Model Engineering for Complex Systems

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Complex systems are hard to define [1]. Nevertheless they are more and more frequently encountered. Examples include a worldwide airline traffic management system, a global telecommunication or energy infrastructure or even the whole legacy portfolio accumulated for more than thirty years in a large insurance company. There are currently few engineering methods and tools to deal with them in practice. The purpose of this Dagstuhl Perspectives Workshop on Model Engineering for Complex Systems was to study the applicability of Model Driven Engineering (MDE) to the development and management of complex systems.

MDE is a software engineering field based on few simple and sound principles. Its power stems from the assumption of considering everything – engineering artefacts, manipulations of artefacts – as a model [3]. Our intuition was that MDE may provide the right level of abstraction to move the study of complex systems from an informal goal to more concrete grounds. In order to provide first evidence in support of this intuition, the workshop studied different visions and different approaches to the development and management of different kinds of complex systems.

Challenges of Complex Systems

There are a number of examples of complex biological, ecological or societal complex systems discussed in the literature [5]. In the context of this seminar, we were interested predominantly in Computer Based Complex Systems (CBCS), i.e. complex systems with a significant number of hardware or software components [16]. These parts may be processing elements (processors, programs, processes, etc.) or data elements (memory, disks, repositories, files, etc.) or any kind of composite elements (hardware and software). One of the most important characteristics of such a complex system is that it is composed of a very large number of individual parts. The interactions between these parts are not random and they follow specific patterns. Very often these relationships are informally characterized but in some occasions they may be explicitly represented. In either case they are quite important. By definition, a CBCS may not be understood by one unique human operator. On the contrary, many stakeholders will have different views on the system. These stakeholders may play different roles (architect, designer, implementer, maintainer, manager, user, etc.)

A CBCS is constantly in *evolution* with a past history, a present, and a future. This evolution is the consequence of the various interactions between the parts of the system. The evolution is permanent, i.e. the CBCS usually never stops, even when some parts are added, removed exchanged or under maintenance or repair.

A CBCS has a structure (or static architecture) and a dynamic behaviour. It is composed of elements that may themselves be CBCSs (with structure and behaviour) and no limit exists on this deep nesting. In addition to structure and behaviour, a CBCS also has a goal defining its purpose in the *context* in which it is operating. As previously stated, this also applies to any component of this system. Important information is also the metadata associated to any component, but the categories of metadata are quite diverse.

Another dimension of a CBCS is *engineering heterogeneity*. Many components are hardware and software elements produced in the last fifty years, with different types of technologies. For example many different hardware technologies, programming languages, APIs, operating systems, database organizations, network protocols, standards, or normative specifications have been used. Furthermore there may be a penalty to the use of any technology. This is often called *accidental* complexity by Fred Brooks [4], and it adds an artificial portion to the *essential* complexity of the base problem. Managing the accidental complexity accumulated by many layers of technological legacy is an important challenge in the management of CBCSs.

A CBCS is also often a *distributed system*, i.e. its elements are located on many widely dispersed physical locations.

An additional property of CBCS is *emergence*. Emergence is the way complex systems and patterns arise out of a multiplicity of relatively simple

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interactions. Emergence is central to the theories of integrative levels and of complex systems. Emergence particularly makes engineering CBCS challenging because the behaviour of the overall system is difficult, if not impossible to predict from the behaviour of the individual components and connectors that make it up.

Requirements for Engineering of CBCS

Overall, the workshop identified the following critical requirements for engineering of CBCS:

- **Dealing with Size:** Since such systems are large, they should be constructed from multiple different viewpoints. There was much discussion at the workshop on the challenges of integrating and reconciling different views (and hence viewpoints) in the CBCS engineering process.
- **Dealing with Heterogeneity:** An overall engineering technology has to bridge different technologies, even from different communities. A particular challenge that was noted at the workshop was the ability to be able to *replace* CBCS elements at run-time, i.e., as the CBCS was attempting to accomplish its goals. A novel flavour of this kind of run-time adaptation was the situation where the replacement is heterogeneous, i.e., where software needs to be replaced by hardware elements, and vice versa.
- **Dealing with Distribution:** Many of the challenges associated with distribution are not new and restricted to CBCS or MDE, but are inherent issues.
- **Dealing with Dynamicity:** Dynamicity combined with distribution poses particular challenges for development. There is the tension between dynamicity and criticality: it is inherently difficult to predict the behaviour of dynamic systems, yet predictability is essential in order to verify and validate a critical CBCS. There was some discussion on the use of contracts and lightweight static analysis for supporting critical CBCS development.
- **Dealing with Autonomy:** CBCS exist that are constructed from autonomous individual components that are themselves capable of carrying out function and attempting to achieve goals. As discussed at the workshop, modeling may be well suited to building individual components that behave in a predictable way, but at the moment it is not clear how to integrate autonomous components using modeling in a disciplined and predictable way, so as to achieve system level goals. That being said, it was noted that this was not a specific difficulty with modeling: rather, it was one of the major challenges in building CBCS.

Model Driven Engineering (MDE)

MDE considers models as first class citizens. A model is a representation of a system (relation *repOf* in Figure 1) and the nature of the model is defined by its metamodel. We say that a model conforms to its metamodel (relation *c2* in *Figure 1*)..

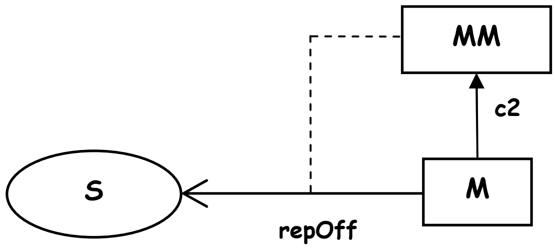

***Figure 1*. The two basic relationships of MDE**

MDE is mainly built on top of these two basic relations of *representation* and *conformance*, like object technology was mainly based on the relations of *instantiation* and *class inheritance*. MDE may be implemented with the help of object technology (or any other like functional). However the basic paradigms of MDE are inherently different from those of object technology.

Any system can be represented by a model. Then, we are able to give a homogeneous representation of a heterogeneous situation or phenomenon.

Metamodels are used as filters to define matter of interest in the system (viewpoints). Used as a typing system, they provide precise semantics to artefacts and relations between these artefacts. This homogeneity of definition of metamodels and models give us the power to apply operations on them in a generic way. Model-to-model transformations encode those operations.

A system can be "filtered" by more than one metamodel. As a complex system can not be understood and managed from one single point of view, being able to have different representations of this system is of great interest. For instance, we can imagine having a model of the static structure of a software application and a model of its execution trace (method calls, etc.) Moreover, as those representations are of the same system, they bear some relations (weaving models).

MDE provides some principles and tools to manage complex systems. But it is not sufficient by itself. The distribution and the handling of numerous artefacts, representation of complex systems as composition of artefacts that may be complex themselves are not addressed directly by MDE.

Applying MDE to CBCS

Managing a CBCS means observing, understanding, and controlling it. However management may imply additional operations like designing it, constructing it, measuring it, managing it, maintaining it, and many more. So, which support can MDE bring to all these operations on CBCS?

Learning from specific communities. Many participants noted that some of the challenges noted were inherent to system engineering in general (particularly issues of size and distribution, and to a lesser extent heterogeneity). They pointed out to investigate specific solutions to challenges of heterogeneity and dynamicity from other communities. For example, it was noted that the database community had well-defined principles and practices for handling heterogeneity in both databases and database management technology and that – at least conceptually – some of these ideas could be usefully applied to CBCS and integrated into state-of-the-art MDE technology as well. The debate on this issue seemed to focus on whether the MDE community understood how to efficiently model behaviour and semantics in a way that allowed their tooling to continue to be used.

Modeling autonomy. A number of participants noted that one rich area for consideration in MDE for CBCS was in dealing with autonomous systems [11], [9]. Such systems – which may be self configuring, self healing, self optimizing – could apparently be at least partly addressed by current MDE techniques, but new ideas from the run-time systems management community (particularly for specifying "safe" or "acceptable" reconfigurations) were needed. On the other hand, several participants from the more traditional complex systems community noted that some of these kinds of systems were inherently challenging, if not impossible, to manage – e.g., bio-inspired systems – and that hoping to capture all the parameters of a "safe" or "acceptable" reconfiguration would be exceptionally difficult. One proposal for dealing with this was to exploit simulation technology – something that MDE can be used to support – to help to predict different possible reconfigurations that might arise, and to use simulation data to help manage, control, or at least direct the path of reconfiguration. This appears to be a challenging, yet likely fruitful direction of future research.

Bridging heterogeneous modelling spaces. At present, MDE in a modelling space is based on a specific, single metalanguage. Modeling complex systems with MDE, however, must deal with many different modeling spaces, also from different engineering sciences. That implies that an MDE for CBCS needs to bridge the gap between metalanguages, modelling approaches, and even modelling communities.

Industrial needs. There was also discussion on industrial needs for MDE and CBCS. Participants discussed the benefits from having process support for MDE of CBCS (i.e., to support documenting and describing the engineering lifecycle), as well as challenges in integrating with legacy components and sub-systems. Technology for model understanding (or model "grokking") was presented that may help with this. Finally, the challenges of verification and validation of CBCS on an industrial scale were summarized and led to much debate that linked in to earlier discussions at the workshop on viewpoints and view integration [15,17]. The feeling was that individual verification technology (such as model checking, static analysis, or theorem proving) was insufficient and that integrated tool chains and workbenches for MDE were needed. Several examples of applying MDE to CBCS were discussed like megamodeling [2], [6], global traceability [8], model weaving [12], model merging [13], action semantics [14], etc.

Conclusion

The workshop has led to increased understanding of the fundamental characteristics of complex systems, the challenges of engineering them, the features for doing this that are currently offered by MDE, and several interesting future directions for research in MDE. Many participants noted that some of the challenges that were discussed had nothing to do with CBCS and MDE, but were simply challenges of building modern large-scale systems. However, it was acknowledged that MDE solutions for complex systems needed to address these challenges as well.

This workshop initiated through efforts in the ModelPlex European Integrated project (2006-2009). You can find more information about the Perspectives Workshop at http://www.dagstuhl.de/08331. The full

manifesto can be obtained at http://drops.dagstuhl.de/portals/08331.

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