Model-Based Data Engineering: Preparing a Paradigm Shift towards Self-Organizing Information Exchange

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ABSTRACT

Current standards for interoperability and composability focus on mandating a common information exchange data model. The Levels of Conceptual Interoperability Model (LCIM) shows that this is not sufficient. A second challenge is that the mapping between system-internal representations to the information exchange data model is left to system developers leading to misinterpretations and ambiguous information exchange. Model-based Data Engineering (MBDE) replaces this with an engineering process. Both ideas together motivate the hypothesis that self-organizing information exchange is possible if the system interfaces and behaviors are captured in machine-understandable meta-information.

1 INTRODUCTION

This paper combines two ideas to generate the hypothesis that we are on the brink to a paradigm shift regarding the standardization of information exchange between systems in support of integratability, interoperability, and composability. Although the research is rooted in the domain of modeling and simulation (M&S), it is applicable in many domains of systems engineering – and in particular in the domain of reuse of data used by systems and system of systems. The ideas have been applied in support of several interoperability and composability projects and have been shown to be feasible and useful.

The first idea is the Levels of Conceptual Interoperability Model (LCIM). It will be used to motivate what kinds of metadata are necessary to enable composability of M&S components and other model-based software. The second idea is Model-based Data Engineering (MBDE), which is an engineering method to align information exchange requirements between model-based components in support of composability. The insights of applying the framework of the LCIM together with MBDE lead to the formulation of the hypothesis that we will soon be able to replace the current paradigm for information exchange with a new paradigm. Current solutions focus on mandating an information exchange model, such as the use of Protocol Data Units in the IEEE 1278 standard for Distributed Interactive Simulation or the use of an agreed Federation Object Model in the IEEE 1516 for the High Level Architecture. Another example is the Test and Training Enabling Architecture (TENA) common object model. Future solutions will be able to use LCIM layers meta-information to describe the system interface and behavior to self-organize the possible information exchange between systems on the basis of MBDE principles.

The paper will start with citing work that contributed to the ideas of MBDE in section 2. After this, a short overview of LCIM in section 3 and MBDE in section 4 will be given, including application examples showing the feasibility, applicability, and utility of the ideas. Section 5 describes the paradigm shift and shows where we are and where we want to go. As the research is just starting, this paper will hopefully produce fruitful discussions in the M&S community that will result in a common and ultimately standardized use of metadata enabling the self-organization envisioned in section 5.

This paper summarizes the research of the data management team chaired by the author, therefore it comprises many self-references to earlier work.

2 RELATED RESEARCH EFFORTS

The work presented here is embedded in the body of knowledge for composability without which the insights would not have been possible. This section will point to the most influential works of others in the field.

Overall, the work described in this paper is based on the solid foundation of heterogeneous federated databases. Experts dealing with very large heterogeneous and distributed data in large corporations like Coca Cola or Puma had to solve inconsistencies in databases and workflows on a big scale. The findings and recommendations led us to a multiple-layer-translation model published by Spaccapietra et al. (1992) and extended by Parent and Spaccapietra (1998). Gorman's (2006) work contributed in particular to the understanding of military challenges.

Another research domain influenced the work in a similar manner, namely Reynolds et al. (1997) and Davis and Bigelow (1998) contributions on multi-resolution modeling challenges in distributed simulation systems.

The idea to use a layered approach to deal with the realm of interoperable and composable solutions has been used before. One of the most influential models is the Levels of Information Systems Interoperability developed by the Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance Interoperability Working Group and published in (C4ISR IWG, 1998). Winters et al. (2006) give an overview how the various layered approaches are related regarding data management issues.

The report of the RAND Corporation on Composability Challenges (Davis and Anderson, 2003) within the US DoD is an excellent summary of current solutions, and their open questions remain valid.

In the M&S domain, the work of Petty and Weisel has led the way for many researchers, in particular their Lexicon for Composability (Petty and Weisel, 2003). They were among the first to identify the need to distinguish between composability and interoperability based on the need identified by Harkrider and Lunceford (1999). Petty's and Weisel's work motivated the first LCIM as presented by Tolk and Muguira (2003). Page et al. (2004) refined the model by introducing integratability as the third concept. The LCIM uses a slight modification of Page's definitions. Hofmann (2004) used these ideas to formulate his challenges for M&S composability.

In addition to the work in the M&S domain, the research regarding semantic web composability was a driving force for the research described here. Welty and Smith (2001) summarized the state of the art in their proceedings and identified the necessity to compose web services in a more consistent way in several papers. How this was answered is best summarized in Agarwal et al. (2005) and the book of Alesso and Smith (2005). Both are using the notion of semantic web services, in which services are described in more detail allowing the user (and ultimately other software components) to identify services that can be composed meaningfully. Current work is referenced on the Semantic Web Service Initiative website. One of the most visionary papers, published by Chen et al. (2006), presented the use of ontology-based knowledge management in support of composable solutions. Finally, the work described in this paper was also influenced by the mathematical foundations for Model Theory as described by Pilley (2000) and the knowledge representation work of Sowa (2000).

Finally, the work of agent mediated solutions in the M&S domain closed the gap between M&S composability and semantic services. To be mentioned in particular is the work of Yilmaz (2004) and Yilmaz and Paspuletti (2005). They used agents to capture the behavior and information exchange requirements of M&S components and let them decide how and what to compose, using meta-structures of the semantic web to support this work.

Unfortunately, even short summaries of these papers are beyond the scope of these conference contributions, but interested readers are highly recommended to utilize these papers for their research.

3 LEVELS OF CONCEPTUAL INTEROPERABILITY MODEL

The LCIM has been developed to provide both a metric of the degree of conceptual representation that exists between interoperating systems and also as a guide showing what is necessary to accommodate a targeted degree of conceptual representation between systems. The model was originally developed to support the interoperability of simulation systems, but has been shown to be useful for other domains, as well. It was first published by Tolk and Muguira (2003) and later enhanced in response to ongoing research, in particular reflecting ideas of Page et al. (2004) and Hofmann (2004). The following figure shows the current LCIM:

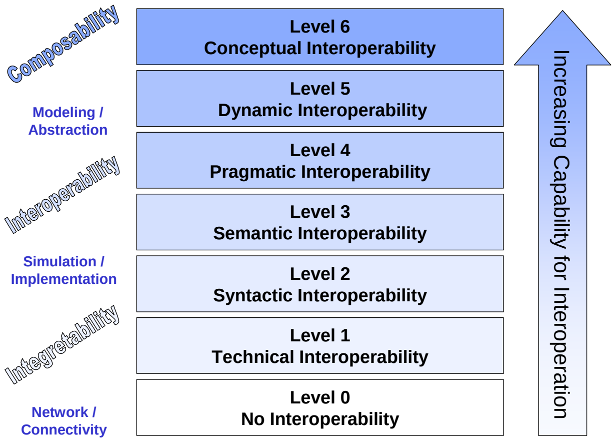

Figure 1: Levels of Conceptual Interoperability Model

The current version of the LCIM distinguishes seven layers, starting with stand-alone systems. The underlying approach is best understood from the by bottom-up.

- Level 0: Stand-alone systems which need *No Interoperability*. No connection exists between any systems.
- Level 1: On the level of *Technical Interoperability*, a communication protocol exists for exchanging data be-

tween participating systems. At this level, a communication infrastructure is established allowing exchanging bits and bytes; the underlying networks and communication protocols are unambiguously defined. This is the minimal form of connectivity required for interoperation of systems: being technically connected.

- Level 2: The *Syntactic Interoperability* level introduces a common structure to exchange information; a common data format is applied where the format of the information exchange is unambiguously defined. Examples for such common formats are the use of XML or the use of the Object Model Templates of HLA. Although a common format is used, nothing ensures that the receiver understands what the sender wants to communicate.
- Level 3: If a common information exchange reference model is used, the level of *Semantic Interoperability* is reached. On this level, the meaning of the data is shared; the content of the information exchange requests are unambiguously defined. Examples are the Protocol Data Units of DIS. Also, if the semantic meaning of the data is captured in the form of a controlled vocabulary with an associated dictionary, this level is supported.
- Level 4: *Pragmatic Interoperability* is reached when the interoperating systems are aware of the methods and procedures that each other are employing. In other words, the use of the data – or the context of its application – is understood by the participating systems; the context in which the information is exchanged is unambiguously defined. In particular in systems in which the necessary information can be submitted in several successive communication instances (like sending several HLA messages or object that in summary comprise the required information, or if more than one PDU is needed to cover the information request), the business objects associated with this sort of work flow between the systems must be known. Another way to think about pragmatic interoperability is that individual meaning of data elements is placed into the context of how the data is used within the functionality of the resulting system.
- Level 5: As system functions and services operate on data over time, the state of that system will change, and this includes the assumptions and constraints that affect its data interchange. If systems have attained *Dynamic Interoperability*, then they are able to comprehend the state changes that occur in the assumptions and constraints that each other is making over time, and are able to take advantage of those changes; the effect of the information exchange within the participating systems is unambiguously defined. As a minimum, the input data is connected to output data including temporal aspects of the systems (white box with behavior). A complete open solution with everything revealed to the user (such as in open source including the system specification of the platform on which the service will be executed) marks the high end of this level.
- Level 6: Finally, if the conceptual models – i.e. the assumptions and constraints of the purposeful abstraction of reality – are aligned, the highest level of interoperability is reached: *Conceptual Interoperability*. On this level, the assumptions and constraints describing the purposeful abstraction of reality are unambiguously defined. This requires that conceptual models will be documented based on engineering methods enabling their interpretation and evaluation by other engineers. In other words, on this we need a "fully specified but implementation independent model" as requested in Davis and Anderson (2003) and not just a text describing the conceptual idea. As pointed out by Robinson (2006), this is one of the major challenges.

Page at al. (2004) introduced the three categories used as well in figure 1: *Integratability* manages the physical and technical realms and challenges of connections between systems, which include hardware and firmware, and protocols. This is the domain of networks and other physical connections between systems. *Interoperability* deals with the software and implementation details of interoperation, including exchange of data elements based on a common data interpretation, which can be mapped to the levels of syntactic and semantic interoperability. Here we are on the simulation side of M&S and how the models are actually implemented and executed. *Composability* addresses the alignment of issues at the model level. The underlying models are meaningful abstractions of reality used for the conceptualization being implemented by the resulting simulation systems.

As pointed out in Tolk (2006), after focusing for decades on solving the simulation challenges, it is now time to seriously think about standardization requirements and engineering-driven solutions for the modeling side. The community needs to agree on how to capture assumptions and constraints so that intelligent software applications, such as intelligent software agents, can understand the assumptions and use this knowledge to compose services in support of the immediate needs of users. MBDE is a first step into this direction.

4 MODEL-BASED DATA ENGINEERING

Although the NATO Code of Best Practice for Command and Control Assessment (NATO, 2002) was obviously written for application in the Command and Control domain, it is applicable in a much broader context, as it is a guide to operational research in complex domains comprising many general principles. Recurring principles in this guide are: the necessity to orchestrate several tools in order to solve a problem; and to address the challenge of data, as models are only as good as the data that can be obtained to feed them. However, as different models are abstractions of reality in different ways (which is a good thing, as we want to evaluate a problem from different viewpoints); it is highly unlikely that they all will use the same data in the same structure.

The user – and ultimately a service in a computer grid – has to know *what* data is located *where*, the *meaning* of data and its *context*, and the *format* of the data to be used by appropriate services composed into a distributed application within the overall system. To generate the answers to these questions is the objective of data administration, data management, data alignment, and data transformation, which can be defined as the building blocks of a new role in the interoperability process: *Data Engineering* (Tolk, 2003). The composing terms are defined as follows:

- *Data Administration* is the process of managing the information exchange needs that exist between the system services, including the documentation of the source, the format, context of validity, and fidelity and credibility of the data. Data Administration therefore is part of the overall information management process for the service architecture. It answers the questions *what data is where in which format* (plus other metadata, such as credibility and reliability of the source, validity of the data, resolution and accuracy, etc.)
- *Data Management* is planning, organizing, and managing of data by defining and using rules, methods, tools, and respective resources to identify, clarify, define, and standardize the meaning of data as of their relations. It defines the *meaning of data elements*.
- *Data Alignment* ensures that the data to be exchanged exists in the participating systems as an information entity or that the necessary information can be derived from the data available, e.g., using the means of aggregation or disaggregation. While the first two disciplines can be executed independently for every source, alignment makes sense only for source-target pairs. It evaluates if the *information exchange capability* exists for source-target pairs.
- *Data Transformation* is the technical process of transforming the information entities of the embedding systems to match the information exchange requirements including the adjustment of the data formats as needed. This is the *physical process* of changing the data of the source to meet the requirements of the target.

No matter which tools are used to support these steps or to capture the results, the engineering process of data engineering must be executed. It should be pointed out that system engineering requires that operational requirements should be stated in operational-level requirements documents and information exchange requirements should be established and explained both in terms of context and format. Furthermore, system specifications should be derived from the operational requirements, and the system developer should work within all the above. However, in practice data engineering tasks are often left to system developers that do not have the knowledge of the overall system-of-system requirements. Furthermore, only parts of the process are done explicitly and implicit common understanding is assumed for the rest. An example is the practice of federation development, in which the unambiguous definition of system-internal representation of data is often not conducted with other experts but as an afterthought when the interface of the simulation system to the federation object model is established by engineers. This often leads to errors in the federation that are hard to discover, if at all, without rigorous data management. The following categories of conflicts were identified in (Spaccapietra et al., 1992; Parent and Spaccapietra, 1998)

- *Semantic Conflicts* occur when concepts of the different local schemata do not match exactly, but have to be aggregated or disaggregated. They may only overlap or be subsets of each other, etc.
- *Descriptive Conflicts* describe homonyms, synonyms, and different names for the same concept, different attributes or slot values for the same concept, etc.
- *Heterogeneous Conflicts* result from substantially different methodologies being used to describe the concepts, such as different relational data modeling methods (IDEF1X versus ORACLE).
- *Structural Conflicts* results from the use of different implementation structures describing the same concept, such as using lists versus vectors.

In their papers, Spaccapietra and colleagues pointed to the necessity of efficient metadata models to deal with these challenges. The ISO/IEC 11179 metadata standard addresses the same issues. Part 3 of this standard is of particular interest to this paper. Part 3 describes the basic elements of the registry meta model shown in Figure 2.

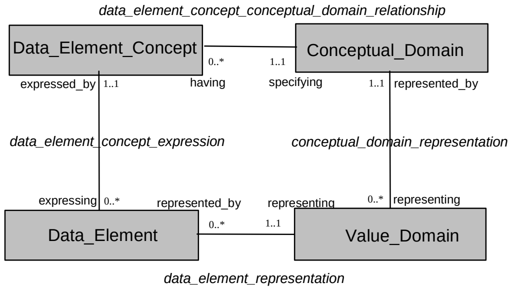

Figure 2: ISO/IEC11179 Meta Model

ISO/IEC11179 distinguishes between contextual information, which is the meaning or semantics of data, and symbolic information, which is the structure or syntax of data. This is expressed by conceptual and representational levels of data elements. The standard uses the following terms to describe a registry:

- *Conceptual Domains* define sets of categories, which are not necessarily finite, where the categories represent the meaning of the permissible values in the associated value domains. They comprise symbolic information on the conceptual level, where symbols represent the meaning of the data.
- *Data Element Concepts* describe the contextual semantics, i.e., the kinds of objects for which data is collected and the particular characteristic of those objects being measured. They comprise the contextual information on the conceptual level, answering the questions of what pieces of data are needed to capture a concept.
- *Data Elements* are the basic containers for data as used in data models. Data may exist purely as an abstraction or exist in some application system. Data elements comprise contextual information on the representation level. (It should be pointed out that entities and relations are normally captured as tables in data models, which means that both categories – table and relations – are represented here and distinguished by contextual information.)
- *Value Domains* comprise the allowed values for the respective data element. Value domains comprise symbolic information on the representation level.

The distinction between contextual and symbolic information becomes essential in the process of data mediation. *Data Mediation* is the application of data transformation to one or a group of data elements that are aligned with each other as they point to the same concept or group of concepts. As such, data mediation is the result of a rigorous engineering process and should not be ad-hoc, as it would lead to the conflicts and errors identified before.

If two data elements are derived from the same data element concept, the mapping can usually be done by a symbolic transformation of their value domains or is even a one-to-one mapping. However, this requires that these concepts be unambiguously defined.

Although in principle it is possible to start with the interface descriptions of the systems and generate a common reference model exclusively for these systems, it is a best practice to look for a common reference model that is already accepted in the application domain or a community of interest. This model should be implementation independent, which means that no value domains are part of it. As such it is comparable to a logical model used in traditional data modeling versus the physical model describing the interface. The constructs of ISO/IEC 11179 can be seen as a connecting bridge between the conceptual structures of the logical view and the specific interface implementation. The logical data model represents the concepts while the implementing entities of the physical data model represent the data element instances. If such a model exists and is used as the core, we are performing *Model-based Data Engineering* (MBDE).

The use of ISO/IEC 11179 by a Community-of-Interest (COI) to develop a common reference model (CRM) is beyond the scope of this paper. However, two application examples are used to illustrate the main ideas.

Within the military community, the Joint Command, Control, and Consultation Information Exchange Data Model (JC3IEDM) has been identified as a potential C2 COI CRM. NATO’s Multinational Interoperability Programme (MIP) is responsible for the configuration management, extensions, and enhancements of this model. Documentation for the data model, its business rules, underlying definitions, and processes are available on the MIP website (http://www.mip-site.org). JC3IEDM was designed to support the *unambiguous definition* of information exchange requirements in the operational domain. The contributions of data modeling experts as well as operational experts and users from more than 20 countries over more than 15 years ensure *technical maturity* and *operational applicability* based on mutual agreement and *multilateral consensus.* This makes the JC3IEDM *unique* in the technical as well as the operational domain. Every recommended alternative to JC3IEDM must be measured against these criteria and achievements.

Other application domains are using richer specification methods than the traditional data modeling based on entity relationship models. An example is Power System Common Information Model (CIM) defined by the Electric Power Research Institute (EPRI, 2001). CIM is an abstract information model that represents real-world objects and information entities exchanged within the value chain of the electric power industry. It was formulated in the Unified Modeling Language and is now also available in Resource Description Format RDF, the Extensible Markup Language XML, and the Web Ontology Language OWL. What is of interest in this paper is that the EPRI CIM can be used as the COI CRM for electrical systems in the same way as JC3IEDM can be used for military applications: as a common core that can be extended and enhanced to reflect the information exchange needs and constraints of participating systems.

Both CRM examples are not only freely available; they are also *managed* and *configured* by an *organization with expert status* in a well-defined community of interest. They are rooted in well defined, *controlled vocabularies* that are configured and managed using data engineering principles, resulting in *standardized data elements* representing *concepts* and their *relations* of real world objects and information entities. These concepts, however, are represented in the common view of the COI and may exist in various implementations and interpretations in the systems as *entities*. We have therefore the three-tier-approach well known in the ontological world: *The real world referent that is represented as a concept that is implemented as an entity.*

MBDE uses the COI CRM to represent the concepts representing the real world objects and applies data engineering principles to relate the data elements and value domains of each system to the data element concepts and conceptual domains represented in the CRM as a first step. In the second step, participating systems' data elements representing the same CRM concepts are identified. The result is an unambiguous documentation of the real information exchange capabilities between systems. The last step is to mediate the data elements representing the same concepts into each other such as by XML transformations (Tolk, 2004; Tolk and Diallo, 2005). An interesting alternative is to use the multi-resolution elements introduced by Reynolds et al. (1997) to represent each concept and to mediate each entity (or entities) based on the documented dependencies.

The ideas described in section 3 and 4 were successfully applied in two projects:

- The NATO PATHFINDER vision targets the implementation of the future NATO training system as described in the NATO Modeling and Simulation Master Plan. The PATHFINDER vision is being implemented through a series of technical activities lead by the NATO M&S Group and coordinated by the M&S Coordination Office. Both organizations are part of the NATO Research & Technology Organization. The work, using the ideas described in this paper, was conducted under technical activity MSG-027 to evaluate a PATHFINDER Integration Environment. MSG-027 conducted several experiments in support of collecting knowledge for a web portal. Among the supporting experiments, some focused on Command and Control system to M&S system Interoperability. Based on web services using the JC3IEDM as a CRM, a transatlantic federation was set up to link the German M&S system PABST, the Spanish M&S system SIMBAD, the Swedish Google Earth Adaptor for Visualization, the WebCOP Command and Control Visualizer, and the US/Danish Command and Control system SITAWARE. The experiment was a success and is described in Tolk and Boulet (2007).
- The Joint Event Data Initialization Services (JEDIS) project is being developed under the sponsorship of US Joint Forces Command as part of their Joint Rapid Scenario Generation (JRSG, former known as Joint Rapid Distributed Database Development Capability (JRD3C)). JRSG seeks to combine authoritative data sources into a set of coherent and consistent joint event data that is distributed via web services. Using the ideas described in this paper, the identified data was mapped using the structures of ISO/IEC 1179 from the source systems to the JC3IEDM and back. Perme et al. (2007) describes how the resulting service-oriented architecture together with mapping examples will be implemented at US Joint Forces Command.

Both applications showed the technical feasibility and operational applicability of the MBDE.

5 HYPOTHESIS: LEADING TOWARDS A NEW PARADIGM FOR INFORMATION EXCHANGE

While the ideas and processes presented thus far have already been proven feasible and applicable, the ideas in this section are hypothetical. As such, the authors propose a research agenda for self-organizing information exchange.

The idea of self-organizing information exchange is popular in several semantic web applications. Su et al. (2001), e.g., describe prototypical experiments on automatable transformations between XML documents. Most of these applications are not very complex and focus on quasi-static data, such as "data describing addresses" or "data describing references to journal papers." Ambiguities and different levels of resolution are not dealt with. Therefore, the existing proposed solutions are not applicable without extensions and modifications.

The current IEEE1278 and IEEE1516 standards support simulation interoperability. They mandate a set of Protocol Data Units in DIS or a Federated Object Model in HLA to exchange information. How the system specific information objects are mapped to the data used for information exchange is not documented. It is not of general concern if the participating systems can provide or use the information at all. Although it starts to become a best practice to capture the information in the federation agreements, this is not part of the standard and is not done in a machine understandable way.

The solution proposed below requests metadata describing system characteristics on all levels of the LCIM in support of agent-mediated composability allowing machines or software agents to:

- parse and compute the information (which requires the use of a formal language, such as XML or OWL)
- select systems for a task based on their described capabilities
- choreograph the execution, and
- orchestrate the process in order to optimize the process support.

The ideas and experiments in this direction were first captured in Yilmaz and Paspuletti (2005) and Yilmaz and Tolk (2006).

The resulting information exchange paradigm shift is to replace the prescriptive use of a common information exchange model with a more flexible one that allows systems to specify their information exchange capabilities and discover – guided by the principles of data engineering and supported by intelligent agents – what information can be exchanged in a meaningful way between respective participating systems. At the same time, the user of the system can specify his view of a problem, which results in how information will be presented by the system to the user.

By applying the methods described in sections 3 and 4, we suggest a model view in alignment with the ideas of Model Theory (Pillay, 2000) for each system interface. This is also a knowledge representation of concepts and associations as described in various implementations by Sowa (2000). Each description comprises:

- information elements to be exchanged in the form of sets of properties that are used to describe the concepts in the application,
- associations between these propertied concepts reflecting represented relations between concepts in the application,
- definitions of valid property values for each property,
- property value constraints based on application specific rules (such as: if value of property a = A then value of property B cannot be A as well),
- propertied concept constraints based on application specific rules (such as: propertied concept C1 cannot be instantiated of propertied concept C2 is nonexistent),
- association constraints based on application specific rules (such as: the context CT requires transmitting the associated propertied concepts PC1 and PC2 in one transaction).

Each of these system specific descriptions (on the third-tier level, which are the implemented entities) must be consistent in itself and represents a structure M. Pillay (2000) defines as:

> "structure M here is simply a set X, say, equipped with a distinguished family of functions from X_n to X (various n) and a distinguished family of subsets of X_n (various n). Here X_n is the Cartesian product X x … x X, n times."

We claim that the metadata sets described in section 3 and 4 are necessary and sufficient to describe these structures. Furthermore, two structures *M1* and *M2* are equivalent if and only if each structure element of *M1* is mapped to exactly one structure element of *M2* under all *n*.

As shown by Pillay (2000) and Sowa (2000), such structures describe various implementations for information technology specific solutions, such as databases, artificial languages (i.e., computer understandable languages, such as specified by grammars), ontological representations (i.e., in computer understandable form, such as captured in OWL), and other examples. In other words, it is possible to algorithmically evaluate if two structures represent equivalent views.

MBDE introduces for each system specific description a system independent description (on the second-tier level, which is the conceptual representation), which in itself is a structure. Currently, the data engineer ensures with his mapping between implementing entities and representing concepts the equivalency of the implementing structure with the conceptual structure.

If we express the metadata, this work can be executed, verified, and validated by intelligent software agents as envisioned by Yilmaz and Paspuletti (2005). However, in order to support such a vision, the assumptions on constraints of simulation systems identified in efforts described by Davis and Anderson (2003), Hofmann (2004) or Yilmaz (2004) and Yilmaz and Tolk (2006) need to be captured in a standardized way and accessible by intelligent agents. Such standards are targeting the conceptual level, which means the modeling part of M&S and clearly contributes to the research agenda proposed by Robinson (2006).

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