

A Model-Driven Approach on Object-Oriented PLC Programming for Manufacturing Systems with Regard to Usability

Martin Obermeier, Steven Braun, and Birgit Vogel-Heuser, *Senior Member, IEEE*

Abstract—This paper presents the modular automation for reuse in manufacturing systems (modAT4rMS) approach to support the model-driven engineering (MDE) of object-oriented manufacturing automation software with regard to its usability and software modularity. With usability, we refer to the aspects' effectiveness, efficiency, and user acceptance as defined by ISO 9241-11. The modAT4rMS notations are based on selected features from the unified modeling language (UML) and the systems modeling language (SysML), and iteratively further developed by a series of empirical studies with industrial practitioners, as well as mechatronics trainees. With modAT4rMS, an MDE approach for programmable logic controller (PLC) programming was developed with the goal to facilitate modular object-oriented programming of PLC software by improving the representation of the relationships between the structure and behavior diagram types, and by reducing the level of abstraction in the structure model. modAT4rMS notations for PLC software structure and software behavior modeling are presented and illustrated with a modeling example using a modAT4rMS editor prototype. For the evaluation of the developed notations, the results from a study with 168 participants are presented, showing the benefits of this new approach in comparison with the classic procedural paradigm (IEC 61131-3) and the domain-specific UML profile (plcML) in regard to programming performance and usability aspects. Finally, the advantages and limitations of the approach are discussed, and an outlook for further development is given.

Index Terms—Manufacturing systems (MSs), model-driven development, model-driven engineering (MDE), object-oriented modeling, object-oriented software engineering, usability.

I. INTRODUCTION

IN MACHINE and plant automation model-driven object-oriented (OO) software engineering of programmable logic controllers (PLCs) remains a challenge [1]. Since the IEC 61131-3 standard [2] is widely accepted in industrial automation [3], using OO features for software model creation in this field is still uncommon [4], [5]. Reasons seem to be manifold: absence of accepted modern PLC software engineering approaches, classical procedural programming languages on the PLCs [2], mostly

application engineers coming from application domains and also the fact that the integration of OO features into the IEC 61131-3 in 2013 is still relatively new and only supported by few PLC developer environments, such as 3S CODESYS V3 [5] and Beckhoff TwinCAT 3 [6].

As Vyatkin mentions in [5], the adaption of developments from general computing allows developers to take advantage of the huge investments into such technologies and relies on proven solutions, such as OO, model-driven engineering (MDE), or component-based design, rather than reinventing the wheel.

In order to increase reuse and quality in manufacturing system (MS) software engineering, modeling techniques from computer science can be applied in automation and control engineering, e.g., unified modeling language (UML) and systems modeling language (SysML). In computer science, object-oriented programming has been considered a solution to many computing challenges. As Mili *et al.* [7] describe, "Software engineers view object orientation (OO) as the answer to their numerous and intractable problems: enhancing software quality, reusability, and providing a seamless development methodology." In order to support software engineers with regard to usability aspects, UML has already been successfully applied, cf. [8]. It is most likely that application and process control engineers will program their solutions using such techniques in the future, as e.g., Thramboulidis and Frey [3] consider the benefit of integrating IEC 61131-3 with UML being able to use several diagrams in order to capture more aspects of the system. This is supposed to result in a more complex yet still comprehensible model.

This paper presents the newly developed modular automation for reuse in manufacturing systems (modAT4rMS) approach which adapts strengths and resolves the weaknesses of notations in PLC software engineering for plant automation, e.g., UML, SysML, and the classical IEC 61131-3 languages. The focus of this work is classical manufacturing automation, i.e., open-loop control, mostly implementing interlocking algorithm, feedback, proportional-integral-derivative (PID), and other simple closed-loop controllers. Three studies with more than 100 participants (including industry practitioners, mechatronic trainees, and researches) have been conducted in the course of its development. For its evaluation, a study with 168 participants (mechatronic trainees and industrial practitioners) was carried out, in order to test modAT4rMS with regard to usability against the state-of-the-art IEC 61131-3

Manuscript received December 05, 2013; revised May 19, 2014; accepted July 21, 2014. Date of publication August 07, 2014; date of current version June 02, 2015. Paper no. TII-13-0933.

The authors are with the Institute of Automation and Information Systems, Technische Universität München, München 85748, Germany.

This paper has supplementary downloadable multimedia material available at <http://ieeexplore.ieee.org> provided by the authors. This includes a PDF file containing the Appendix. This material is 227 kB in size.

Digital Object Identifier 10.1109/TII.2014.2346133

and an UML-based MDE approach (plcML). The reason for the evaluation against IEC 61131-3 function block diagram (FBD) is evidently the need for a well-known comparison basis from industrial practice for empirical experimentation. The plcML, as described in Sections II-A2 and III, is a predecessor of the modAT4rMS and was therefore used as a comparison approach. In the following section, the state-of-the-art on modeling notations and a short overview of the previously conducted studies are presented. The challenges when adapting UML to design modular machine software are shown, and necessary steps in order to facilitate the use of UML or domain-specific UML profiles for modeling the structure and behavior of automation systems are derived, resulting in the modAT4rMS notations. In Section III, the concepts of the modAT4rMS behavior and structure notations are shown. The latest study, evaluating the modAT4rMS, is discussed in short in Section IV and its results are presented. Finally, the paper is concluded in Section V, and an outlook on future work is given.

II. RELATED WORK

This chapter covers relevant notations in the context of PLC programming followed by related results from previously conducted studies.

A. Notations for PLC Programming

In the following, related aspects on the widely used IEC 61131-3 [2] standard languages will be discussed first, and in contrast thereof, the UML and its relevant domain-specific profiles will be covered.

1) *IEC 61131-3*: The IEC 61131-3 [2] with its textual [structured text (ST), instruction list (IL)] and its graphical languages [ladder diagram (LD), FBD] as well as its sequential function chart (SFC) is still accepted and widely used by software engineers to specify the software part of industrial automation systems [9].

The clean encapsulation of code and data in function blocks (FBs) is possible but is often disturbed by the use of global variables, which leads to poor reusability of modules, cf. [10]. In order to provide an elemental basis of reuse, IEC 61131-3 software can be structured into program organization units (POUs), e.g., FBs. FBs capture the structure and behavior of a collection of objects used in automation projects [9] and can be regarded as a specific type of class being instantiated before the system's operation. Hajarnavis and Young [11] evaluated an object-oriented approach in comparison to IEC 61131-3 approaches in an experiment with 63 participants. Their results showed that "there is a difference in completion rate and time between the programming tools under test. Although the object-oriented programming tool used here proved best suited to the facilitation of fast and correct process changes, ladder logic based on a step-based structure was found to give comparable results when used by skilled programmers." cf. [11].

As Fantuzzi proposes in [12], a modular quasi-object-oriented program structure is possible, through the application of design patterns. In [5], Vyatkin mentions the centralized programmable control model of PLCs as a critical aspect as it

could "cause unpredictable results and overheads when two or more controllers communicate via network, and its centralized, cyclically scanned program execution model limits the reuse of the components in case of reconfiguration."

2) *UML and Domain-Specific UML Profiles for MS*: UML is an established standard for software development being used to create models from a conceptual basis or software perspective. The current UML specification (V2.4.1 [13]) contains 16 diagrams providing both a structural view, e.g., class diagram, defining the dependencies between FBs or classes and a behavior view, e.g., state machines and activity diagrams, easing the implementation of behavioral aspects of the system. The object-oriented paradigm encourages a modular design by different relation types, such as association among classes and inheritance for hierarchical structuring. The UML class diagram illustrates the structure of automation control software and helps to understand the interdependencies of components.

Thramboulidis and Frey [9], Thramboulidis [14], Secchi *et al.* [15], [16], and Basile *et al.* [17] highlighted the benefit of using modeling notations through improving modularity and reuse as well as system understanding compared to traditional approaches using pure IEC 61131-3 programming languages. In [18], alongside a model-checking approach using UML, a UML-based hardware/software codesign platform for embedded systems using field programmable gate array (FPGA) devices is proposed in order to support the direct interaction between the UML models and the real hardware architecture.

However, Secchi *et al.* [16] mentioned that it is not sufficient to employ UML with its 16 diagrams but to provide an adapted modeling language for domain-specific applications, i.e., UML-RT, in order to provide modeling of real-time software architectures by means of encapsulated software parts interacting with each other through ports following a communication protocol.

Kim *et al.* presented in [19] a state-chart approach for embedded systems that includes the necessary time and resources for actions in the state-chart model in order to describe the competition between processes using shared resources.

In [20], Bicchierai *et al.* presented an MDE approach adapting UML for modeling and analysis of real-time and embedded systems [21], with a selected number of diagrams (component, class, object, and activity diagrams), for managing a documentation process and in combination for providing guidance for its translation into preemptive Time Petri Nets.

In order to model a holistic view of the automation system considering all disciplines involved in engineering, the SysML may be used [9], [22]–[24]. Hästbacka *et al.* [25] use the UML automation profile in their AUKOTON approach in order to provide domain-specific modeling constructs for a holistic view including requirements, automation components, and devices as well as the process system and the control systems. As this paper focuses on the PLC software part of the system represented in notations, related work specific to this aspect is discussed further.

In several works [23], [26]–[30], the attempt to integrate IEC 61131-3 notations with UML or SysML has been made. Yet, previous research on software engineering with UML shows that while using more diagrams is confusing [23], using adapted subsets of UML is beneficial, cf. [27].

Therefore, based on the findings in [27], the plcML, a domain-specifically adapted UML profile for PLCs, was developed by Witsch, cf. [31], [32]. The plcML reduces the number of notations to three, offering the class diagram for structure modeling and adapted activity and state-chart diagrams for behavior modeling. These diagrams are described in detail in [31] and [32], where their model transformation using Object Constraint Language (OCL) is also described as well as their model formalization, in order to enable code generation and bidirectional mapping for IEC 61131-3 development environments. Editors for the plcML notations and the corresponding code generation are in the making as a plugin for CODESYS V3 and will provide a fully real-time capable plcML programming environment (product name CODESYS Prof. Developer Edition—CODESYS UML), cf. [32].

The presented related work on IEC 61131-3 and UML approaches leads to the development of the new modAT4rMS approach with the following basic conclusions on the notation's design: Only a limited number of domain-specific diagrams should be provided, not the full UML/SysML. The notation should support effective and efficient OO MDE with regard to user satisfaction in comparison to the state-of-the-art IEC61131-3 approach, as this is a major focus of MDE, cf. [5]. These conclusions were refined through the results of a series of previously conducted studies, described in Section II-B.

B. Results From Previously Conducted Studies

In a series of previously conducted studies, the influence of different factors of notations on the usability for PLC programming was evaluated and the new modAT4rMS notations for structure and behavior modeling were developed. For these studies, the usability was measured according to the aspects' effectiveness, efficiency, and user acceptance defined in ISO 9241-11 [33]. For the measurement of the effectiveness, the task completion was determined using code review, supported by review guidelines which included all programming tasks with their respective subtasks down to the creation of an attribute/variable of the structure model, respectively, a function/operation call in the behavior model. Each review on task completion was carried out by two evaluators in order to verify the objectivity of the evaluation method. The level of task completion was then calculated as the percentage of solved tasks over all given tasks.

In the first study, conducted in 2011 and presented in [4] and [34], the model-driven plcML approach's state-chart and class diagrams, cf. [31], [32], were experimentally evaluated in comparison to the IEC 61131-3 FBD. The results of this study showed no significant differences in programming performance between FBD and plcML. The required level of abstraction for creating classes proved problematic for the participants, who needed tendentially more time for structure creation (time measured until they started creating the behavior model: $m_{\text{IEC 61131-3}} = 49.83$ min; $m_{\text{plcML}} = 56.05$ min; probability of results occurring by chance $p = 0.06$) and created superfluous classes, cf. [4]. From these results, a need for an adapted, less abstract structure notation, supporting the creation of modular software was deduced.

Therefore, a first draft of the modAT4rMS notations was developed, which used an object-centered structure diagram and tried to visualize the connection between structure and behavior diagram by using an adapted UML state chart for behavior modeling, cf. [35]. This draft was evaluated in a 4-h study with 10 researchers of the Institute for Automation and Information Systems at the Technische Universität München. In this study, the participants first had to program a known automation lab demonstrator, using only the new draft notations. In the second part, a given model had to be interpreted. Overall, 35 min of training, 45 min for solving the model creation task (structure and behavior), and 35 min for the interpretation task were given. After solving all test tasks, the participants had to answer questionnaires with scaled and open answer possibilities on the subjective usability, adapted from [33] and [36] and took part in a focus group discussion on the new notations. The test task results showed a mean task completion level of 68.5% for structure and 59.5% for behavior model creation. The mean result on the interpretation task was 77.66% completion. Further results from the questionnaires and the focus group were positive for the developed structure notation and showed that the behavior notation in this draft was rated better than UML state-chart diagrams. Yet, the behavior diagram was criticized for being unclear in regard to the connection between structure and behavior for seasoned UML-modeling experts. The structure model had worked very well with a few exceptions and was therefore developed further on this base. For clearer connections between the blocks of the structure and the processes that shaped the software model, the behavior notation was changed in the next draft, which subsequently led to the final modAT4rMS notations.

In the second draft, the behavior notation was changed to a notation adapting plcML activity diagram and UML sequence diagram features. This proved to solve the criticized lack of clarity of the connection between structure and behavior diagram in the second evaluation, being conducted with eight industrial PLC programming experts and nine trainees on electronics. In this study, the participants had to program a known automation system used for the apprentices' PLC programming training, with the second draft modAT4rMS notations. As in the previous study, the same questionnaires were used for the measurement of subjective usability and workload. The results of this study led to the final version of the modAT4rMS notations described in Section III.

III. MODAT4RMS APPROACH

From the related work on modeling notations, it can be deduced that the strength of UML and SysML to represent many different aspects of the development of a mechatronic system is not optimally applicable for the user in the specific case of PLC software engineering for MS. This is reflected in the discussed previous evaluation results in Section II, which pointed out especially the criticized high complexity of the class diagram and the problem of representing relationships between the structure and behavior diagram types as the key aspects for usability improvement.

With the modAT4rMS approach, a solution for these aspects for central PLC systems is proposed. In general, the modAT4rMS approach is intended to guide the user from the first step on through the modeling process to gain a highly modularized MS structure, including the functional relations of the system. Among other aspects, this is targeting to improve the detection of similar or identical objects, which proved difficult in previous studies, cf. Section II-B. Further central aspects are to reduce the required level of abstraction skills by the use of less abstract blocks instead of abstract classes and by the proposition of a strictly limited level of inheritance. In this section, the modAT4rMS structure and the behavior models are presented. As formal definitions are not the focus of this paper, and formalizations and transformations of similar diagrams have already been presented in several publications [18], [19], [26], [28], [29], [32], [37], only relevant metamodel descriptions and their connections to the UML and plcML are given for each notation showing the changes made in order to improve the effectiveness, efficiency, and acceptance of the model-driven OO PLC programming process. The metamodel for the modAT4rMS including the structure implementation, behavior implementation, and the connecting execution structure is shown in Fig. 1. For the corresponding specification and implementation of the UML class and state diagram and the basic activity diagram in an IEC 61131-3 environment, cf. [31], [32]. Also, a comprised synthetic description of plcML from [32], on which part of modAT4rMS is based on, is given in the Appendix. Subsequently, the notation's elements and features are described using exemplary structure and behavior models of a stamping unit, created in a prototypical editor.

A. Structure Model Notation

In the modAT4rMS structure model, the UML class element is called block, adapted from the SysML, and is defined as shown in Fig. 2. It shows the extended block properties (additional variant and object name) as well as its integrated blocks, while in the upper third of Fig. 1, the underlying metamodel is shown. These properties were added to improve the usability of the structure model notation, by lowering the level of abstraction in comparison using UML standard diagrams, which would require at least the class and object diagram to provide the same information. This metamodel allows creating an inherited block in order to create variants of blocks. The inheritance corresponds to an inherited class of the class diagram or block of the SysML Block Definition diagram and uses the metamodel's *HierarchyVariant* in order to provide information on its base block as well as the possibility to realize variants of blocks, cf. Fig. 1.

As a restriction to prevent the misuse of hardware descriptions through inheritance as software specifications, and vice versa, as well as in order to facilitate structure model comprehension, as deduced from the results in Section II-B, it is recommended to limit the inheritance depth to one. Through this limitation, there is always only one base for different variants of a block, which can be easily recognized by the base block name.

All blocks are specified in this manner, although the minimum functional level for a block is considered to be the sensor and actuator or component level. The level of the block is defined in the metamodel of modAT4rMS as the attribute *Type: Classtype* of the *Class*, cf. Fig. 1. A component block in the context of this paper represents the smallest unit integrated in an MS, e.g., sensors which supply only a signal value (digital/analog) and actuators which are being controlled by a single signal such as a simple valve. They are typically physically connected by a controller input or output. Aside from component level blocks, all other blocks can contain various other integrated blocks in their respective variant.

All blocks offer a functional interface through their methods and optionally their properties. This interface can only be accessed on the same hierarchy level or from the adjacent higher hierarchy level. Due to the strong hierarchy and the already large number of possible variants, the inheritance depth of one is deemed sufficient. Independent system functions are encapsulated in a *Systemclass*, cf. Fig. 1. As a limitation, the recommendation on inheritance depth is probably less capable to improve structure model comprehension for large-scale models with many different variants of modules and little reuse, due to the possibly resulting high number of overall classes in such a scenario.

The *Systemclass* and its functions are exclusively accessible from every hierarchy level, and therefore, should be used only for block independent functions. Areas, where deeper inheritance levels would be required, can be intercepted by a new conception for the base block or by an independent base in the form of an independent implementation-specific inserted block and are thus left to the user. In order to get an impression of the modAT4rMS's structural metamodel and its connection to the corresponding behavior metamodel, cf. Fig. 1.

An exemplary underlying structure model for a generic *Block_X* and its variants is shown in Fig. 3, and an approach for its creation is shown in the following. In a best practice manner for modAT4rMS model creation, it is recommended to model the most common variant as the base block and to create all other variants through the addition or adaption of functions, attributes, and integrated blocks, cf. Fig. 3 (*Block_X*, *Variant1*, and *Variant2*).

If the base block is chosen poorly at first and a new base block is in order, the modAT4rMS approach proposes changing the original base block into a variant block of this new base block. This is shown in Fig. 4 for the former base block *Block_X Variant3* and the new base for *Block_X*. All already existing variants of the original base block can become variants of the new base block, but keep their distinct functionalities, attributes, and integrated blocks from before, cf. Fig. 4. Through this proposed variant-handling approach, the user is easily capable of keeping the inheritance structure clear and without the need for further structure modeling notations as the class diagram. The actual structure model created by the user is oriented on the UML object diagram as it is created as a specific instance for a specific machine. Its metamodel including the connection to the behavior model is defined as shown in Fig. 1.

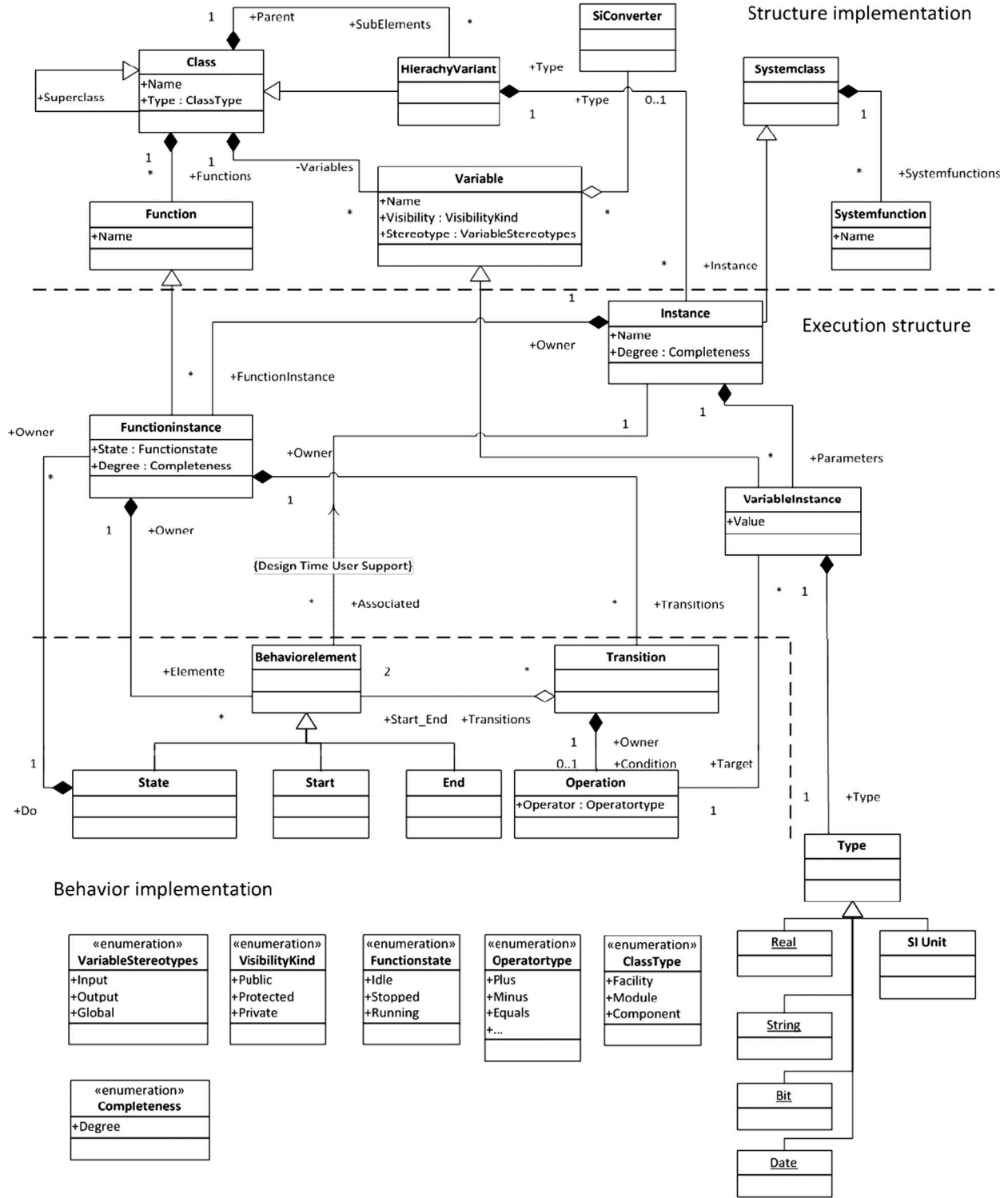


Fig. 1. Metamodel of modAT4rMS: upper-third structure implementation, middle execution structure, lower-third behavior implementation.

B. Behavior Model Notation

The behavior model is based on the fundamental ideas of the state and activity diagram of UML and, respectively, their plcML adaptations, cf. [31], [32]. The modAT4rMS behavior notation describes sequences within the set of functions defined in the respective structure model. The connection between the structure and behavior model is defined via the execution

structure depicted in Fig. 1. The graphical representation of the modAT4rMS adapts parts of the UML sequence diagram, as it uses object-specific columns divided by swim lanes, cf. Fig. 5. In contrast to the sequence diagram, the modAT4rMS behavior notation is capable of describing all scenarios of the modeled function. In order to create a clear connection between the structure and behavior model, the available objects are based on the

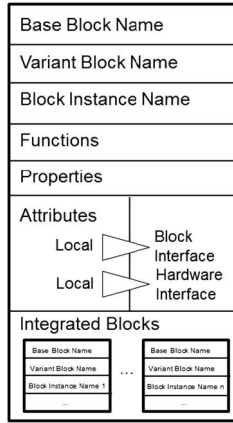


Fig. 2. modAT4rMS block definition.

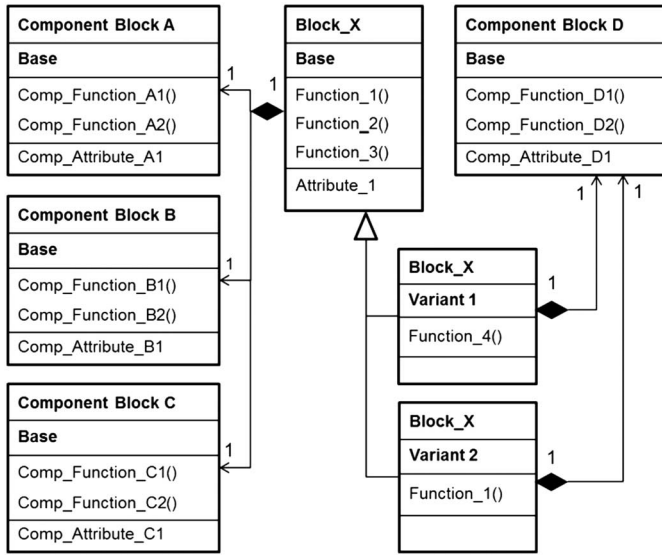


Fig. 3. Exemplary underlying modAT4rMS structure model for block variant handling (block instance names and further irrelevant details not depicted).

structure model of the function's host block. Additionally, the columns are structured into separate fields. In general, each field of the behavior diagram can be used to call one function (symbolized with an oval frame, cf. Fig. 5) or to access an attribute (symbolized with a rectangular frame, cf. Fig. 5) of the corresponding block, as defined in their structure model. The underlain metamodel defines states corresponding to the definition of the *Behaviorelement*, cf. Fig. 1, respectively, the state element of the plcML, cf. [31], [32]. The definitions in terms of cyclic execution as well as priorities and execution routines, such as "entry," "Do," "Exit," are also taken over completely from plcML, cf. [31], [32].

Functions and operations can also access the attributes of blocks (symbolized by a surrounding additional frame around the function call or operation and the corresponding attributes/parameters, as labeled in Fig. 5). Operations can use this feature only for condition forming, cf. Fig. 5 upper additional frame, whereas functions can use it if their structure model defines one or more function call parameters.

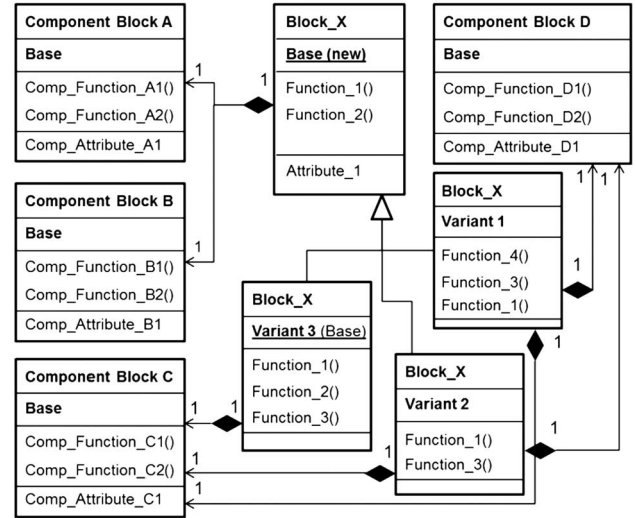


Fig. 4. modAT4rMS Block variant handling with base block change, original variant names in brackets, cf. Fig. 2 (irrelevant details not depicted).

A function call creates a *Functioninstance* and can contain several states in which operations or other functions are called. An operation is owned by a transition and either manipulates a *Variableinstance*, e.g., `Signal := 1` or describes a condition, e.g., `pressureSensor.Signal == 1`, cf. Fig. 5.

Start and end points are reused from the plcML activity diagram or, respectively, the plcML state-chart diagram. In regard to the cyclic nature of PLC program processing, all nodes in the behavior model are multicycle nodes, cf. [31], [32]. In short, a new PLC cycle is started after the operation/function is finished in the active node either before the operation/function is repeated in the next cycle or an enabled outgoing transition leads to a new active node.

Two types of transitions have been defined in modAT4rMS in order to connect start/end points: function calls and attribute operations, whereas the transition metamodel is reused from the plcML, cf. [31], [32]. The presentation of the necessary condition is achieved by a separate element. The default transition type for function calls is the Completion Transition, adapted from plcML, which executes the following function call only after the previous function has ended. The other type of transition uses attributes as switching conditions, e.g., sensor signals. For this condition, an attribute can either be compared to a fixed value, a function call parameter (cf. Fig. 5), or another attribute at the same hierarchy level. The use of the second type of transition makes it necessary to define how the conditions preceding function call is handled. It is possible to interrupt the function and continue with the next call at this point; another possibility is to interrupt the function and start the function from its beginning when it is next called or to let the function continue.

C. modAT4rMS-Modeling Example

In order to evaluate the developed modAT4rMS approach, a prototypical model editor was created, which was used to create the modeling example that is described in the

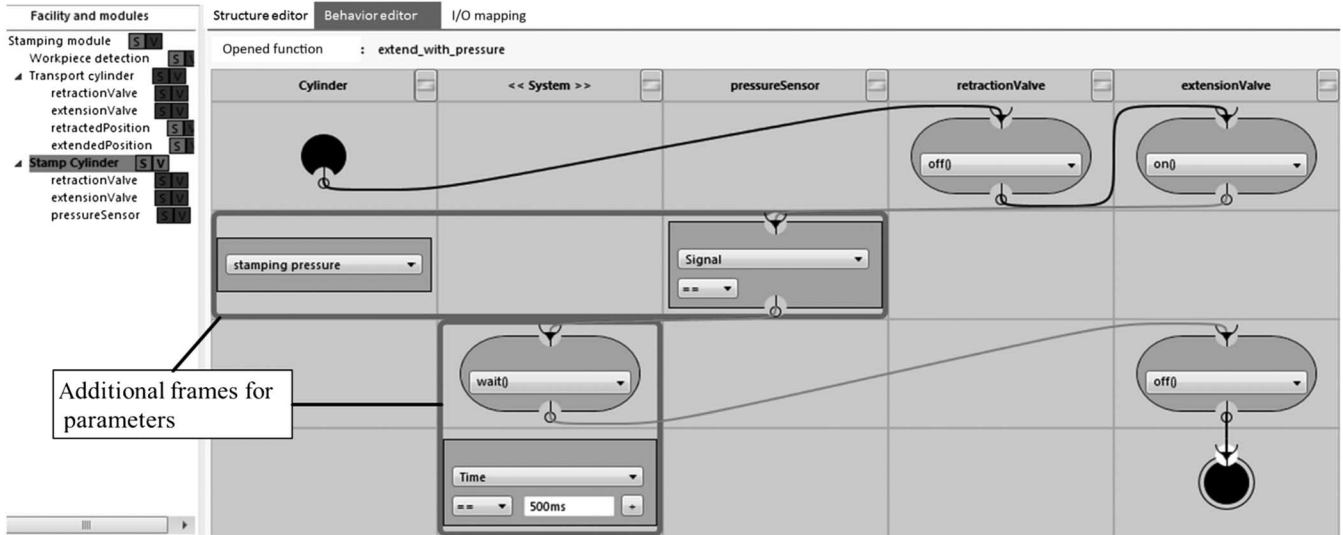


Fig. 5. Exemplary behavior model for a stamping cylinder function in the developed editor.

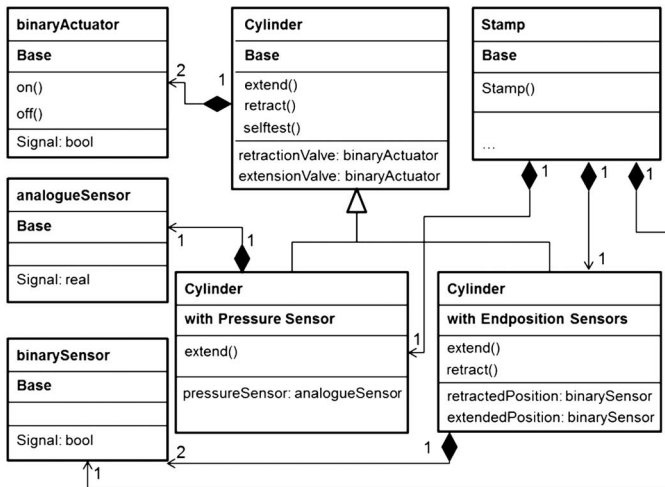


Fig. 6. Simplified underlying structure model of the modAT4rMS-modeling example (not visible in the modAT4rMS editor).

following. It applies the modAT4rMS approach for an automation example of a stamping unit. Fig. 6 shows the underlying structure model of the example, whereas Fig. 7 shows the modAT4rMS depiction of the Stamp module and a part of the developed graphical user interface, used in the evaluation, cf. Section IV.

In order to facilitate the creation of the users' mental models of the system, and therefore, the creation of the software model, technical sketches, or pictures of the corresponding hardware modules can optionally be put in the editor's background, and only integrated blocks of the next lower hierarchy level of the block are shown. The abstraction level of the structure diagram of modAT4rMS is reduced by giving the block name, variant name, and instance name in one diagram additionally to its attributes, interfaces, and functions. This aims to lower the subjective workload and to rise the efficiency of the modeling process.

For the *Stamp* block, shown in Fig. 6, this means two different pneumatic cylinder variants created from the same base cylinder are integrated as well as one *binarySensor* block, cf. also Fig. 7.

The *Transport Cylinder* is a cylinder variant, which possesses two additional binary end position sensors, cf. Fig. 6. The *Stamp Cylinder* variant includes an analog pressure sensor, cf. Fig. 7 (lower half) and Fig. 6 (*pressureSensor*). The base cylinder block (cf. Fig. 6, not shown in Fig. 7) integrates two *binaryActuator* blocks, which are controlled by the cylinder functions *extend()* and *retract()*. Both cylinder block variants inherit the two valves from the base cylinder, cf. Fig. 6. The functional interface in the form of a collection of functions (*extend()*, *retract()*, and *selftest()*) also is inherited, which is symbolized through a padlock symbol in front of the function names, cf. Fig. 7 (lower half). If a function of the block variant has been altered, the padlock is opened, if not it is closed. Additionally to his inherited functions, the variant includes a new function, which can be recognized by a key symbol in front of the function name. In combination with the limitation of inheritance depth to one, this enables a quick overview of structure dependence between base and variant blocks without the need to use an additional structure notation. Continuing the modeling example of the stamping unit, the behavior model for the adapted *extend()* function of the stamping cylinder will be discussed in the following and is shown in Fig. 5.

The functions and attributes of these blocks can be used to create the behavior model for functions of the *Stamp Cylinder*, such as the *extend()* function, cf. Fig. 5. All integrated blocks are shown in the top row of the behavior model, divided by swim lanes. This facilitates the representation and, respectively, recognition of the structural context of the corresponding behavior model, as demanded in the results of Section II-B. Additional fields, always present in the top row, are the block itself and the so-called system or library functions. The system or library functions are exempt from all inheritance and access

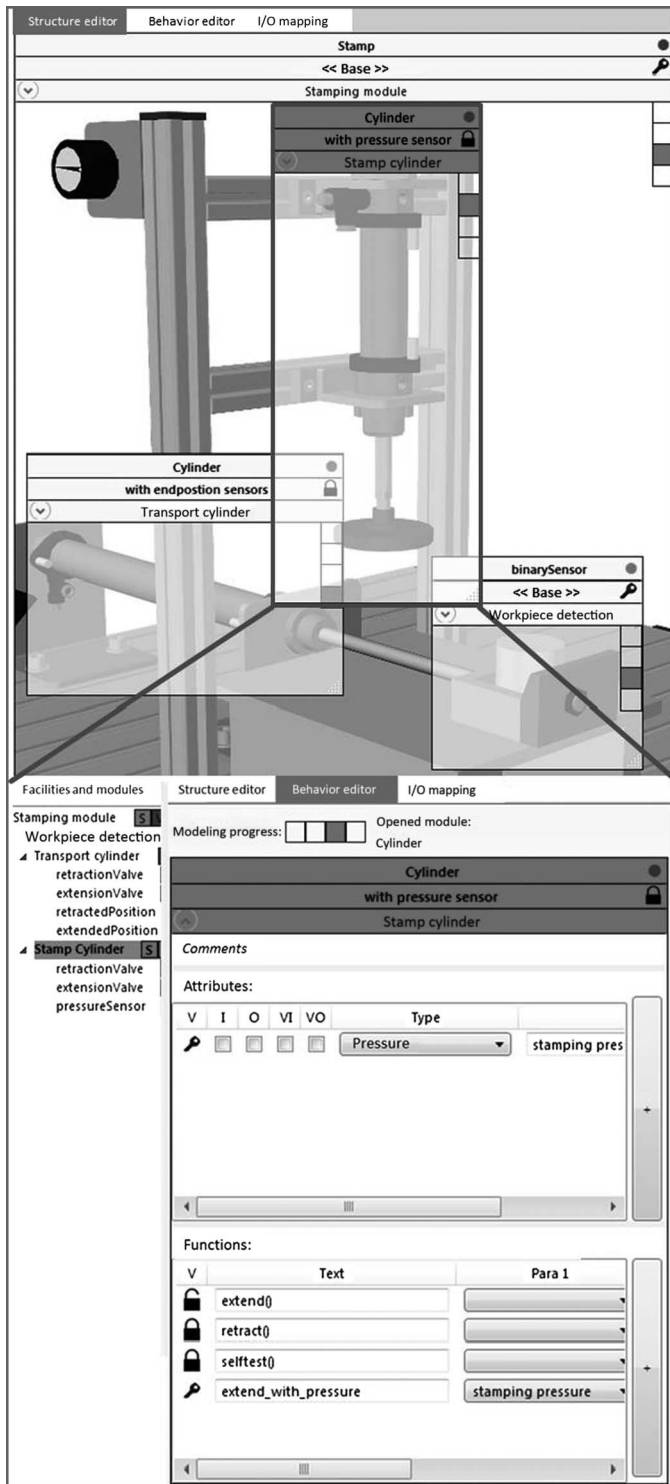


Fig. 7. Exemplary structure model for the *Stamp* unit in the developed editor.

limitations defined in this paper. This is necessary to ease the use of programming environment tools such as logic operations, timers, and independently implemented standalone software functions. On the one hand, these cannot be assigned to any block, and on the other hand, it makes no sense to implement them anew in the modAT4rMS diagrams, rather than reusing their high-level language implementations. Therefore,

these functions are handled in a black-box manner, only offering an interface for the user with the possibility to transfer parameters for the function call.

IV. EVALUATION

In order to evaluate the new modAT4rMS notations, an experimental study was conducted, comparing it to the state-of-the-art IEC 61131-3 FBD and the domain-specific plcML notation. The study took place from November 2012 until January 2013 at the Technische Universität München (1-day training, 1-day experimentation per group). The sample of 168 participants consisted of five school classes (three beginner second year classes, two intermediate third year classes) from a vocational school for production engineering in Munich with specialization in mechatronics, as these apprentices form the relevant group of novice and intermediate PLC programmers in Germany, and two expert classes consisting only of industrial practitioners with several years of work experience from a school for state-certified technicians in Munich. Programming performance was measured by the level of task completion, cf. [4]. In addition, user acceptance aspects, the subjective ease of use, frustration, and usability were measured using scaled questions on the aspects defined in [33] and [36]. Similar to the previous studies in Section II-B, the task completion measure was used to evaluate the programming performance, respectively, the effectiveness. The analysis of the model and code was carried out by two evaluators per notation in order to verify the objectivity of the evaluation method through the level of agreement using Cohen's Kappa coefficient [38]. This provides an objective basis as a prerequisite for a correct evaluation. In order to analyze the results, the inferential statistics method of multivariate analysis of variance (MANOVA) was used in combination with *post hoc* Scheffé tests, cf. [39]. In principle, this test allows analyzing the variance of results between more than two groups of results in order to test for significant differences between the different group-pairs directly, e.g., between plcML and FBD, modAT4rMS and FBD, etc. For the probability of results occurring by chance (*p*-value), the threshold of 5% for significant and <1% for highly significant differences were used. The automation problem for testing the approach was adapted from industrial practice, where it is used as a final exam for PLC programmers after at least 3 years of training. In cooperation with PLC programmers from industrial contacts (e.g., Liebherr-Verzahnstechnik GmbH) and PLC and automation teachers of the vocational school of the participants, the test was validated, to be generalizable for automation problems in industrial practice and in teaching. The given task includes the creation of a control program model for an MS consisting of five transport portals and four processing units (overall using 100 I/Os). This task was divided in three sub-tasks: 1a (creation of portals 1–4 and processing units 1–3, 74 I/Os), 1b (creation of portal 5 and processing unit 4 as specialized variants, 26 I/Os), and 1c (modification of functions calls with parameters for portals 1–4 and processing units 1–4) for which 60 min (1a), 50 min (1b), and 25 min (1c) were given.

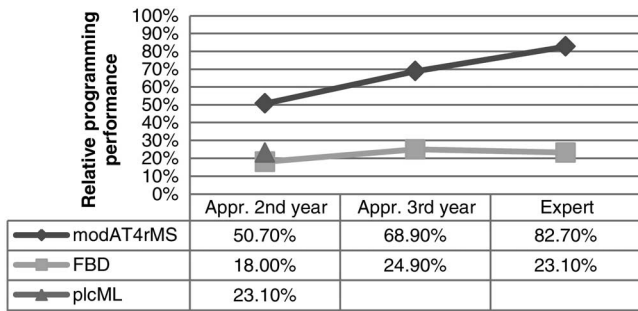


Fig. 8. Results on relative overall programming performance in the model creation subtask 1a.

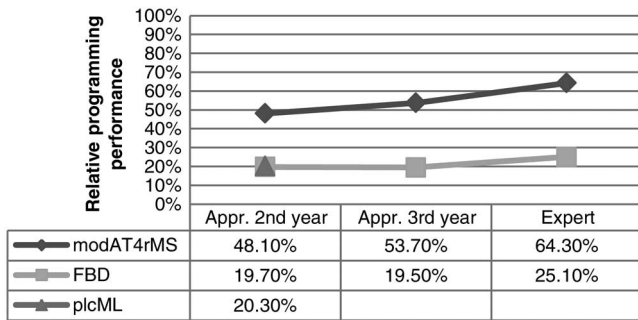


Fig. 9. Results on relative overall programming performance in the model creation and reuse subtask 1b.

Further detail on the experimental design and a full description of all further measured variables and results will be published in papers focusing on these additional aspects as soon as all necessary data are processed.

A. Results on Programming Performance

All results on programming performance (task completion) for each test task are presented in relation to the experience level of the participants, cf. Figs. 8–10. The results on the overall programming performance in the model creation task 1a showed highly significant effects ($p < 0.001$) in favor of modAT4rMS, cf. Fig. 8.

There was a significant interaction effect between notation and experience. As depicted in Fig. 8, the more experienced groups profited more of the modAT4rMS notations than the lesser experienced; although no prior experience in modAT4rMS modeling was present. The results for the overall programming performance in the model creation and reuse task 1b also showed highly significant effects ($p < 0.001$) in favor of modAT4rMS, cf. Fig. 9.

Between the IEC 61131-3 FBD and the plcML, no significant difference occurred and no significant interaction effects between experience and programming performance were measured.

Fig. 10 shows the results of subtask 1c, which required modifying existing functions to become parameterized functions and to integrate them into the existing control programs.

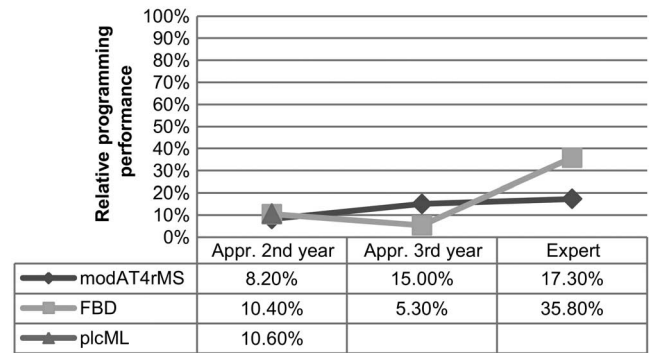


Fig. 10. Results on relative overall programming performance in the modifying existing functions subtask 1c.

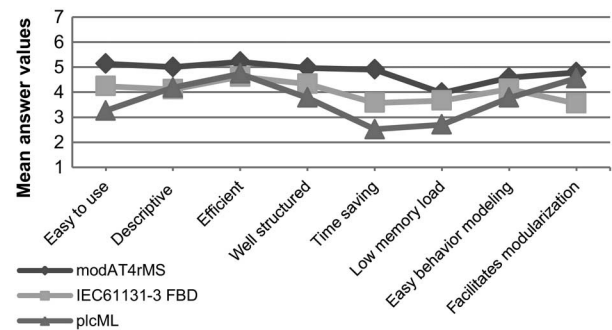


Fig. 11. Results on subjective feedback questionnaire (scale from 1 = statement not fitting at all to 7 = statement completely fitting).

The MANOVA showed no significant differences between the notations alone with regard to programming performance for this subtask ($p = 0.549$), but a significant interaction effect between the notation and experience levels ($p = 0.032$), in favor of the expert level using FBD and the third year level using modAT4rMS, cf. Fig. 10.

B. Results on the Subjective Usability: Ease of Use, Frustration, and Workload

The workload differed significantly ($p < 0.001$) with respect to the used programming notation. The *post hoc* Scheffé test showed that the groups who worked with the notations of modAT4rMS experienced highly significantly less stress than the comparison notations of the IEC 61131-3 FBD ($p < 0.001$) and the plcML ($p = 0.001$). No differences were found between IEC 61131-3 and the plcML ($p = 0.999$). Furthermore, the experience of the subjects showed no significant effect on workload ($p = 0.469$). Also, no interaction effects ($p = 0.837$) were observed.

Just as with workload, the analysis of the frustration data showed highly significant results ($p < 0.001$). The evaluation of the *post hoc* Scheffé tests showed again that subjects who worked with the notations of modAT4rMS were highly significantly less frustrated than the subjects with the comparison notations of IEC61131-3 FBD ($p < 0.001$) and the plcML ($p = 0.001$). No significant differences were found between IEC61131-3 FBD and the plcML ($p = 0.433$). Furthermore, the

experience of the subjects showed no significant effect on their stated frustration ($p = 0.714$). Also, no significant interaction effects ($p = 0.134$) were observed.

The mean subjective questionnaire values for the used modeling notations are shown in Fig. 11. The statements were in the form of “The used notation is/causes. . .” Overall modAT4rMS received the most positive feedback, whereas plcML and IEC 61131-3 FBD received mixed feedback, cf. Fig. 11.

C. Discussion of the Results

The programming performance of subjects when creating a new PLC program model indicates clear advantages of the modAT4rMS notations, cf. Figs. 8 and 9. Because of the interaction effects (experience * notation), the better programming performance of the subjects in programming the system behavior cannot be considered separately. However, the results show clear performance differences in favor of modAT4rMS notations. Furthermore, the results on the programming performance in terms of the experience in PLC programming show mostly a particularly positive effect on the modAT4rMS notations, cf. Fig. 8. Only for the subtask on modifying existing functions 1c, FBD seems to profit stronger than modAT4rMS from the experts’ experience in IEC 61131-3. The subjective answers on workload, frustration, and further usability aspects, all show a highly significant positive effect of the modAT4rMS notations. Overall, the gained results show that the developed notations offer an objective and subjective significantly better usable alternative to existing notations in order to promote model-driven OO programming for PLCs in the MS field. The results on the compared plcML and modAT4rMS notations, both with the same formal basis, also show that an improvement in usability does not necessarily require a different formal basis.

V. CONCLUSION AND OUTLOOK

In this paper, the modAT4rMS approach for the creation of well-structured and comprehensible PLC software was presented. The goal of this new approach was to facilitate the use of OO programming in machine and plant automation by providing domain-specific modeling notations. Problems during the structure and behavior creation were identified in previous studies and were taken into account in the development of the modAT4rMS. The final modAT4rMS notations significantly eased former problems as shown in the results of the empirical evaluation. In all but one of the presented programming subtasks, the modAT4rMS proved significantly superior, and the subjective results are in favor of the developed approach as well.

Based on these results, the proposed block and component-based structure of the control software should also provide a good basis to communicate with the domain of mechanical and process engineering as well with PLC programmers. As the data analysis of the conducted evaluation experiment is still ongoing, further results on the proposed structure abstraction layer, occurred errors, etc., will be presented in future work. As the modAT4rMS metamodel is based on the plcML, its notations can be transformed to real-time-capable IEC 61131-3 code and

could possibly be integrated into an IEC 61131-3 programming environment in the future.

REFERENCES

- [1] A. L. Ramos, J. V. Ferreira, and J. Barceló, “Model-based systems engineering: An emerging approach for modern systems,” *IEEE Trans. Syst. Man, Cybern. C, Appl. Rev.*, vol. 42, no. 1, pp. 101–111, Jan. 2012.
- [2] International Electrotechnical Commission, “IEC International Standard IEC 61131-3: Programmable Logic Controllers, Part 3: Programming Languages,” Feb. 2003.
- [3] K. Thramboulidis, “Towards a model-driven IEC 61131-based development process in industrial automation,” *J. Softw. Eng. Appl.*, vol. 4, no. 4, pp. 217–226, 2011.
- [4] B. Vogel-Heuser, S. Braun, M. Obermeier, F. Jobst, and K. Schweizer, “Usability evaluation on teaching and applying model-driven object oriented approaches for PLC software,” in *Proc. Amer. Control Conf. (ACC)*, Montréal, Canada, 2012, pp. 4463–4469.
- [5] V. Vyatkin, “Software engineering in industrial automation: State-of-the-art review,” *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1234–1249, Aug. 2013.
- [6] BECKHOFF New Automation Technology [Online]. Available: <http://www.beckhoff.de/default.asp?twincat/default.htm>, accessed on Jul. 22, 2014.
- [7] H. Mili, F. Mili, and A. Mili, “Reusing software: Issues and research directions,” *IEEE Trans. Softw. Eng.*, vol. 21, no. 6, pp. 528–562, Jun. 1995.
- [8] F. Ricca, M. Di Penta, M. Torchiano, and P. Tonella, “How developers’ experience and ability influence web application comprehension tasks supported by UML stereotypes: A series of four experiments,” *IEEE Trans. Softw. Eng.*, vol. 36, no. 1, pp. 96–118, Jan. 2010.
- [9] K. Thramboulidis and G. Frey, “Towards a model-driven IEC 61131-based development process in industrial automation,” *J. Softw. Eng. Appl.*, vol. 4, no. 4, pp. 217–226, 2011.
- [10] A. Zoitl and V. Vyatkin, “IEC 61499 architecture for distributed automation: The ‘Glass Half Full,’” *IEEE Ind. Electron. Mag.*, vol. 3, no. 4, pp. 7–23, 2009.
- [11] V. Hajarnavis and K. Young, “An assessment of PLC software structure suitability for the support of flexible manufacturing processes,” *IEEE Trans. Autom. Sci. Eng.*, vol. 5, no. 4, pp. 641–650, Oct. 2008.
- [12] C. Fantuzzi, M. Bonfe, F. Fanfoni, and C. Secchi, “A design pattern for translating UML software models into IEC 61131-3 programming languages,” in *Proc. 18th IFAC World Congr.*, Milano, Italy, 2011, pp. 9158–9163.
- [13] OMG. (2011, Aug.). *UML 2.4.1* [Online]. Available: <http://www.omg.org/spec/UML/2.4.1/>, accessed on Jan. 24, 2013.
- [14] K. Thramboulidis, “Model-integrated mechatronics—Toward a new paradigm in the development of manufacturing systems,” *IEEE Trans. Ind. Informat.*, vol. 1, no. 1, pp. 54–61, Feb. 2005.
- [15] C. Secchi, M. Bonfé, C. Fantuzzi, R. Borsari, and D. Borghi, “Object-oriented modeling of complex mechatronic components for the manufacturing industry,” *IEEE ASME Trans. Mechatron.*, vol. 12, no. 6, pp. 696–702, Dec. 2007.
- [16] C. Secchi, M. Bonfe, and C. Fantuzzi, “On the use of UML for modeling mechatronic systems,” *IEEE Trans. Autom. Sci. Eng.*, vol. 4, no. 1, pp. 105–113, Jan. 2007.
- [17] F. Basile, P. Chiacchio, and D. Gerbasio, “On the implementation of industrial automation systems based on PLC,” *IEEE Trans. Autom. Sci. Eng.*, vol. 10, no. 4, pp. 990–1003, Oct. 2013.
- [18] C.-H. Huang and P.-A. Hsiung, “Model-based verification and estimation framework for dynamically partially reconfigurable systems,” *IEEE Trans. Ind. Informat.*, vol. 7, no. 2, pp. 287–301, May 2011.
- [19] J. Kim, I. Kang, J.-Y. Choi, and I. Lee, “Timed and resource-oriented statecharts for embedded software,” *IEEE Trans. Ind. Informat.*, vol. 6, no. 4, pp. 568–578, Nov. 2010.
- [20] I. Bicchierai, G. Bucci, L. Carnevali, and E. Vicario, “Combining UML-MARTE and preemptive time Petri nets: An industrial case study,” *IEEE Trans. Ind. Informat.*, vol. 9, no. 4, pp. 1806–1818, Nov. 2013.
- [21] OMG, “A UML Profile for MARTE, Version 1.1,” Object Manag. Group, Jun. 2011.
- [22] K. Thramboulidis, “The 3+1 SysML view-model in model integrated mechatronics,” *J. Softw. Eng. Appl.*, vol. 3, no. 2, pp. 109–118, 2010.
- [23] L. Bassi, C. Secchi, M. Bonfé, and C. Fantuzzi, “A SysML-based methodology for manufacturing machinery modeling and design,” *IEEE ASME Trans. Mechatron.*, vol. 16, no. 6, pp. 1049–1062, Dec. 2011.

- [24] G. DeTommasi, R. Vitelli, L. Boncagni, and A. C. Neto, "Modeling of MARTE-based real-time applications with SysML," *IEEE Trans. Ind. Informat.*, vol. 9, no. 4, pp. 2407–2415, Nov. 2013.
- [25] D. Hästbacka, T. Vepsäläinen, and S. Kuikka, "Model-driven development of industrial process control applications," *J. Syst. Softw.*, vol. 84, no. 7, pp. 1100–1113, Jul. 2011.
- [26] D. N. Ramos-Hernandez, P. J. Fleming, and J. M. Bass, "A novel object-oriented environment for distributed process control systems," *Control Eng. Pract.*, vol. 13, no. 2, pp. 213–230, Feb. 2005.
- [27] U. Katzke and B. Vogel-Heuser, "Combining UML with IEC 61131-3 languages to preserve the usability of graphical notations in the software development of complex automation systems," *Anal. Des. Eval. Hum.-Mach. Syst.*, vol. 10, pp. 90–94, 2007.
- [28] E. Estévez, M. Marcos, and D. Orive, "Automatic generation of PLC automation projects from component-based models," *Int. J. Adv. Manuf. Technol.*, vol. 35, no. 5–6, pp. 527–540, Jul. 2007.
- [29] N. Papakonstantinou and S. Sierla, "Generating an object oriented IEC 61131-3 software product line architecture from SysML," in *Proc. IEEE 18th Conf. Emerg. Technol. Fact. Autom. (ETFA)*, Cagliari, Italy, 2013, pp. 1–8.
- [30] N. Papakonstantinou, S. Sierla, and K. Koskinen, "Object oriented extensions of IEC 61131-3 as an enabling technology of software product lines," in *Proc. 16th IEEE Conf. Emerg. Technol. Fact. Autom. (ETFA)*, Toulouse, France, 2011, pp. 1–8.
- [31] D. Witsch and B. Vogel-Heuser, "PLC-statecharts: An approach to integrate UML-statecharts in open-loop control engineering—Aspects on behavioral semantics and model-checking," in *Proc. 18th IFAC World Congr.*, Milano, Italy, 2011, vol. 18, pp. 7866–7872.
- [32] D. Witsch, "Modellgetriebene Entwicklung von Steuerungssoftware auf Basis der UML unter Berücksichtigung der domänenspezifischen Anforderungen des Maschinen- und Anlagenbaus," Ph.D. dissertation, Technische Universität München, Lehrstuhl für Automatisierung und Informationssysteme, München, Germany, 2013.
- [33] European Committee for Standardization, "Ergonomic requirements for office work with visual display terminals (VDTs)—Part 11: Guidance on usability (ISO 9241-11: 1998)," Beuth Verlag GmbH, 1998.
- [34] B. Vogel-Heuser *et al.*, "Evaluation of a UML-based versus an IEC 61131-3-based software engineering approach for teaching PLC programming," *IEEE Trans. Edu.*, vol. 56, no. 3, pp. 329–335, Aug. 2013.
- [35] S. Braun, M. Obermeier, and B. Vogel-Heuser, "Usability challenges in the design workflow of reusable PLC software for machine and plant automation," in *Proc. 9th Int. Multi-Conf. Syst. Signals Devices (SSD)*, 2012, pp. 1–6.
- [36] S. G. Hart and L. E. Stavenland, "Development of NASA-TLX (task load index): Results of empirical and theoretical research," in *Human Mental Workload*, P. A. Hancock and N. Meshkati, Eds. Amsterdam, The Netherlands: Elsevier, 1988, pp. 139–183.
- [37] E. Estevez and M. Marcos, "Model-based validation of industrial control systems," *IEEE Trans. Ind. Informat.*, vol. 8, no. 2, pp. 302–310, May 2012.
- [38] J. Cohen, "A coefficient of agreement for nominal scales," *Edu. Psychol. Meas.*, vol. 20, no. 1, pp. 37–46, Apr. 1960.
- [39] H. Scheffé, *The Analysis of Variance*. Hoboken, NJ, USA: Wiley, 1959.



Martin Obermeier received the Dipl.Ing. degree in mechanical engineering (focus on control theory and information technology) from the Technische Universität München, München, Germany, in 2009. He is currently pursuing the Ph.D. degree at the Institute of Automation and Information Systems, Technische Universität München.

He is an Alumni with the Institute of Automation and Information Systems, Technische Universität München. His research interests include the design and evaluation of model-based programming software for automation systems in regard to model quality, modularity aspects, and usability.



Steven Braun received the Dipl.Ing. degree in mechanical engineering (focus on mechatronics and information technology) from the Technische Universität München, München, Germany, in 2008, and received the Ph.D. degree in mechanical engineering from the Institute of Automation and Information Systems, Technische Universität München, in 2014.

He is an Alumni with the Institute of Automation and Information Systems, Technische Universität München. His research interests include the design and evaluation of model-based programming software for automation systems.



Birgit Vogel-Heuser (M'04–SM'12) received the Dipl.Ing. degree in electrical engineering in 1987, and the Ph.D. degree in mechanical engineering from the Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen, Aachen, Germany, in 1991.

She is a Full Professor and Director with the Institute of Automation and Information Systems, Technische Universität München, München, Germany. She worked for nearly 10 years in the industrial automation for machine and plant manufacturing industry. After holding different chairs of automation in Hagen, Wuppertal, and Kassel, Germany, she has been the Head of the Automation and Information Systems Institute, Technische Universität München, since 2009. Her research interests include modeling and education in automation engineering for hybrid process and heterogeneous distributed and intelligent systems using a human centered approach.

Prof. Vogel-Heuser is a Member of the VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik (National Member Organization of the International Federation of Automatic Control). She received four awards, the Special Award of the Initiative D21 Women in Research (2005), the Borchers Medal of the RWTH Aachen (1991), the GfR Sponsorship Award (1990), and the Adam Opel Award (1989).