel Wimmer, Gerti Kappel, Angelika Kusel, Werner Retschitzegger, Johannes Schoenboeck, Wieland Schwinger. “Towards an Expressivity Benchmark for Mappings Based on a Systematic Classification of Heterogeneities”. In: Proceedings of the First International Workshop on Model-Driven Interoperability. MDI ’10. Oslo, Norway: ACM, 2010, pp. 32–41. ISBN: 978-1-4503-0292-0. DOI: 10.1145/1866272.1866278.

[SF08] François Scharffe, Dieter Fensel. “Correspondence Patterns for Ontology Alignment”. In: Knowledge Engineering: Practice and Patterns. Proceedings of the 16th International Conference on Knowledge Engineering and Knowledge Management (EKAW). Ed. by Aldo Gangemi and Jérôme Euzenat. Lecture Notes in Artificial Intelligence 5268. Springer, 2008, pp. 83–92. ISBN: 978-3-540-87696-0. DOI: 10.1007/978-3-540-87696-0_10.

[GM06] Guido L. Geerts, William E. McCarthy. “Policy-Level Specifications in REA Enterprise Information Systems”. In: Journal of Information Systems 20.2 (2006), pp. 37–63.

[GM02] Guido L. Geerts, William E. McCarthy. “An ontological analysis of the economic primitives of the extended-REA enterprise information architecture”. In: International Journal of Accounting Information Systems 3.1 (2002), pp. 1–16. ISSN: 1467-0895. DOI: 10.1016/S1467-0895(01)00020-3.

[GM00] Guido L. Geerts, William E. McCarthy. “The Ontological Foundation of REA Enterprise Information Systems”. In: Annual Meeting of the American Accounting Association, Philadelphia, PA. Vol. 362. 2000, pp. 127–150.

[GM99] Guido L. Geerts, William E. McCarthy. “An accounting object infrastructure for knowledge-based enterprise models”. In: IEEE Intelligent Systems 14.4 (1999), pp. 89–94.

[GM97] Guido L. Geerts, William E. McCarthy. “Modeling Business Enterprises as Value-Added Process Hierarchies with Resource-Event-Agent Object Templates”. In: Business Object Design and Implementation. Ed. by Jeff Sutherland, Cory Casanave, Joaquin Miller, Philip Patel, and Glenn Hollowell. Springer, 1997, pp. 94–113. ISBN: 978-3-540-76096-2. DOI: 10.1007/978-1-4471-0947-1_10.

[JW97] Ralph Johnson, Bobby Woolf. “Type Object”. In: Pattern Languages of Program Design 3. Ed. by Robert C. Martin, Dirk Riehle, and Frank Buschmann. Addison-Wesley Longman Publishing, 1997, pp. 47–65. ISBN: 0-201-31011-2.

[Coa92] Peter Coad. "Object-Oriented Patterns". In: Communications of the ACM 35.9 (1992), pp. 152–159.

[McC82] William E. McCarthy. "The REA Accounting Model: A Generalized Framework for Accounting Systems in a Shared Data Environment". In: The Accounting Review 57.3 (1982), pp. 554–578.

2.4 AutomationML, ISA-95 and Others: Rendezvous in the OPC UA Universe

Citation

Bernhard Wally, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "AutomationML, ISA-95 and Others: Rendezvous in the OPC UA Universe". In: Proceedings of the 14th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2018, pp. 1381–1387. ISBN: 978-1-5386-3594-0. DOI: 10.1109/COASE.2018.8560600.

Contribution

Conceptualization, Methodology, Investigation, Implementation, Writing

Abstract

OPC Unified Architecture (UA) is a powerful and versatile platform for hosting information from a large variety of domains. In some cases, the domain-specific information models provide overlapping information, such as (i) different views on a specific entity or (ii) different levels of detail of a single entity. Emerging from a multi-disciplinary engineering process, these different views can stem from various tools that have been used to deal with that entity, or from different stages in an engineering process, e.g., from requirements engineering over system design and implementation to operations. In this work, we provide a concise but expressive set of OPC UA reference types that unobtrusively allow the persistent instantiation of additional knowledge with respect to relations between OPC UA nodes. We will show the application of these reference types on the basis of a rendezvous of AutomationML and ISA-95 in an OPC UA server.

Cited Works

[Wal18] **Bernhard Wally**. Provisioning for MES and ERP. Support for IEC 62264 and B2MML. Application Recommendation. AR_MES_ERP 1.1.0. Nov. 2018.

[WHM17a] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "Aligning Business Services with Production Services: The Case of REA and ISA-95". In: Proceedings of the 10th IEEE International Conference on Service Oriented Computing and Applications (SOCA). Nov. 2017, pp. 9–17. ISBN: 978-1-5386-1327-6. DOI: 10.1109/SOCA.2017.10.

[WHM17b] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. “A View on Model-Driven Vertical Integration: Alignment of Production Facility Models and Business Models”. In: Proceedings of the 13th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2017. ISBN: 978-1-5090-6782-4. DOI: 10.1109/COASE.2017.8256235.

[Wal+17] **Bernhard Wally**, Miriam Schleipen, Nicole Schmidt, Nikolai D’Agostino, Robert Henßen, Yingbing Hua. “AutomationML auf höheren Automatisierungsebenen. Eine Auswahl relevanter Anwendungsfälle”. In: Proceedings of AUTOMATION 2017. Technology networks Processes. 18. Leitkongress der Mess- und Automatisierungstechnik. VDI-Berichte 2293. VDI-Verlag, June 2017. ISBN: 978-3-18-092293-5.

[WHM17c] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. “Entwining Plant Engineering Data and ERP Information: Vertical Integration with AutomationML and ISA-95”. In: Proceedings of the 3rd IEEE International Conference on Control, Automation and Robotics (ICCAR). Apr. 2017. ISBN: 978-1-5090-6089-4. DOI: 10.1109/ICCAR.2017.7942718.

[WHM17d] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. “ISA-95 based Task Specification Layer for REA in Production Environments”. In: Proceedings of the 11th International Workshop on Value Modeling and Business Ontologies (VMBO). Mar. 2017.

[GO17] German Machine Tool Builders’ Association (VDW), OPC Foundation. OPC UA Information Model for CNC Systems. Companion Specification. OPC-CNC:2017. 2017.

[Lüd+17] Arndt Lüder, Miriam Schleipen, Nicole Schmidt, Julius Pfrommer, Robert Henßen. “One step towards an Industry 4.0 component”. In: Proceedings of the 13th IEEE Conference on Automation Science and Engineering (CASE). 2017, pp. 1268–1273. DOI: 10.1109/COASE.2017.8256275.

[OMG17] Object Management Group. OMG Systems Modeling Language. 2017.

[OE17] OPC Foundation, Ethernet POWERLINK Standardization Group. OPC Unified Architecture POWERLINK. Companion Specification. OPC-POWERLINK:2017. 2017.

[OC17] OPC Foundation, CC-Link Partner Association. OPC Unified Architecture for Control & Communication System Profile (for Machine). Companion Specification. OPC-CSP+:2017. 2017.

[Sur+17] Benny Suryajaya, Chao-Chun Chen, Min-Hsiung Hung, Yu-Yang Liu, Jia-Xuan Liu, Yu-Chuan Lin. “A fast large-size production data transformation scheme for supporting smart manufacturing in semiconductor industry”. In: Proceedings of the 13th IEEE International Conference on Automation

Science and Engineering (CASE). 2017, pp. 275–281. DOI: 10.1109/COASE.2017.8256114.

[Aut16] AutomationML consortium. AutomationML Best Practice Recommendation – External Data Reference. Best Practice Recommendation. AML BPR-EDR:2016. 2016.

[DIN16a] Deutsches Institut für Normung. Combining OPC Unified Architecture and Automation Markup Language. DIN SPEC 16592:2016-12. 2016.

[DIN16b] Deutsches Institut für Normung. Reference Architecture Model Industrie 4.0 (RAMI4.0). DIN SPEC 91345:2016-04. 2016.

[Fel+16] Stefan Feldmann, Manuel Wimmer, Konstantin Kernschmidt, Birgit Vogel-Heuser. “A comprehensive approach for managing inter-model inconsistencies in automated production systems engineering”. In: Proceedings of the 12th IEEE International Conference on Automation Science and Engineering (CASE). 2016, pp. 1120–1127. DOI: 10.1109/COASE.2016.7743530.

[Sab+16] Marta Sabou, Fajar Ekaputra, Olga Kovalenko, Stefan Biffl. “Supporting the Engineering of Cyber-Physical Production Systems with the AutomationML Analyzer”. In: Proceedings of the 1st International Workshop on Cyber-Physical Production Systems (CPPS). IEEE, 2016. ISBN: 978-1-5090-1156-8. DOI: 10.1109/CPPS.2016.7483919.

[Wal+15] **Bernhard Wally**, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer. “Model-Driven Retail Information System based on REA Business Ontology and Retail-H”. In: Proceedings of the 17th IEEE Conference on Business Informatics (CBI). Vol. 1. July 2015, pp. 116–124. ISBN: 978-1-4673-7340-1. DOI: 10.1109/CBI.2015.49.

[Aut15] AutomationML consortium. AutomationML Whitepaper Part 3 – Geometry and Kinematics. Whitepaper. AML Part 3:2015. 2015.

[Bif+15] Stefan Biffl, Emanuel Mätzler, Manuel Wimmer, Arndt Lüder, Nicole Schmidt. “Linking and Versioning Support for AutomationML: A Model-Driven Engineering Perspective”. In: Proceedings of the 13th IEEE International Conference on Industrial Informatics (INDIN). 2015, pp. 499–506. ISBN: 978-1-4799-6649-3. DOI: 10.1109/INDIN.2015.7281784.

[IEC15] International Electrotechnical Commission. Engineering data exchange format for use in industrial automation systems engineering – Automation markup language – Part 2: Role class libraries. International Standard. IEC 62714-2:2015. 2015.

[OMG15] Object Management Group. OMG Unified Modeling Language (OMG UML). Specification. 2015.

[HS14] Robert Henßen, Miriam Schleipen. “Interoperability between OPC UA and AutomationML”. In: Proceedings of the 8th International Conference on Digital Enterprise Technology (DET). Disruptive Innovation in Manufacturing Engineering towards the 4th Industrial Revolution. 2014.

[IEC14] International Electrotechnical Commission. Engineering data exchange format for use in industrial automation systems engineering – Automation markup language – Part 1: Architecture and general requirements. International Standard. IEC 62714-1:2014. 2014.

[IEC13a] International Electrotechnical Commission. Programmable controllers – Part 3: Programming languages. IEC 61131-3:2013. 2013.

[IEC13b] International Electrotechnical Commission. Enterprise–control system integration – Part 1: Models and terminology. International Standard. IEC 62264-1:2013. 2013.

[IEC13c] International Electrotechnical Commission. Enterprise–control system integration – Part 2: Objects and attributes for enterprise–control system integration. International Standard. IEC 62264-2:2013. 2013.

[KV13] Konstantin Kernschmidt, Birgit Vogel-Heuser. “An interdisciplinary SysML based modeling approach for analyzing change influences in production plants to support the engineering”. In: Proceedings of the 9th IEEE International Conference on Automation Science and Engineering (CASE). IEEE, 2013, pp. 1113–1118. ISBN: 978-1-4799-1515-6. DOI: 10.1109/CoASE.2013.6654030.

[MES13] Manufacturing Enterprise Solutions Association International. Business To Manufacturing Markup Language. Standards and Tools. MESA B2MML V0600. 2013.

[MO13] MTConnect Institute, OPC Foundation. MTConnect OPC UA. Companion Specification. OPC-MTConnect:2013. 2013.

[Ono+13] Toshio Ono, Shahzad Ali, Paul Hunkar, Dennis Brandl. OPC Unified Architecture for ISA-95 Common Object Model. Companion Specification. 2013.

[Aut10] AutomationML consortium. AutomationML Whitepaper Part 4 – AutomationML Logic Description. Whitepaper. AML Part 4:2010. 2010.

[IEC10] International Electrotechnical Commission. OPC Unified Architecture – Part 1: Overview and Concepts. IEC 62541-1:2010. 2010.

[PO10] PLCopen, OPC Foundation. OPC UA Information Model for IEC-61131-3. Companion Specification. PLCopen-OPC:2010. 2010.

[MLD09] Wolfgang Mahnke, Stefan-Helmut Leitner, Matthias Damm. OPC Unified Architecture. Springer, 2009. ISBN: 978-3-540-68898-3.

[PLC09] PLCopen Technical Committee 6. XML Formats for IEC 61131-3. Technical Paper. PLCopen XML:2009. 2009.

[IEC08] International Electrotechnical Commission. Representation of process control engineering – Requests in P&I diagrams and data exchange between P&ID tools and PCE-CAE tools. International Standard. IEC 62424:2008. 2008.

[Béz+06] Jean Bézivin, Salim Bouzitouna, Marcos Didonet Del Fabro, Marie-Pierre Gervais, Fréderic Jouault, Dimitrios Kolovos, Ivan Kurtev, Richard F. Paige. "A Canonical Scheme for Model Composition". In: Proceedings of the 2nd European Conference on Model Driven Architecture – Foundations and Applications (ECMDA-FA). LNCS 4066. 2006, pp. 346–360. ISBN: 978-3-540-35909-8.

[JW97] Ralph Johnson, Bobby Woolf. "Type Object". In: Pattern Languages of Program Design 3. Ed. by Robert C. Martin, Dirk Riehle, and Frank Buschmann. Addison-Wesley Longman Publishing, 1997, pp. 47–65. ISBN: 0-201-31011-2.

[Coa92] Peter Coad. "Object-Oriented Patterns". In: Communications of the ACM 35.9 (1992), pp. 152–159.

[McC82] William E. McCarthy. "The REA Accounting Model: A Generalized Framework for Accounting Systems in a Shared Data Environment". In: The Accounting Review 57.3 (1982), pp. 554–578.

2.5 A Variability Information Model for OPC UA

Citation

Bernhard Wally, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "A Variability Information Model for OPC UA". In: Proceedings of the 23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). Sept. 2018. ISBN: 978-1-5386-7109-2. DOI: 10.1109/ETFA.2018.8502502.

Contribution

Conceptualization, Methodology, Investigation, Implementation, Writing

Abstract

OPC Unified Architecture (UA) is a powerful technology for modeling and instantiating domain-specific information in a standardized manner. Its initial application scenario is in the domain of automated production systems, that increasingly have to deal with variability information, (i) regarding the products being manufactured and (ii) regarding the production systems themselves. In this work we propose a non-intrusive OPC UA information model for the modeling and querying of variability information using feature models, which are a well-known paradigm in the management of software product lines. Our information model can be applied "aside" existing domain information without interfering with their internal structure.

Cited Works

[Deu+18] Jochen Deuse, Christoph Heuser, Benedikt Konrad, David Lenze, Thomas Maschek, Mario Wiegand, Peter Willats. "Pushing the Limits of Lean Thinking – Design and Management of Complex Production Systems". In: Closing the Gap Between Practice and Research in Industrial Engineering. Ed. by Elisabeth Viles, Marta Ormazábal, and Alvaro Lleó. Springer, 2018, pp. 335–342. ISBN: 978-3-319-58409-6.

[Lüd+17] Arndt Lüder, Miriam Schleipen, Nicole Schmidt, Julius Pfrommer, Robert Henßen. "One step towards an Industry 4.0 component". In: Proceedings of the 13th IEEE Conference on Automation Science and Engineering (CASE). 2017, pp. 1268–1273. DOI: 10.1109/COASE.2017.8256275.

[Pau+17] Florian Pauker, Sabine Wolny, Solmaz Mansour Fallah, Manuel Wimmer. “UML2OPC-UA – Transforming UML Class Diagrams to OPC UA Information Models”. In: Proceedings of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering (CIRP ICME). 2017, pp. 128–133. DOI: 10.1016/j.procir.2017.12.188.

[Wim+17] Manuel Wimmer, Petr Novák, Radek Šindelár, Luca Berardinelli, Tanja Mayerhofer, Alexandra Mazak. “Cardinality-based Variability Modeling with AutomationML”. In: Proceedings of the 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2017. ISBN: 978-1-5090-6505-9. DOI: 10.1109/ETFA.2017.8247711.

[DIN16] Deutsches Institut für Normung. Combining OPC Unified Architecture and Automation Markup Language. DIN SPEC 16592:2016-12. 2016.

[MWM15] Emanuel Mätzler, **Bernhard Wally**, Alexandra Mazak. “A Common Home for Features and Requirements: Retrofitting the House of Quality with Feature Models”. In: Proceedings of the 9th International Workshop on Variability Modeling in Software-intensive Systems (VaMoS). ACM, Jan. 2015. ISBN: 978-1-4503-3273-6. DOI: 10.1145/2701319.2701334.

[IEC15] International Electrotechnical Commission. OPC Unified Architecture – Part 3: Address Space Model. International Standard. IEC 62541-3:2015. 2015.

[Vog+15a] Birgit Vogel-Heuser, Alexander Fay, Ina Schaefer, Matthias Tichy. “Evolution of software in automated production systems: Challenges and research directions”. In: Journal of Systems and Software 110 (2015), pp. 54–84. ISSN: 0164-1212. DOI: https://doi.org/10.1016/j.jss.2015.08.026.

[Vog+15b] Birgit Vogel-Heuser, Jakob Mund, Matthias Kowal, Christoph Legat, Jens Folmer, Sabine Teufl, Ina Schaefer. “Towards interdisciplinary variability modeling for automated production systems: Opportunities and challenges when applying delta modeling: A case study”. In: Proceedings of the 13th IEEE International Conference on Industrial Informatics (INDIN). 2015, pp. 322–328. DOI: 10.1109/INDIN.2015.7281754.

[HØ14] Øystein Haugen, Ommund Øgård. “BVR – Better Variability Results”. In: Proceedings of the 8th International Conference on System Analysis and Modeling (SAM). Ed. by Daniel Amyot, Pau Fonseca i Casas, and Gunter Mussbacher. Springer, 2014, pp. 1–15. ISBN: 978-3-319-11743-0.

[Ant+13] Michał Antkiewicz, Kacper Bąk, Alexandr Murashkin, Rafael Olaechea, Jia Hui Jimmy Liang, Krzysztof Czarnecki. “Clafer tools for product line engineering”. In: Proceedings of the 17th International Software Product Line Conference co-located workshops. ACM. 2013, pp. 130–135.

[Vya13] Valeriy Vyatkin. “Software Engineering in Industrial Automation: State-of-the-Art Review”. In: IEEE Transactions on Industrial Informatics 9.3 (2013), pp. 1234–1249. ISSN: 1551-3203. DOI: 10.1109/TII.2013.2258165.

[PSK11] Nikolaos Papakonstantinou, Seppo Sierla, Kari Koskinen. “Object oriented extensions of IEC 61131-3 as an enabling technology of software product lines”. In: Proceedings of the 16th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2011. ISBN: 978-1-4577-0017-0. DOI: 10.1109/ETFA.2011.6059113.

[BCW10] Kacper Bąk, Krzysztof Czarnecki, Andrzej Wąsowski. “Feature and Meta-Models in Clafer: Mixed, Specialized, and Coupled”. In: Software Language Engineering - Third International Conference (SLE 2010). Vol. 6563. Lecture Notes in Computer Science. Springer, 2010, pp. 102–122.

[BSR10] David Benavides, Sergio Segura, Antonio Ruiz-Cortés. “Automated Analysis of Feature Models 20 Years Later: A Literature Review”. In: Information Systems 35.6 (2010), pp. 615–636. ISSN: 0306-4379. DOI: 10.1016/j.is.2010.01.001.

[Sch10] Ina Schaefer. “Variability modelling for model-driven development of software product lines”. In: Proceedings of the 4th International Workshop on Variability Modelling of Software-Intensive Systems (VaMoS). 2010.

[CW07] Krzysztof Czarnecki, Andrzej Wąsowski. “Feature diagrams and logics: There and back again”. In: Proceedings of the 11th International Conference on Software Product Lines (SPLC). IEEE. 2007, pp. 23–34.

[Bat05] Don Batory. “Feature Models, Grammars, and Propositional Formulas”. In: Proceedings of the 9th International Conference on Software Product Lines (SPLC). Ed. by Henk Obbink and Klaus Pohl. Vol. 3714. Lecture Notes in Computer Science. Springer, 2005, pp. 7–20.

[CHE05] Krzysztof Czarnecki, Simon Helsen, Ulrich Eisenecker. “Formalizing cardinality-based feature models and their specialization”. In: Software Process: Improvement and Practice 10.1 (2005), pp. 7–29. DOI: 10.1002/spip.213.

[CK05] Krzysztof Czarnecki, Chang Hwan Peter Kim. “Cardinality-Based Feature Modeling and Constraints: A Progress Report”. In: Proceedings of the International Workshop on Software Factories, Colocated with OOPSLA’05. 2005.

[Kan+90] Kyo C. Kang, Sholom G. Cohen, James A. Hess, William E. Novak, A. Spencer Peterson. Feature-Oriented Domain Analysis (FODA) Feasibility Study. Technical Report CMU/SEI-90-TR-21. DTIC Document, 1990.

[HC88] John R. Hauser, Don Clausing. "The House of Quality". In: Harvard Business Review (1988).

2.6 Application Recommendation – Provisioning for MES and ERP – Support for IEC 62264 and B2MML

Contribution

Conceptualization, Methodology, Investigation, Implementation, Writing

Citation

Bernhard Wally. Provisioning for MES and ERP. Support for IEC 62264 and B2MML. Application Recommendation. AR_MES_ERP 1.1.0. Nov. 2018.

Notes

This application recommendation has been iteratively improved in accordance with the AutomationML technical advisory council. For the purpose of this thesis, we are always referring to the latest revision of this application recommendation, which was, at the time of writing, revision 1.1.0. Releases so far:

Revision 1.0.0 from June, 2018 [Wal18b]
Revision 1.1.0 from November, 2018 [Wal18a]

Abstract

In a fully integrated production environment, business and manufacturing functions are aligned in order to foster an efficient data flow. For the data exchange between Enterprise Resource Planning (ERP) systems and Manufacturing Execution Systems (MES) a data standard has been specified in the IEC 62264 series, based on a standard that has been standardized by the American National Standards Institute (ANSI) and the International Society of Automation (ISA): ANSI/ISA-95. A complete XML implementation of IEC 62264 has been published as the Business To Manufacturing Markup Language (B2MML) by the Manufacturing Enterprise Solutions Association (MESA) International. After IEC 62264 enables the linking of the business layer (ERP and supply chain management) to the manufacturing layer, linking objects from AML to elements of IEC 62264 further fosters the integration of manufacturing layers.

Cited Works

[Aut16] AutomationML consortium. AutomationML Best Practice Recommendation – External Data Reference. Best Practice Recommendation. AML BPR-EDR:2016. 2016.

[DIN16] Deutsches Institut für Normung. Combining OPC Unified Architecture and Automation Markup Language. DIN SPEC 16592:2016-12. 2016.

[IEC15] International Electrotechnical Commission. Engineering data exchange format for use in industrial automation systems engineering – Automation markup language – Part 2: Role class libraries. International Standard. IEC 62714-2:2015. 2015.

[IEC14] International Electrotechnical Commission. Engineering data exchange format for use in industrial automation systems engineering – Automation markup language – Part 1: Architecture and general requirements. International Standard. IEC 62714-1:2014. 2014.

[FKH13] Ned Freed, John Klensin, Tony Hansen. Media Type Specifications and Registration Procedures. Best Current Practice. RFC6838. 2013.

[IEC13a] International Electrotechnical Commission. Enterprise–control system integration – Part 1: Models and terminology. International Standard. IEC 62264-1:2013. 2013.

[IEC13b] International Electrotechnical Commission. Enterprise–control system integration – Part 2: Objects and attributes for enterprise–control system integration. International Standard. IEC 62264-2:2013. 2013.

[Ono+13] Toshio Ono, Shahzad Ali, Paul Hunkar, Dennis Brandl. OPC Unified Architecture for ISA-95 Common Object Model. Companion Specification. 2013.

[IEC10] International Electrotechnical Commission. OPC Unified Architecture – Part 1: Overview and Concepts. IEC 62541-1:2010. 2010.

2.7 Modeling Variability and Persisting Configurations in OPC UA

Citation

Bernhard Wally, Christian Huemer, Alexandra Mazak, Manuel Wimmer, Radek Šindelár. "Modeling Variability and Persisting Configurations in OPC UA". In: Procedia CIRP. Vol. 81: Proceedings of the 52nd CIRP Conference on Manufacturing Systems (CMS). Ed. by Peter Butala, Edvard Govekar, and Rok Vrabič. June 2019, pp. 13–18. DOI: 10.1016/j.procir.2019.03.003.

Contribution

Conceptualization, Methodology, Investigation, Implementation, Writing

Abstract

Variability is crucial in the design of many advanced goods and it is also receiving increasing attention in production systems engineering. Since OPC Unified Architecture plays an important role when it comes to standardized information exchange in modern production systems, it can be a melting pot for information from various engineering domains, such as product design and production engineering—thus, it is an ideal place to hold variability information of products and production systems alike. Based on an initial variability information model we propose additional concepts for the persisting of configurations.

Cited Works

[Wal+18] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "A Variability Information Model for OPC UA". In: Proceedings of the 23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). Sept. 2018. ISBN: 978-1-5386-7109-2. DOI: 10.1109/ETFA.2018.8502502.

[Deu+18] Jochen Deuse, Christoph Heuser, Benedikt Konrad, David Lenze, Thomas Maschek, Mario Wiegand, Peter Willats. "Pushing the Limits of Lean Thinking – Design and Management of Complex Production Systems". In: Closing the Gap Between Practice and Research in Industrial Engineering. Ed. by Elisabeth Viles, Marta Ormazábal, and Alvaro Lleó. Springer, 2018, pp. 335–342. ISBN: 978-3-319-58409-6.

[Lüd+17] Arndt Lüder, Miriam Schleipen, Nicole Schmidt, Julius Pfrommer, Robert Henßen. “One step towards an Industry 4.0 component”. In: Proceedings of the 13th IEEE Conference on Automation Science and Engineering (CASE). 2017, pp. 1268–1273. DOI: 10.1109/COASE.2017.8256275.

[Pau+17] Florian Pauker, Sabine Wolny, Solmaz Mansour Fallah, Manuel Wimmer. “UML2OPC-UA – Transforming UML Class Diagrams to OPC UA Information Models”. In: Proceedings of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering (CIRP ICME). 2017, pp. 128–133. DOI: 10.1016/j.procir.2017.12.188.

[Wim+17] Manuel Wimmer, Petr Novák, Radek Šindelár, Luca Berardinelli, Tanja Mayerhofer, Alexandra Mazak. “Cardinality-based Variability Modeling with AutomationML”. In: Proceedings of the 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2017. ISBN: 978-1-5090-6505-9. DOI: 10.1109/ETFA.2017.8247711.

[MWM15] Emanuel Mätzler, **Bernhard Wally**, Alexandra Mazak. “A Common Home for Features and Requirements: Retrofitting the House of Quality with Feature Models”. In: Proceedings of the 9th International Workshop on Variability Modeling in Software-intensive Systems (VaMoS). ACM, Jan. 2015. ISBN: 978-1-4503-3273-6. DOI: 10.1145/2701319.2701334.

[Vog+15a] Birgit Vogel-Heuser, Alexander Fay, Ina Schaefer, Matthias Tichy. “Evolution of software in automated production systems: Challenges and research directions”. In: Journal of Systems and Software 110 (2015), pp. 54–84. ISSN: 0164-1212. DOI: https://doi.org/10.1016/j.jss.2015.08.026.

[Vog+15b] Birgit Vogel-Heuser, Jakob Mund, Matthias Kowal, Christoph Legat, Jens Folmer, Sabine Teufl, Ina Schaefer. “Towards interdisciplinary variability modeling for automated production systems: Opportunities and challenges when applying delta modeling: A case study”. In: Proceedings of the 13th IEEE International Conference on Industrial Informatics (INDIN). 2015, pp. 322–328. DOI: 10.1109/INDIN.2015.7281754.

[Ant+13] Michał Antkiewicz, Kacper Bąk, Alexandr Murashkin, Rafael Olaechea, Jia Hui Jimmy Liang, Krzysztof Czarnecki. “Clafer tools for product line engineering”. In: Proceedings of the 17th International Software Product Line Conference co-located workshops. ACM. 2013, pp. 130–135.

[Rei13] Alexander Rein-Jury. “Feature Constraint Propagation along Configuration Links for Advanced Feature Models”. PhD Thesis. Technische Universität Berlin, 2013.

[Vya13] Valeriy Vyatkin. “Software Engineering in Industrial Automation: State-of-the-Art Review”. In: IEEE Transactions on Industrial Informatics 9.3 (2013), pp. 1234–1249. ISSN: 1551-3203. DOI: 10.1109/TII.2013.2258165.

[Lut11] Christoph Lutz. “Rechnergestütztes Konfigurieren und Auslegen individualisierter Produkte”. PhD Thesis. Vienna University of Technology, Faculty of Mechanical et al., 2011.

[PSK11] Nikolaos Papakonstantinou, Seppo Sierla, Kari Koskinen. “Object oriented extensions of IEC 61131-3 as an enabling technology of software product lines”. In: Proceedings of the 16th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2011. ISBN: 978-1-4577-0017-0. DOI: 10.1109/ETFA.2011.6059113.

[BCW10] Kacper Bąk, Krzysztof Czarnecki, Andrzej Wąsowski. “Feature and Meta-Models in Clafer: Mixed, Specialized, and Coupled”. In: Software Language Engineering - Third International Conference (SLE 2010). Vol. 6563. Lecture Notes in Computer Science. Springer, 2010, pp. 102–122.

[BSR10] David Benavides, Sergio Segura, Antonio Ruiz-Cortés. “Automated Analysis of Feature Models 20 Years Later: A Literature Review”. In: Information Systems 35.6 (2010), pp. 615–636. ISSN: 0306-4379. DOI: 10.1016/j.is.2010.01.001.

[Sch10] Ina Schaefer. “Variability modelling for model-driven development of software product lines”. In: Proceedings of the 4th International Workshop on Variability Modelling of Software-Intensive Systems (VaMoS). 2010.

[TBU10] James F. Terwilliger, Philip A. Bernstein, Adi Unnithan. “Automated Co-Evolution of Conceptual Models, Physical Databases, and Mappings”. In: Proceedings of the 29th International Conference on Conceptual Modeling (ER). Vol. 6412. Lecture Notes in Computer Science. 2010, pp. 146–159. ISBN: 978-3-642-16372-2. DOI: 10.1007/978-3-642-16373-9_11.

[Wei09] Laurenz Josef Hubert Weilguny. “Fertigungsgerechte Produktgestaltung mittels integrierter Produkt- und Prozess-Features: Knowledge-based Engineering unter Einsatz von Feature-Technologie in der Automobilindustrie”. PhD Thesis. Vienna University of Technology, Faculty of Mechanical et al., 2009.

[Rei08] Mark-Oliver Reiser. “Managing Complex Variability in Automotive Software Product Lines with Subscoping and Configuration Links”. PhD Thesis. Technische Universität Berlin, 2008.

[CW07] Krzysztof Czarnecki, Andrzej Wąsowski. “Feature diagrams and logics: There and back again”. In: Proceedings of the 11th International Conference on Software Product Lines (SPLC). IEEE. 2007, pp. 23–34.

[Bat05] Don Batory. "Feature Models, Grammars, and Propositional Formulas". In: Proceedings of the 9th International Conference on Software Product Lines (SPLC). Ed. by Henk Obbink and Klaus Pohl. Vol. 3714. Lecture Notes in Computer Science. Springer, 2005, pp. 7–20.

[CHE05] Krzysztof Czarnecki, Simon Helsen, Ulrich Eisenecker. "Formalizing cardinality-based feature models and their specialization". In: Software Process: Improvement and Practice 10.1 (2005), pp. 7–29. DOI: 10.1002/spip.213.

[CK05] Krzysztof Czarnecki, Chang Hwan Peter Kim. "Cardinality-Based Feature Modeling and Constraints: A Progress Report". In: Proceedings of the International Workshop on Software Factories, Colocated with OOPSLA'05. 2005.

[Kan+90] Kyo C. Kang, Sholom G. Cohen, James A. Hess, William E. Novak, A. Spencer Peterson. Feature-Oriented Domain Analysis (FODA) Feasibility Study. Technical Report CMU/SEI-90-TR-21. DTIC Document, 1990.

[HC88] John R. Hauser, Don Clausing. "The House of Quality". In: Harvard Business Review (1988).

2.8 Flexible Production Systems: Automated Generation of Operations Plans Based on ISA-95 and PDDL

Citation

Bernhard Wally, Jiří Vyskočil, Petr Novák, Christian Huemer, Radek Šindelár, Petr Kadera, Alexandra Mazak, Manuel Wimmer. "Flexible Production Systems: Automated Generation of Operations Plans based on ISA-95 and PDDL". In: Robotics and Automation Letters 4.4 (Oct. 2019), pp. 4062–4069. ISSN: 2377-3766. DOI: 10.1109/LRA.2019.2929991.

Contribution

Conceptualization, Methodology, Investigation, Implementation, Writing

Award

Nominated for the Best Application Paper Award of the 15th IEEE International Conference on Automation Science and Engineering (CASE) 2019.

Abstract

Model-driven engineering (MDE) provides tools and methods for the manipulation of formal models. In this letter, we leverage MDE for the transformation of production system models into flat files that are understood by general purpose planning tools and that enable the computation of "plans", i.e., sequences of production steps that are required to reach certain production goals. These plans are then merged back into the production system model, thus enriching the formalized production system knowledge.

Cited Works

[Wal18] **Bernhard Wally**. Provisioning for MES and ERP. Support for IEC 62264 and B2MML. Application Recommendation. AR_MES_ERP 1.1.0. Nov. 2018.

[Wal+18] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "IEC 62264-2 for AutomationML". In: Proceedings of the 5th AutomationML User Conference (AutomationML). Oct. 2018.

[HKH18] Manuel Heusner, Thomas Keller, Malte Helmert. "Best-Case and Worst-Case Behavior of Greedy Best-First Search". In: Proceedings of the 27th International Joint Conference on Artificial Intelligence. 2018, pp. 1463–1470.

[IEC18] International Electrotechnical Commission. Engineering data exchange format for use in industrial automation systems engineering – Automation Markup Language – Part 1: Architecture and general requirements. International Standard. IEC 62714-1:2018. 2018.

[NHL18] Tim Niemueller, Till Hofmann, Gerhard Lakemeyer. "CLIPS-based Execution for PDDL Planners". In: Proceedings of the Workshop on Integrated Planning, Acting, and Execution (IntEx). 2018.

[RFN18] Antje Rogalla, Alexander Fay, Oliver Niggemann. "Improved Domain Modeling for Realistic Automated Planning and Scheduling in Discrete Manufacturing". In: Proceedings of the 23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2018, pp. 464–471. DOI: 10.1109/ETFA.2018.8502631.

[WHM17a] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "Aligning Business Services with Production Services: The Case of REA and ISA-95". In: Proceedings of the 10th IEEE International Conference on Service Oriented Computing and Applications (SOCA). Nov. 2017, pp. 9–17. ISBN: 978-1-5386-1327-6. DOI: 10.1109/SOCA.2017.10.

[WHM17b] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "A View on Model-Driven Vertical Integration: Alignment of Production Facility Models and Business Models". In: Proceedings of the 13th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2017. ISBN: 978-1-5090-6782-4. DOI: 10.1109/COASE.2017.8256235.

[WHM17c] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "Entwining Plant Engineering Data and ERP Information: Vertical Integration with AutomationML and ISA-95". In: Proceedings of the 3rd IEEE International Conference on Control, Automation and Robotics (ICCAR). Apr. 2017. ISBN: 978-1-5090-6089-4. DOI: 10.1109/ICCAR.2017.7942718.

[WHM17d] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "ISA-95 based Task Specification Layer for REA in Production Environments". In: Proceedings of the 11th International Workshop on Value Modeling and Business Ontologies (VMBO). Mar. 2017.

[NKW17] Petr Novák, Petr Kadera, Manuel Wimmer. "Model-Based Engineering and Virtual Commissioning of Cyber-Physical Manufacturing Systems – Transportation System Case Study". In: Proceedings of the 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2017. ISBN: 978-1-5090-6506-6. DOI: 10.1109/ETFA.2017.8247743.

[GNT16] Malik Ghallab, Dana S. Nau, Paolo Traverso. Automated Planning and Acting. Cambridge University Press, 2016. ISBN: 978-1-107-03727-4.

[Wal+15] **Bernhard Wally**, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer. "Model-Driven Retail Information System based on REA Business Ontology and Retail-H". In: Proceedings of the 17th IEEE Conference on Business Informatics (CBI). Vol. 1. July 2015, pp. 116–124. ISBN: 978-1-4673-7340-1. DOI: 10.1109/CBI.2015.49.

[IEC15] International Electrotechnical Commission. Enterprise–control system integration – Part 4: Object model attributes for manufacturing operations management integration. International Standard. IEC 62264-4:2015. 2015.

[SOM14] Fadi Shrouf, Joaquín B. Ordieres Meré, Giovanni Miragliotta. "Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm". In: Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). 2014, pp. 697–701. DOI: 10.1109/IEEM.2014.7058728.

[IEC13a] International Electrotechnical Commission. Enterprise–control system integration – Part 1: Models and terminology. International Standard. IEC 62264-1:2013. 2013.

[IEC13b] International Electrotechnical Commission. Enterprise–control system integration – Part 2: Objects and attributes for enterprise–control system integration. International Standard. IEC 62264-2:2013. 2013.

[ST13] Alexandre Rodrigues Sousa, José Jean-Paul Zanlucchi de Souza Tavares. "Toward Automated Planning Algorithms Applied to Production and Logistics". In: IFAC Proceedings Volumes 46.24 (2013), pp. 165–170.

[Sch12] Miriam Schleipen. "Adaptivität und semantische Interoperabilität von Manufacturing Execution Systemen (MES)". German. PhD Thesis. Karlsruher Institut für Technologie (KIT), 2012. 388 pp. ISBN: 978-3-86644-955-8. DOI: 10.5445/KSP/1000031462.

[Kov11] Daniel L. Kovacs. Complete BNF description of PDDL 3.1. Language Specification. Department of Measurement, Information Systems, Budapest University of Technology, and Economics, 2011.

[Cla+09] Koen Claessen, Niklas Eén, Mary Sheeran, Niklas Sörensson, Alexey Voronov, Knut Åkesson. "SAT-Solving in Practice, with a Tutorial Example from Supervisory Control". In: Discrete Event Dynamic Systems 19.4 (2009), pp. 495–524. DOI: 10.1007/s10626-009-0081-8.

[Hel06] Malte Helmert. "The Fast Downward Planning System". In: Journal of Artificial Intelligence Research 26.1 (July 2006), pp. 191–246. ISSN: 1076-9757.

[Sch06] Douglas C. Schmidt. “Model-driven engineering”. In: COMPUTER 39.2 (2006), pp. 25–31.

[Béz04] Jean Bézivin. “In Search of a Basic Principle for Model Driven Engineering”. In: UPGRADE 5.2 (2004), pp. 21–24. ISSN: 1684-5285.

[GNT04] Malik Ghallab, Dana S. Nau, Paolo Traverso. Automated Planning. Theory and Practice. Artificial Intelligence. Morgan Kaufmann, 2004. ISBN: 978-1-55860-856-6. DOI: 10.1016/B978-1-55860-856-6.X5000-5.

[FL03] Maria Fox, Derek Long. “PDDL 2.1: An Extension to PDDL for Expressing Temporal Planning Domains”. In: Journal of Artificial Intelligence Research 20 (2003), pp. 61–124.

[Ken02] Stuart Kent. “Model Driven Engineering”. In: Proceedings of the 3rd International Conference on Integrated Formal Methods (IFM). Ed. by Michael Butler, Luigia Petre, and Kaisa Sere. Vol. 2335. LNCS. Springer, 2002, pp. 286–298. ISBN: 978-3-540-47884-3.

[KMM00] Matt Kaufmann, Panagiotis Manolios, and J Strother Moore, eds. Computer-Aided Reasoning: ACL2 Case Studies. 2000. ISBN: 978-1-4419-4981-3. DOI: 10.1007/978-1-4757-3188-0.

[ENS95] Kutluhan Erol, Dana S. Nau, Venkatramanan Siva Subrahmanian. “Complexity, Decidability and Undecidability Results for Domain-Independent Planning”. In: Artificial Intelligence 76.1–2 (1995), pp. 75–88. ISSN: 0004-3702. DOI: 10.1016/0004-3702(94)00080-K.

2.9 Production Planning with IEC 62264 and PDDL

Citation

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Contribution

Conceptualization, Methodology, Investigation, Implementation, Writing

Abstract

Smart production systems need to be able to adapt to changing environments and market needs. They have to reflect changes in (i) the reconfiguration of the production systems themselves, (ii) the processes they perform or (iii) the products they produce. Manual intervention for system adaptation is costly and potentially error-prone. In this article, we propose a model-driven approach for the automatic generation and regeneration of production plans that can be triggered anytime a change in any of the three aforementioned parameters occurs.

Cited Works

[Wal18] **Bernhard Wally**. Provisioning for MES and ERP. Support for IEC 62264 and B2MML. Application Recommendation. AR_MES_ERP 1.1.0. Nov. 2018.

[Wal+18] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "IEC 62264-2 for AutomationML". In: Proceedings of the 5th AutomationML User Conference (AutomationML). Oct. 2018.

[IEC18] International Electrotechnical Commission. Engineering data exchange format for use in industrial automation systems engineering – Automation Markup Language – Part 1: Architecture and general requirements. International Standard. IEC 62714-1:2018. 2018.

[Kus18] Andrew Kusiak. "Smart manufacturing". In: International Journal of Production Research 56.1–2 (2018), pp. 508–517. DOI: 10.1080/00207543.2017.1351644.

[mon18] montratec GmbH. montrac Design Guide 2017/2018. Manual. 2018.

[NHL18] Tim Niemueller, Till Hofmann, Gerhard Lakemeyer. "CLIPS-based Execution for PDDL Planners". In: Proceedings of the Workshop on Integrated Planning, Acting, and Execution (IntEx). 2018.

[RFN18] Antje Rogalla, Alexander Fay, Oliver Niggemann. "Improved Domain Modeling for Realistic Automated Planning and Scheduling in Discrete Manufacturing". In: Proceedings of the 23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2018, pp. 464–471. DOI: 10.1109/ETFA.2018.8502631.

[Tao+18] Fei Tao, Jiangfeng Cheng, Qinglin Qi, Meng Zhang, He Zhang, Fangyuan Sui. "Digital twin-driven product design, manufacturing and service with big data". In: International Journal of Advanced Manufacturing Technology 94.9–12 (2018), pp. 3563–3576. ISSN: 1433-3015. DOI: 10.1007/s00170-017-0233-1.

[WHM17a] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "A View on Model-Driven Vertical Integration: Alignment of Production Facility Models and Business Models". In: Proceedings of the 13th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2017. ISBN: 978-1-5090-6782-4. DOI: 10.1109/COASE.2017.8256235.

[WHM17b] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "Entwining Plant Engineering Data and ERP Information: Vertical Integration with AutomationML and ISA-95". In: Proceedings of the 3rd IEEE International Conference on Control, Automation and Robotics (ICCAR). Apr. 2017. ISBN: 978-1-5090-6089-4. DOI: 10.1109/ICCAR.2017.7942718.

[SPT17] Edward Allen Silver, David F. Pyke, Douglas J. Thomas. Inventory and Production Management in Supply Chains. 4th ed. 2017. ISBN: 978-1466558618.

[Cad+15] Juan Cadavid, Mauricio Alférez, Sébastien Gérard, Patrick Tessier. "Conceiving the Model-Driven Smart Factory". In: Proceedings of the International Conference on Software and System Processes (ICSSP). 2015, pp. 72–76. ISBN: 978-1-4503-3346-7. DOI: 10.1145/2785592.2785602.

[IEC15] International Electrotechnical Commission. Enterprise–control system integration – Part 4: Object model attributes for manufacturing operations management integration. International Standard. IEC 62264-4:2015. 2015.

[LGM15] Wilfried Lepuschitz, Benjamin Groessing, Munir Merdan. "Automation Agents for Controlling the Physical Components of a Transportation System". In: Industrial Agents. 2015, pp. 323–339. ISBN: 978-0-12-800341-1. DOI: 10.1016/B978-0-12-800341-1.00018-8.

[And14] Reiner Anderl. "Industrie 4.0 – Advanced Engineering of Smart Products and Smart Production". In: Proceedings of the 19th International Seminar on High Technology. 2014. ISBN: 978-3-540-47884-3.

[BW13] Alexander Bergmayr, Manuel Wimmer. "Generating Metamodels from Grammars by Combining Transformation and By-Example Techniques". In: Proceedings of the 1st International Workshop on MDE By Example (MDEBE). 2013. ISBN: 978-3-540-47884-3.

[IEC13] International Electrotechnical Commission. Enterprise–control system integration – Part 2: Objects and attributes for enterprise–control system integration. International Standard. IEC 62264-2:2013. 2013.

[OMG13] Object Management Group. Business Process Model and Notation (BPMN). Specification. 2013.

[Dav+12] Jim Davis, Thomas Edgar, James Porter, John Bernaden, Michael Sarli. "Smart manufacturing, manufacturing intelligence and demand-dynamic performance". In: Computers & Chemical Engineering 47 (2012), pp. 145–156. ISSN: 0098-1354. DOI: 10.1016/j.compchemeng.2012.06.037.

[Xu+12] Li Da Xu, Chengen Wang, Zhuming Bi, Jiapeng Yu. "AutoAssem: An Automated Assembly Planning System for Complex Products". In: IEEE Transactions on Industrial Informatics 8.3 (2012), pp. 669–678. ISSN: 1551-3203. DOI: 10.1109/TII.2012.2188901.

[AO11] Hakan Akillioglu, Mauro Onori. "Evolvable production systems and impacts on production planning". In: Proceedings of the IEEE International Symposium on Assembly and Manufacturing (ISAM). 2011. DOI: 10.1109/ISAM.2011.5942328.

[Kov11] Daniel L. Kovacs. Complete BNF description of PDDL 3.1. Language Specification. Department of Measurement, Information Systems, Budapest University of Technology, and Economics, 2011.

[Hel06] Malte Helmert. "The Fast Downward Planning System". In: Journal of Artificial Intelligence Research 26.1 (July 2006), pp. 191–246. ISSN: 1076-9757.

[GSS06] Alfonso Gerevini, Alessandro Saetti, Ivan Serina. "An Approach to Temporal Planning and Scheduling in Domains with Predictable Exogenous Events". In: Journal of Artificial Intelligence Research 25 (2006), pp. 187–231. DOI: 10.1613/jair.1742.

[MVK06] László Monostori, Jozsef Váncza, Soundar R. T. Kumara. "Agent-Based Systems for Manufacturing". In: CIRP Annals 55.2 (2006), pp. 697–720. ISSN: 0007-8506. DOI: 10.1016/j.cirp.2006.10.004.

[Sch06] Douglas C. Schmidt. "Model-driven engineering". In: COMPUTER 39.2 (2006), pp. 25–31.

[CH05] Jian-Hung Chen, Shinn-Ying Ho. "A novel approach to production planning of flexible manufacturing systems using an efficient multi-objective genetic algorithm". In: International Journal of Machine Tools and Manufacture 45.7 (2005). ISSN: 0890-6955. DOI: 10.1016/j.ijmachtools.2004.10.010.

[Ger+04] Alfonso Gerevini, Alessandro Saetti, Ivan Serina, Paolo Toninelli. "Planning in PDDL 2.2 domains with LPG-TD". In: Booklet of the International Planning Competition. 2004.

[GNT04] Malik Ghallab, Dana S. Nau, Paolo Traverso. Automated Planning. Theory and Practice. Artificial Intelligence. Morgan Kaufmann, 2004. ISBN: 978-1-55860-856-6. DOI: 10.1016/B978-1-55860-856-6.X5000-5.

[Ken02] Stuart Kent. "Model Driven Engineering". In: Proceedings of the 3rd International Conference on Integrated Formal Methods (IFM). Ed. by Michael Butler, Luigia Petre, and Kaisa Sere. Vol. 2335. LNCS. Springer, 2002, pp. 286–298. ISBN: 978-3-540-47884-3.

[Mel+02] Stephen J. Mellor, Kendall Scott, Axel Uhl, Dirk Weise. "Model-Driven Architecture". In: Advances in Object-Oriented Information Systems. Ed. by Jean-Michel Bruel and Zohra Bellahsene. 2002, pp. 290–297. ISBN: 978-3-540-46105-0.

[ANS00] American National Standards Institute. Enterprise–Control System Integration Part 1: Models and Terminology. ANSI Standard. ANSI/ISA 95.00.01-2000. 2000.

[Gha+98] Malik Ghallab, Adele Howe, Craig Knoblock, Drew McDermott, Ashwin Ram, Manuela Veloso, Daniel Weld, David Wilkins. PDDL – The Planning Domain Definition Language. APIS-98 Planning Competition Committee. 1998.

[SPP98] Edward Allen Silver, David F. Pyke, Rein Peterson. Inventory Management and Production Planning and Scheduling. 3rd ed. 1998. ISBN: 978-0471119470.

[Knu64] Donald E. Knuth. "Backus Normal Form vs. Backus Naur Form". In: Commun. ACM 7.12 (1964), pp. 735–736. ISSN: 0001-0782. DOI: 10.1145/355588.365140.

Bibliography

[GF20] Morteza Ghobakhloo, Masood Fathi. “Corporate survival in Industry 4.0 era: the enabling role of lean-digitized manufacturing”. In: Journal of Manufacturing Technology Management 31.1 (2020), pp. 1–30. ISSN: 1741-038X. DOI: 10.1108/JMTM-11-2018-0417.

[Maz+20] Alexandra Mazak, Manuel Wimmer, Christian Huemer, **Bernhard Wally**, Thomas Frühwirth, Wolfgang Kastner. “Rahmenwerk zur modellbasierten horizontalen und vertikalen Integration von Standards für Industrie 4.0”. In: Handbuch Industrie 4.0. Ed. by Michael ten Hompel, Birgit Vogel-Heuser, and Thomas Bauernhansl. Springer, 2020.

[Wal+19a] **Bernhard Wally**, Jiří Vyskočil, Petr Novák, Christian Huemer, Radek Šindelár, Petr Kadera, Alexandra Mazak, Manuel Wimmer. “Flexible Production Systems: Automated Generation of Operations Plans based on ISA-95 and PDDL”. In: Robotics and Automation Letters 4.4 (Oct. 2019), pp. 4062–4069. ISSN: 2377-3766. DOI: 10.1109/LRA.2019.2929991.

[RDU19] Erwin Rauch, Patrick Dallasega, Marco Unterhofer. “Requirements and Barriers for Introducing Smart Manufacturing in Small and Medium-Sized Enterprises”. In: IEEE Engineering Management Review 47.3 (Sept. 2019), pp. 87–94. ISSN: 1937-4178. DOI: 10.1109/EMR.2019.2931564.

[Wal+19b] **Bernhard Wally**, Laurens Lang, Rafał Włodarski, Radek Šindelár, Christian Huemer, Alexandra Mazak, Manuel Wimmer. “Generating Structured AutomationML Models from IEC 62264 Information”. In: Proceedings of the 5th AutomationML PlugFest. Sept. 2019.

[Ehr+19] Matthias Ehrendorfer, Jürgen-Albrecht Fassmann, Jürgen Mangler, Stefanie Rinderle-Ma. “Conformance Checking and Classification of Manufacturing Log Data”. In: 21st IEEE International Conference on Business Informatics (CBI). Vol. 01. July 2019, pp. 569–577. DOI: 10.1109/CBI.2019.00072.

[Wal+19c] **Bernhard Wally**, Jiří Vyskočil, Petr Novák, Christian Huemer, Radek Šindelár, Petr Kadera, Alexandra Mazak, Manuel Wimmer. “Production Planning with IEC 62264 and PDDL”. In: Proceedings of the 17th IEEE International Conference on Industrial Informatics (INDIN). July 2019, pp. 492–499. ISBN: 978-1-7281-2928-0. DOI: 10.1109/INDIN41052.2019.8972050.

[Wal+19d] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer, Radek Šindelár. “Modeling Variability and Persisting Configurations in OPC UA”. In: Procedia CIRP. Vol. 81: Proceedings of the 52nd CIRP Conference on Manufacturing Systems (CMS). Ed. by Peter Butala, Edvard Govekar, and Rok Vrabič. June 2019, pp. 13–18. DOI: 10.1016/j.procir.2019.03.003.

[Mit+19] Sameer Mittal, Muztoba Ahmad Khan, David Romero, Thorsten Wuest. “Smart manufacturing: Characteristics, technologies and enabling factors”. In: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 233.5 (2019), pp. 1342–1361. DOI: 10.1177/0954405417736547.

[Qu+19] Y. J. Qu, X. G. Ming, Z. W. Liu, X. Y. Zhang, Z. T. Hou. “Smart manufacturing systems: state of the art and future trends”. In: International Journal of Advanced Manufacturing Technology 103 (2019), pp. 3751–3768. DOI: 10.1007/s00170-019-03754-7.

[Yao+19] Xifan Yao, Jiajun Zhou, Yingzi Lin, Yun Li, Hongnian Yu 5, Ying Liu. “Smart manufacturing based on cyber-physical systems and beyond”. In: Journal of Intelligent Manufacturing 30 (2019), pp. 2805–2817. DOI: 10.1007/s10845-017-1384-5.

[Wal18a] **Bernhard Wally**. Provisioning for MES and ERP. Support for IEC 62264 and B2MML. Application Recommendation. AR_MES_ERP 1.1.0. Nov. 2018.

[BRS18] Joachim Burlein, Matthias Rassl, Nicole Schmidt. Introducing AutomationML in a heterogeneous software tool landscape – a success story. Presentation at the 5th AutomationML User Conference. last visited: February 29, 2020. Daimler AG, Oct. 24, 2018. URL: https://www.automationml.org/o.red/uploads/dateien/1548668148-03_Burlein-Rassl_AutomationML-Heterogeneous-Software-Tool-Landscape.pdf.

[Wal+18a] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. “IEC 62264-2 for AutomationML”. In: Proceedings of the 5th AutomationML User Conference (AutomationML). Oct. 2018.

[Wal+18b] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. “A Variability Information Model for OPC UA”. In: Proceedings of the 23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). Sept. 2018. ISBN: 978-1-5386-7109-2. DOI: 10.1109/ETFA.2018.8502502.

[Wal+18c] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. “AutomationML, ISA-95 and Others: Rendezvous in the OPC UA Universe”. In: Proceedings of the 14th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2018, pp. 1381–1387. ISBN: 978-1-5386-3594-0. DOI: 10.1109/COASE.2018.8560600.

[MTC18] MTConnect Institute. MTConnect Standard. ANSI Standard. ANSI/MTC1.4. July 12, 2018.

[Wal18b] **Bernhard Wally**. Provisioning for MES and ERP. Support for IEC 62264 and B2MML. Application Recommendation. AR_MES_ERP 1.0.0. June 2018.

[And+18] Ann-Louise Andersen, Hoda ElMaraghy, Waguih ElMaraghy, Thomas D. Brunoe, Kjeld Nielsen. “A participatory systems design methodology for changeable manufacturing systems”. In: International Journal of Production Research 56.8 (2018), pp. 2769–2787. DOI: 10.1080/00207543.2017.1394594.

[Boy+18] Hugh Boyes, Bil Hallaq, Joe Cunningham, Tim Watson. “The industrial internet of things (IIoT): An analysis framework”. In: Computers in Industry 101 (2018), pp. 1–12. ISSN: 0166-3615. DOI: 10.1016/j.compind.2018.04.015.

[Deu+18] Jochen Deuse, Christoph Heuser, Benedikt Konrad, David Lenze, Thomas Maschek, Mario Wiegand, Peter Willats. “Pushing the Limits of Lean Thinking – Design and Management of Complex Production Systems”. In: Closing the Gap Between Practice and Research in Industrial Engineering. Ed. by Elisabeth Viles, Marta Ormazábal, and Alvaro Lleó. Springer, 2018, pp. 335–342. ISBN: 978-3-319-58409-6.

[Ger18] Stanley B. Gershwin. “The future of manufacturing systems engineering”. In: International Journal of Production Research 56.1–2 (2018), pp. 224–237. ISSN: 0020-7543. DOI: 10.1080/00207543.2017.1395491.

[Kus18] Andrew Kusiak. “Smart manufacturing”. In: International Journal of Production Research 56.1–2 (2018), pp. 508–517. DOI: 10.1080/00207543.2017.1351644.

[Tao+18] Fei Tao, Jiangfeng Cheng, Qinglin Qi, Meng Zhang, He Zhang, Fangyuan Sui. “Digital twin-driven product design, manufacturing and service with big data”. In: International Journal of Advanced Manufacturing Technology 94.9–12 (2018), pp. 3563–3576. ISSN: 1433-3015. DOI: 10.1007/s00170-017-0233-1.

[WHM17a] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. “Aligning Business Services with Production Services: The Case of REA and ISA-95”. In: Proceedings of the 10th IEEE International Conference on Service Oriented Computing and Applications (SOCA). Nov. 2017, pp. 9–17. ISBN: 978-1-5386-1327-6. DOI: 10.1109/SOCA.2017.10.

[You+17] Bobbi Young, Judd Cheatwood, Todd Peterson, Rick Flores, Paul Clements. "Product Line Engineering Meets Model Based Engineering in the Defense and Automotive Industries". In: Proceedings of the 21st International Systems and Software Product Line Conference (SPLC). Sept. 2017, pp. 175–179. ISBN: 978-1-4503-5221-5. DOI: 10.1145/3106195.3106220.

[WHM17b] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "A View on Model-Driven Vertical Integration: Alignment of Production Facility Models and Business Models". In: Proceedings of the 13th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2017. ISBN: 978-1-5090-6782-4. DOI: 10.1109/COASE.2017.8256235.

[Wal+17] **Bernhard Wally**, Miriam Schleipen, Nicole Schmidt, Nikolai D'Agostino, Robert Henßen, Yingbing Hua. "AutomationML auf höheren Automatisierungsebenen. Eine Auswahl relevanter Anwendungsfälle". In: Proceedings of AUTOMATION 2017. Technology networks Processes. 18. Leitkongress der Mess- und Automatisierungstechnik. VDI-Berichte 2293. VDI-Verlag, June 2017. ISBN: 978-3-18-092293-5.

[WHM17c] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "Entwining Plant Engineering Data and ERP Information: Vertical Integration with AutomationML and ISA-95". In: Proceedings of the 3rd IEEE International Conference on Control, Automation and Robotics (ICCAR). Apr. 2017. ISBN: 978-1-5090-6089-4. DOI: 10.1109/ICCAR.2017.7942718.

[WHM17d] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "ISA-95 based Task Specification Layer for REA in Production Environments". In: Proceedings of the 11th International Workshop on Value Modeling and Business Ontologies (VMBO). Mar. 2017.

[BGL17] Stefan Biffl, Detlef Gerhard, Arndt Lüder. "Introduction to the Multi-Disciplinary Engineering for Cyber-Physical Production Systems". In: Multi-Disciplinary Engineering for Cyber-Physical Production Systems: Data Models and Software Solutions for Handling Complex Engineering Projects. Ed. by Stefan Biffl, Arndt Lüder, and Detlef Gerhard. Springer International Publishing, 2017, pp. 1–24. ISBN: 978-3-319-56345-9. DOI: 10.1007/978-3-319-56345-9_1.

[MPM17] Tobias Meudt, Malte Pohl, Joachim Metternich. Die Automatisierungspyramide – Ein Literaturüberblick. Tech. rep. Technische Universität Darmstadt, Institute of Production Management, Technology and Machine Tools, 2017, p. 13.

[FWW16] Solmaz Mansour Fallah, Sabine Wolny, Manuel Wimmer. "Towards model-integrated service-oriented manufacturing execution system". In: 1st International Workshop on Cyber-Physical Production Systems (CPPS). Apr. 2016. ISBN: 978-1-5090-1156-8. DOI: 10.1109/CPPS.2016.7483917.

[BSS16] Matthias Bartelt, Adrian Schyja, Sven Stumm. "Datenaustausch". In: conexing Abschlussbericht. Werkzeug zur interdisziplinären Planung und produktbezogenen virtuellen Optimierung von automatisierten Produktionssystemen. Ed. by Matthias Bartelt and Bernd Kuhlenkötter. Maschinenbau 10. Westdeutscher Universitätsverlag, Feb. 4, 2016. Chap. 3, pp. 47–62. ISBN: 978-3-89966-765-3.

[GK16] Björn Grimm, Ralf Kellermann. "Planung von Produktionsanlagen". In: conexing Abschlussbericht. Werkzeug zur interdisziplinären Planung und produktbezogenen virtuellen Optimierung von automatisierten Produktionssystemen. Ed. by Matthias Bartelt and Bernd Kuhlenkötter. Maschinenbau 10. Westdeutscher Universitätsverlag, Feb. 4, 2016. Chap. 2, pp. 11–46. ISBN: 978-3-89966-765-3.

[DIN16a] Deutsches Institut für Normung. Combining OPC Unified Architecture and Automation Markup Language. DIN SPEC 16592:2016-12. 2016.

[DIN16b] Deutsches Institut für Normung. Reference Architecture Model Industrie 4.0 (RAMI4.0). DIN SPEC 91345:2016-04. 2016.

[Kan+16] Hyoung Seok Kang, Ju Yeon Lee, SangSu Choi, Hyun Kim, Jun Hee Park, Ji Yeon Son, Bo Hyun Kim, Sang Do Noh. "Smart manufacturing: Past research, present findings, and future directions". In: International Journal of Precision Engineering and Manufacturing-Green Technology 3.1 (2016), pp. 111–128. ISSN: 2288-6206. DOI: 10.1007/s40684-016-0015-5.

[LMF16] Yan Lu, Katherine C. Morris, Simon P. Frechette. Current Standards Landscape for Smart Manufacturing Systems. NIST Interagency/Internal Report NISTIR 8107. 2016. DOI: 10.6028/NIST.IR.8107.

[OST16] Justice Opara-Martins, Reza Sahandi, Feng Tian. "Critical analysis of vendor lock-in and its impact on cloud computing migration: a business perspective". In: Journal of Cloud Computing 5.4 (2016). ISSN: 2192-113X. DOI: 10.1186/s13677-016-0054-z.

[Maz+15] Alexandra Mazak, Manuel Wimmer, Christian Huemer, Gerti Kappel, Wolfgang Kastner. "Rahmenwerk zur modellbasierten horizontalen und vertikalen Integration von Standards für Industrie 4.0". In: Handbuch Industrie 4.0. Produktion, Automatisierung und Logistik. Ed. by Birgit Vogel-Heuser, Thomas Bauernhansl, and Michael ten Hompel. Springer NachschlageWissen. Springer, Dec. 15, 2015. ISBN: 978-3-662-45537-1. DOI: 10.1007/978-3-662-45537-1_94-1.

[Wal+15a] **Bernhard Wally**, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer. “Model-Driven Retail Information System based on REA Business Ontology and Retail-H”. In: Proceedings of the 17th IEEE Conference on Business Informatics (CBI). Vol. 1. July 2015, pp. 116–124. ISBN: 978-1-4673-7340-1. DOI: 10.1109/CBI.2015.49.

[Wal+15b] **Bernhard Wally**, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer, Peter Regatschnig, Dieter Mayrhofer. “REAlist – A Tool Demo”. In: Proceedings of the 9th International Workshop on Value Modeling and Business Ontology (VMBO). Feb. 2015.

[MWM15] Emanuel Mätzler, **Bernhard Wally**, Alexandra Mazak. “A Common Home for Features and Requirements: Retrofitting the House of Quality with Feature Models”. In: Proceedings of the 9th International Workshop on Variability Modeling in Software-intensive Systems (VaMoS). ACM, Jan. 2015. ISBN: 978-1-4503-3273-6. DOI: 10.1145/2701319.2701334.

[MH15a] Alexandra Mazak, Christian Huemer. “HoVer: A modeling framework for horizontal and vertical integration”. In: Proceedings of the 13th IEEE International Conference on Industrial Informatics (INDIN). IEEE, 2015, pp. 1642–1647. DOI: 10.1109/INDIN.2015.7281980.

[MH15b] Alexandra Mazak, Christian Huemer. “From Business Functions to Control Functions: Transforming REA to ISA-95”. In: Proceedings of the 17th IEEE Conference on Business Informatics (CBI). Vol. 1. IEEE, 2015, pp. 33–42. DOI: 10.1109/CBI.2015.50.

[Vog+15d] Birgit Vogel-Heuser, Jakob Mund, Matthias Kowal, Christoph Legat, Jens Folmer, Sabine Teufl, Ina Schaefer. “Towards interdisciplinary variability modeling for automated production systems: Opportunities and challenges when applying delta modeling: A case study”. In: Proceedings of the 13th IEEE International Conference on Industrial Informatics (INDIN). 2015, pp. 322–328. DOI: 10.1109/INDIN.2015.7281754.

[WH14a] **Bernhard Wally**, Christian Huemer. “Defining Business Rules for REA Business Models”. In: Proceedings of the 16th IEEE International Conference on Business Informatics (CBI). Vol. 2 – Workshop Papers. 1st Workshop on Enterprise Engineering Theories and Methods (WEETM). July 2014. ISBN: 978-1-4799-5779-8. DOI: 10.1109/CBI.2014.52.

[WH14b] **Bernhard Wally**, Christian Huemer. “Towards a Generic Data Model for REA based Applications”. In: Proceedings of the 4th International Symposium on Business Modeling and Software Design (BMSD). June 2014, pp. 153–158. ISBN: 978-989-758-032-1. DOI: 10.5220/0005425401530158.

[Wal+14a] **Bernhard Wally**, Alexandra Mazak, Dieter Mayrhofer, Christian Huemer. "A Generic REA Software Architecture based on Fragments and Declarations". In: Proceedings of the 8th International Workshop on Value Modeling and Business Ontology (VMBO). Mar. 2014.

[Wal+14b] **Bernhard Wally**, Alexandra Mazak, Dieter Mayrhofer, Christian Huemer. "Defining Business Rules for REA based on Fragments and Declarations". In: Proceedings of the 8th International Workshop on Value Modeling and Business Ontology (VMBO). Mar. 2014.

[And14] Reiner Anderl. "Industrie 4.0 – Advanced Engineering of Smart Products and Smart Production". In: Proceedings of the 19th International Seminar on High Technology. 2014. ISBN: 978-3-540-47884-3.

[FE14] Niels Fallenbeck, Claudia Eckert. "IT-Sicherheit und Cloud Computing". In: Industrie 4.0 in Produktion, Automatisierung und Logistik. Anwendung · Technologien · Migration. Ed. by Thomas Bauernhansl, Michael ten Hompel, and Birgit Vogel-Heuser. Springer, 2014, pp. 397–431. ISBN: 978-3-658-04682-8. DOI: 10.1007/978-3-658-04682-8_20.

[OMG14] Object Management Group. Decision Model and Notation. Specification. OMG DMN 1.0 Beta 1. 2014.

[SOM14] Fadi Shrouf, Joaquín B. Ordieres Meré, Giovanni Miragliotta. "Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm". In: Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). 2014, pp. 697–701. DOI: 10.1109/IEEM.2014.7058728.

[IEC13a] International Electrotechnical Commission. Enterprise–control system integration – Part 1: Models and terminology. International Standard. IEC 62264-1:2013. 2013.

[MES13] Manufacturing Enterprise Solutions Association International. Business To Manufacturing Markup Language. Standards and Tools. MESA B2MML V0600. 2013.

[Ono+13] Toshio Ono, Shahzad Ali, Paul Hunkar, Dennis Brandl. OPC Unified Architecture for ISA-95 Common Object Model. Companion Specification. 2013.

[GMA13] VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik (GMA). Cyber-Physical Systems. Chancen und Nutzen aus Sicht der Automation. Thesen und Handlungsfelder. VDI-Stellungnahme. Verein Deutscher Ingenieure (VDI), 2013.

[Dav+12] Jim Davis, Thomas Edgar, James Porter, John Bernaden, Michael Sarli. “Smart manufacturing, manufacturing intelligence and demand-dynamic performance”. In: Computers & Chemical Engineering 47 (2012), pp. 145–156. ISSN: 0098-1354. DOI: 10.1016/j.compchemeng.2012.06.037.

[Ola+12] Rafael Olaechea, Steven Stewart, Krzysztof Czarnecki, Derek Rayside. “Modelling and Multi-objective Optimization of Quality Attributes in Variability-rich Software”. In: Proceedings of the 4th International Workshop on Nonfunctional System Properties in Domain Specific Modeling Languages (NFSP-DSML). ACM, 2012. ISBN: 978-1-4503-1807-5. DOI: 10.1145/2420942.2420944.

[Sch12] Miriam Schleipen. “Adaptivität und semantische Interoperabilität von Manufacturing Execution Systemen (MES)”. German. PhD Thesis. Karlsruher Institut für Technologie (KIT), 2012. 388 pp. ISBN: 978-3-86644-955-8. DOI: 10.5445/KSP/1000031462.

[Kov11] Daniel L. Kovacs. Complete BNF description of PDDL 3.1. Language Specification. Department of Measurement, Information Systems, Budapest University of Technology, and Economics, 2011.

[Sch10] Ina Schaefer. “Variability modelling for model-driven development of software product lines”. In: Proceedings of the 4th International Workshop on Variability Modelling of Software-Intensive Systems (VaMoS). 2010.

[SD09] Miriam Schleipen, Rainer Drath. “Three-view-concept for modeling process or manufacturing plants with AutomationML”. In: Proceedings of the 14th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2009. ISBN: 978-1-4244-2728-4. DOI: 10.1109/etfa.2009.5347260.

[BS07] Jörg Becker, Reinhard Schütte. “Reference Modeling for Business Systems Analysis”. In: ed. by Peter Fettke and Peter Loos. Idea Group, 2007. Chap. Reference Model for Retail Enterprises, pp. 182–205.

[II07] International Organization for Standardization, International Electrotechnical Commission. Business Transaction Scenarios – Accounting and Economic Ontology. ISO/IEC 15944-4:2007(E). 2007.

[Sch06] Douglas C. Schmidt. “Model-driven engineering”. In: COMPUTER 39.2 (2006), pp. 25–31.

[Bat05] Don Batory. “Feature Models, Grammars, and Propositional Formulas”. In: Proceedings of the 9th International Conference on Software Product Lines (SPLC). Ed. by Henk Obbink and Klaus Pohl. Vol. 3714. Lecture Notes in Computer Science. Springer, 2005, pp. 7–20.

[CHE05] Krzysztof Czarnecki, Simon Helsen, Ulrich Eisenecker. “Formalizing cardinality-based feature models and their specialization”. In: Software Process: Improvement and Practice 10.1 (2005), pp. 7–29. DOI: 10.1002/spip.213.

[Dre+05] Alexander Dreiling, Michael Rosemann, Wil M. P. van der Aalst, Wasim Sadiq, Sana Khan. “Model-Driven Process Configuration of Enterprise Systems”. In: Proceedings der 7. Internationalen Tagung Wirtschaftsinformatik (WI). Ed. by Otto K. Ferstl, Elmar J. Sinz, Sven Eckert, and Tilman Isselhorst. Physica-Verlag, 2005, pp. 687–706. ISBN: 978-3-7908-1574-0. DOI: 10.1007/3-7908-1624-8_36.

[Ebe05] Stephan Eberle. “Adaptive Internetanbindung von Feldbussystemen”. PhD Thesis. Universität Stuttgart, Fakultät Informatik, Elektrotechnik und Informationstechnik, Institut für Automatisierungs- und Softwaretechnik, 2005. ISBN: 3-8322-4088-8.

[Sau05] Thilo Sauter. “Integration aspects in automation – a technology survey”. In: Proceedings of the 10th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). Vol. 2. 2005, pp. 255–263. ISBN: 0-7803-9401-1. DOI: 10.1109/ETFA.2005.1612688.

[BS04] Jörg Becker, Reinhard Schütte. Handelsinformationssysteme. 2nd ed. MI Wirtschaftsbuch, 2004.

[Hev+04] Alan R. Hevner, Salvatore T. March, Jinsoo Park, Suda Ram. “Design Science in Information Systems Research”. In: MIS Quarterly 28.1 (2004), pp. 75–106.

[FL03b] Maria Fox, Derek Long. “PDDL 2.1: An Extension to PDDL for Expressing Temporal Planning Domains”. In: Journal of Artificial Intelligence Research 20 (2003), pp. 149–154.

[Wag03] Thomas Wagner. “An Agent-Oriented Approach to Industrial Automation Systems”. In: An Agent-Oriented Approach to Industrial Automation Systems. NODe 2002 Agent-Related Workshops Erfurt, Germany, October 7–10, 2002 Revised Papers. Ed. by Jaime G. Carbonell, Jörg Siekmann, Ryszard Kowalczyk, Jörg P. Müller, Huaglory Tianfield, and Rainer Unland. Vol. 2592. Lecture Notes in Artificial Intelligence 2592. Springer, 2003, pp. 314–328. ISBN: 978-3-540-36559-4.

[Ken02] Stuart Kent. “Model Driven Engineering”. In: Proceedings of the 3rd International Conference on Integrated Formal Methods (IFM). Ed. by Michael Butler, Luigia Petre, and Kaisa Sere. Vol. 2335. LNCS. Springer, 2002, pp. 286–298. ISBN: 978-3-540-47884-3.

[LKL02] Kwanwoo Lee, Kyo C. Kang, Jaejoon Lee. "Concepts and Guidelines of Feature Modeling for Product Line Software Engineering". In: Proceedings of the 7th International Conference of Software Reuse: Methods, Techniques, and Tools (ICSR-7). Ed. by Cristina Gacek. Vol. 2319. Lecture Notes in Computer Science. Springer, 2002, pp. 62–77. ISBN: 978-3-540-43483-2. DOI: 10.1007/3-540-46020-9_5.

[ANS00] American National Standards Institute. Enterprise–Control System Integration Part 1: Models and Terminology. ANSI Standard. ANSI/ISA 95.00.01-2000. 2000.

[GM00] Guido L. Geerts, William E. McCarthy. "The Ontological Foundation of REA Enterprise Information Systems". In: Annual Meeting of the American Accounting Association, Philadelphia, PA. Vol. 362. 2000, pp. 127–150.

[GM99] Guido L. Geerts, William E. McCarthy. "An accounting object infrastructure for knowledge-based enterprise models". In: IEEE Intelligent Systems 14.4 (1999), pp. 89–94.

[Wes99] Richard Weston. "Model-driven, component-based approach to reconfiguring manufacturing software systems". In: International Journal of Operations & Production Management 19.8 (1999), pp. 834–855. DOI: 10.1108/01443579910274437.

[GFd98] Martin L. Griss, John Favaro, Massimo d'Alessandro. "Integrating feature modeling with the RSEB". In: Proceedings of the 5th International Conference on Software Reuse. 1998, pp. 76–85. DOI: 10.1109/ICSR.1998.685732.

[GM97] Guido L. Geerts, William E. McCarthy. "Modeling Business Enterprises as Value-Added Process Hierarchies with Resource-Event-Agent Object Templates". In: Business Object Design and Implementation. Ed. by Jeff Sutherland, Cory Casanave, Joaquin Miller, Philip Patel, and Glenn Hollowell. Springer, 1997, pp. 94–113. ISBN: 978-3-540-76096-2. DOI: 10.1007/978-1-4471-0947-1_10.

[Kan+90] Kyo C. Kang, Sholom G. Cohen, James A. Hess, William E. Novak, A. Spencer Peterson. Feature-Oriented Domain Analysis (FODA) Feasibility Study. Technical Report CMU/SEI-90-TR-21. DTIC Document, 1990.

[McC82] William E. McCarthy. "The REA Accounting Model: A Generalized Framework for Accounting Systems in a Shared Data Environment". In: The Accounting Review 57.3 (1982), pp. 554–578.

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Abbreviations

ACM Association for Computing Machinery 12

AML Automation Markup Language 55, *see* AutomationML

ANSI American National Standards Institute 55

API Application Programming Interface 14, 19

APS Automated Production System ix, 1, 4, 13, 15–17, 25, 51

AR Application Recommendation 16, 23–25, 55

ATL ATL Transformation Language 7, 25, 26, 86

AutomationML Automation Markup Language 7, 8, 10–12, 15–18, 21, 23–26, 45, 55, 81, 86

B2MML Business To Manufacturing Markup Language 16, 23, 55

BNF Backus-Naur-Form 6

BPMN Business Process Model and Notation 25

CAEX Computer Aided Engineering Exchange 8, 15, 18, 25

CBI Conference on Business Informatics 12, 35, 86

CDL Christian Doppler Laboratory vii, 28

CIIRC Czech Institute of Informatics, Robotics and Cybernetics 26, 27

CIRP Collège International pour la Recherche en Productique (en. International Academy for Production Engineering) 11, 12

CPPS Cyber-Physical Production System 1, 7

CTU Czech Technical University 8, 9, 26, 27

DB Database 14, 19

DMN Decision Model and Notation 14

DRD Decision Requirements Diagram 14

DSL Domain Specific Language 16

e. V. Eingetragener Verein (en. Registered Voluntary Association) 83

ERP Enterprise Resource Planning x, 2, 3, 5, 6, 10, 12, 14–16, 21–24, 28, 31, 35, 39, 55, 86

ETO Engineer to Order 2

FFG Österreichische Forschungsförderungsgesellschaft mbH (en. Austrian Research Promotion Agency) 28

FH Fachhochschule (en. University of Applied Sciences) 85

FM Feature Model 6, 8, 9, 18, 20, 51

Glulam Glued-Laminated Timber 16

GPS Global Positioning System 14

GUI Graphical User Interface 14, 19

HoQ House of Quality 18

I/O Input/Output 3, 13

I4.0 Industry 4.0 1, 4, 5, 7–9, 17, 26, 27, 83

IEC International Electrotechnical Commission 5–10, 12, 14–18, 21–28, 55, 65

IEEE Institute of Electrical and Electronics Engineers 12, 35, 61, 86

IIoT Industrial Internet of Things 1, 7

INDIN Industrial Informatics 12

IoT Internet of Things 82, 86

IS Information System 3–5, 10, 83

ISA International Society of Automation 16, 17, 39, 45, 55, 61, 86

ISO International Organization for Standardization 5, 6, 8, 14, 18, 21

IT Information Technology ix, x, 1–3, 11, 13

iViP Integrated Virtual Product Creation 86

mbH mit beschränkter Haftung (en. with limited liability) 82, 85

MDE Model-driven Engineering ix, x, 3, 4, 10, 16, 28, 61

MDSE Model-driven Software Engineering ix, 1, 10

MES Manufacturing Execution System 3, 16, 21, 39, 55, 86

MESA Manufacturing Enterprise Solutions Association 55

MIS Management Information System 12

MOF Meta Object Facility 6

MOM Manufacturing Operations Management x, 2, 3, 5–7, 12, 15, 17, 23, 24

OPC UA OPC Unified Architecture 6–9, 16, 18–21, 24, 25, 45, 51, 57

P&ID Piping and Instrumentation Diagram 15

PDDL Planning Domain Definition Language 6–10, 17, 23, 26–28, 61, 65

PLC Programmable Logic Controller ix, 3, 13

PLIM Production Lifecycle Information Management 86

QFD Quality Function Deployment 18

RA-L Robotics and Automation Letters 12

RAMI4.0 Reference Architecture Model Industry 4.0 7

REA Resource-Event-Agent 5, 9, 14–16, 18–23, 28, 31, 35, 39, 86

RIS Retail Information System 9, 14, 19, 20, 35

SCADA Supervisory Control and Data Acquisition 12

SoS System of Systems 1

TU Technical University 81, 85

UI User Interface 82

UML Unified Modeling Language 5

VDI Verein Deutscher Ingenieure (en. Association of German Engineers) e. V. 11, 12

XML Extensible Markup Language 6, 8, 15, 25, 55

Curriculum Vitae

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Work Experience

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Committees

Position	Committee
Contributing Member	AutomationML – Technical Advisory Council
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Member	IEEE CBI 2020 – Program Committee

Advised Master Theses

Student	Start	End	Title
Laurens Lang	Dec. 2018	—	A Graphical Toolkit for ISA-95
Markus Reichstädter	June 2019	—	Integration and Evaluation of Planning Solvers in Production Environments
Philip Polczer	Oct. 2019	—	Interlinking ERP and MES by the Example of REA and ISA-95

Advised Bachelor Theses

Student	Start	End	Title
Rafał Włodarski	July 2019	—	Consistent ATL Transformations between ISA-95 and AutomationML
Zsigmond Tömösváry	Apr. 2019	—	Systematic Literature Study on Modeling Approaches for IoT
Patryk Kusion	Oct. 2019	—	Vergleich von Modellierungssprachen für IoT Anwendungen

Publications

Journal Articles

[Wal+19a] **Bernhard Wally**, Jiří Vyskočil, Petr Novák, Christian Huemer, Radek Šindelár, Petr Kadera, Alexandra Mazak, Manuel Wimmer. “Flexible Production Systems: Automated Generation of Operations Plans based on ISA-95 and PDDL”. In: Robotics and Automation Letters 4.4 (Oct. 2019), pp. 4062–4069. ISSN: 2377-3766. DOI: 10.1109/LRA.2019.2929991.

[WF09] **Bernhard Wally**, Alois Ferscha. “Staged Façades: Peripheral Displays in the Public”. In: International Journal of Ambient Computing and Intelligence 1.2 (Apr. 2009), pp. 20–30.

Patents

[Fer+10] Alois Ferscha, Roland Eckl, Stefan Gusenbauer, **Bernhard Wally**, Cornel Klein, Christoph Kuhmünch, Asa MacWilliams, Jelena Mitic. "Method and Device for Controlling a System". Pat. WO/2010/009915. 2010.

Book Chapters

[Fer+09] Alois Ferscha, Clemens Holzmann, Manfred Hechinger, Bernadette Emsenhuber, Stefan Resmerita, Simon Vogl, **Bernhard Wally**. "Pervasive Computing". In: Hagenberg Research. Ed. by Bruno Buchberger, Michael Affenzeller, Alois Ferscha, Michael Haller, Tudor Jebelean, Erich Peter Klement, Peter Paule, Gustav Pomberger, Wolfgang Schreiner, Robert Stubenrauch, Roland Wagner, Gerhard Weiss, and Wolfgang Windsteiger. Springer, 2009, pp. 379–431. ISBN: 978-3-642-02126-8. DOI: 10.1007/978-3-642-02127-5.

Whitepapers

[Wal18a] **Bernhard Wally**. Provisioning for MES and ERP. Support for IEC 62264 and B2MML. Application Recommendation. AR_MES_ERP 1.1.0. Nov. 2018.

Conference Proceedings

[Isa+19] Haris Isakovic, Vanja Bisanovic, **Bernhard Wally**, Thomas Rausch, Denise Ratasich, Schahram Dustar, Gerti Kappel, Radu Grosu. "Sensyml: Simulation Environment for large-scale IoT Applications". In: Proceedings of the 45th IEEE Annual Conference of the Industrial Electronics Society (IECON). Oct. 2019, pp. 3024–3030. ISBN: 978-1-7281-4879-3. DOI: 10.1109/IECON.2019.8927756.

[Wal+19b] **Bernhard Wally**, Laurens Lang, Rafał Włodarski, Radek Šindelár, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "Generating Structured AutomationML Models from IEC 62264 Information". In: Proceedings of the 5th AutomationML PlugFest. Sept. 2019.

[Wal+19c] **Bernhard Wally**, Jiří Vyskočil, Petr Novák, Christian Huemer, Radek Šindelár, Petr Kadera, Alexandra Mazak, Manuel Wimmer. "Production Planning with IEC 62264 and PDDL". In: Proceedings of the 17th IEEE International Conference on Industrial Informatics (INDIN). July 2019, pp. 492–499. ISBN: 978-1-7281-2928-0. DOI: 10.1109/INDIN41052.2019.8972050.

[Wal+19d] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer, Radek Šindelár. "Modeling Variability and Persisting Configurations in OPC UA". In: Procedia CIRP. Vol. 81: Proceedings of the 52nd CIRP Conference on Manufacturing Systems (CMS). Ed. by Peter Butala, Edvard Govekar, and Rok Vrabič. June 2019, pp. 13–18. DOI: 10.1016/j.procir.2019.03.003.

[Wal+18a] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "IEC 62264-2 for AutomationML". In: Proceedings of the 5th AutomationML User Conference (AutomationML). Oct. 2018.

[Wal+18b] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "A Variability Information Model for OPC UA". In: Proceedings of the 23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). Sept. 2018. ISBN: 978-1-5386-7109-2. DOI: 10.1109/ETFA.2018.8502502.

[Wal+18c] **Bernhard Wally**, Christian Huemer, Alexandra Mazak, Manuel Wimmer. "AutomationML, ISA-95 and Others: Rendezvous in the OPC UA Universe". In: Proceedings of the 14th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2018, pp. 1381–1387. ISBN: 978-1-5386-3594-0. DOI: 10.1109/COASE.2018.8560600.

[WHM17a] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "Aligning Business Services with Production Services: The Case of REA and ISA-95". In: Proceedings of the 10th IEEE International Conference on Service Oriented Computing and Applications (SOCA). Nov. 2017, pp. 9–17. ISBN: 978-1-5386-1327-6. DOI: 10.1109/SOCA.2017.10.

[WHM17b] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "A View on Model-Driven Vertical Integration: Alignment of Production Facility Models and Business Models". In: Proceedings of the 13th IEEE International Conference on Automation Science and Engineering (CASE). Aug. 2017. ISBN: 978-1-5090-6782-4. DOI: 10.1109/COASE.2017.8256235.

[Wal+17] **Bernhard Wally**, Miriam Schleipen, Nicole Schmidt, Nikolai D'Agostino, Robert Henßen, Yingbing Hua. "AutomationML auf höheren Automatisierungsebenen. Eine Auswahl relevanter Anwendungsfälle". In: Proceedings of AUTOMATION 2017. Technology networks Processes. 18. Leitkongress der Mess- und Automatisierungstechnik. VDI-Berichte 2293. VDI-Verlag, June 2017. ISBN: 978-3-18-092293-5.

[WHM17c] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "Entwining Plant Engineering Data and ERP Information: Vertical Integration with AutomationML and ISA-95". In: Proceedings of the 3rd IEEE International Conference on Control, Automation and Robotics (ICCAR). Apr. 2017. ISBN: 978-1-5090-6089-4. DOI: 10.1109/ICCAR.2017.7942718.

[Wal+15a] **Bernhard Wally**, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer. “Model-Driven Retail Information System based on REA Business Ontology and Retail-H”. In: Proceedings of the 17th IEEE Conference on Business Informatics (CBI). Vol. 1. July 2015, pp. 116–124. ISBN: 978-1-4673-7340-1. DOI: 10.1109/CBI.2015.49.

[WH14b] **Bernhard Wally**, Christian Huemer. “Towards a Generic Data Model for REA based Applications”. In: Proceedings of the 4th International Symposium on Business Modeling and Software Design (BMSD). June 2014, pp. 153–158. ISBN: 978-989-758-032-1. DOI: 10.5220/0005425401530158.

[GWF11a] Benedikt Gollan, **Bernhard Wally**, Alois Ferscha. “Automatic Attention Estimation in an Interactive System based on Behaviour Analysis”. In: Proceedings of the 15th Portuguese Conference on Artificial Intelligence (EPIA). Oct. 2011.

[GWF11b] Benedikt Gollan, **Bernhard Wally**, Alois Ferscha. “ID Management Strategies for Interactive Systems in Multi-Camera Scenarios”. In: Proceedings of the 73rd Vehicular Technology Conference (VTC). 4th Conference on Context Awareness for Proactive Systems (CAPS). May 2011. ISBN: 978-1-4244-8332-7. DOI: 10.1109/VETECS.2011.5956474.

[Zam+11] Franco Zambonelli, Gabriella Castelli, Laura Ferrari, Marco Mamei, Alberto Rosi, Giovanna Di Marzo, Matteo Risoldi, Akla-Esso Tchao, Simon Dobson, Graeme Stevenson, Juan Ye, Elena Nardini, Andrea Omicini, Sara Montagna, Mirko Viroli, Alois Ferscha, Sascha Maschek, **Bernhard Wally**. “Self-aware Pervasive Service Ecosystems”. In: Procedia Computer Science. Vol. 7: Proceedings of the 2nd European Future Technologies Conference and Exhibition (FET). Ed. by Elisabeth Giacobino and Rolf Pfeifer. Elsevier, May 2011, pp. 197–199. DOI: 10.1016/j.procs.2011.09.006.

[Fer+08] Alois Ferscha, Simon Vogl, Bernadette Emsenhuber, **Bernhard Wally**. “Physical Shortcuts for Media Remote Controls”. In: Proceedings of the 2nd International Conference on INtelligent TEechnologies for Interactive EnterTAINment (INTETAIN). ICST, Jan. 2008. ISBN: 978-963-9799-13-4.

Workshop Proceedings

[Isa+18] Haris Isakovic, Denise Ratasich, Christian Hirsch, Michael Platzer, **Bernhard Wally**, Thomas Rausch, Dejan Nickovic, Willibald Krenn, Gerti Kappel, Schahram Dustdar, Radu Grosu. “CPS/IoT Ecosystem: A Platform for Research and Education”. In: Cyber Physical Systems. Model-Based Design. 8th International Workshop, CyPhy 2018, and 14th International Workshop, WESE 2018, Turin, Italy, October 4–5, 2018, Revised Selected Papers. Ed. by Roger Chamberlain, Walid Taha, and Martin Törngren. Lecture Notes in Computer

Science 11615. Springer, Oct. 2018. ISBN: 978-3-030-23702-8. DOI: 10.1007/978-3-030-23703-5_12.

[WMW18] Sabine Wolny, Alexandra Mazak, **Bernhard Wally**. "An Initial Mapping Study on MDE4IoT". In: Proceedings of MODELS 2018 Workshops: ModComp, MRT, OCL, FlexMDE, EXE, COMMitMDE, MDETools, GEMOC, MORSE, MDE4IoT, MDEbug, MoDeVVa, ME, MULTI, HuFaMo, AMMoRe, PAINS. Ed. by Regina Hebig and Thorsten Berger. CEUR Workshop Proceedings 2245. 2nd International Workshop on Model-Driven Engineering for the Internet-of-Things (MDE4IoT). Oct. 2018, pp. 524–529.

[WHM17d] **Bernhard Wally**, Christian Huemer, Alexandra Mazak. "ISA-95 based Task Specification Layer for REA in Production Environments". In: Proceedings of the 11th International Workshop on Value Modeling and Business Ontologies (VMBO). Mar. 2017.

[Wal+15b] **Bernhard Wally**, Alexandra Mazak, Bernhard Kratzwald, Christian Huemer, Peter Regatschnig, Dieter Mayrhofer. "REAlist – A Tool Demo". In: Proceedings of the 9th International Workshop on Value Modeling and Business Ontology (VMBO). Feb. 2015.

[MWM15] Emanuel Mätzler, **Bernhard Wally**, Alexandra Mazak. "A Common Home for Features and Requirements: Retrofitting the House of Quality with Feature Models". In: Proceedings of the 9th International Workshop on Variability Modeling in Software-intensive Systems (VaMoS). ACM, Jan. 2015. ISBN: 978-1-4503-3273-6. DOI: 10.1145/2701319.2701334.

[WH14a] **Bernhard Wally**, Christian Huemer. "Defining Business Rules for REA Business Models". In: Proceedings of the 16th IEEE International Conference on Business Informatics (CBI). Vol. 2 – Workshop Papers. 1st Workshop on Enterprise Engineering Theories and Methods (WEETM). July 2014. ISBN: 978-1-4799-5779-8. DOI: 10.1109/CBI.2014.52.

[May+14] Dieter Mayrhofer, Alexandra Mazak, **Bernhard Wally**, Christian Huemer, Peter Regatschnig. "REAlist: Towards a Business Model Adapting Multi-Tenant ERP System in the Cloud". In: Proceedings of the 8th International Workshop on Value Modeling and Business Ontology (VMBO). Mar. 2014.

[Wal+14a] **Bernhard Wally**, Alexandra Mazak, Dieter Mayrhofer, Christian Huemer. "A Generic REA Software Architecture based on Fragments and Declarations". In: Proceedings of the 8th International Workshop on Value Modeling and Business Ontology (VMBO). Mar. 2014.

[Wal+14b] **Bernhard Wally**, Alexandra Mazak, Dieter Mayrhofer, Christian Huemer. "Defining Business Rules for REA based on Fragments and Declarations". In: Proceedings of the 8th International Workshop on Value Modeling and Business Ontology (VMBO). Mar. 2014.

[DWF09] Boxian Dong, **Bernhard Wally**, Alois Ferscha. “Tokenized Interaction Architecture”. In: Proceedings of the 2nd International Workshop on Pervasive Advertising. Sept. 2009.

[WFL09] **Bernhard Wally**, Alois Ferscha, Markus Lenger. “Presence Sensing Billboards”. In: Proceedings of the 2nd International Workshop on Pervasive Advertising. Sept. 2009.

[WF08] **Bernhard Wally**, Alois Ferscha. “Ambient Façades”. In: Proceedings of the 2nd Workshop on Ambient Information Systems. Sept. 2008.

Video Proceedings

[Fer+07] Alois Ferscha, Bernadette Emsenhuber, Stefan Gusenbauer, **Bernhard Wally**. “PowerSaver: Pocket-Worn Activity Tracker for Energy Management”. In: Adjunct Proceedings of the 9th International Conference on Ubiquitous Computing (UBICOMP). 2007, pp. 321–324. ISBN: 978-3-00-022600-7.

Master’s Thesis

[Wal06] **Bernhard Wally**. “Entwicklung einer Steuerinstanz zur interaktiven Kopplung verteilter Geräte”. German. MA thesis. Campus Hagenberg, FH Oberösterreich, 2006. 101 pp.