Towards defining the role of AD in the data driven age of systems engineering

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Abstract. In 2018 Boeing defined the Diamond model as a framework for model-based engineering. The Diamond model extends the V-Model with a top part in which models are developed, mirroring the V-Model design phases, and used mirroring the V-Model test phases. In this paper we present a model inspired by the diamond model linking model based engineering to axiomatic design. Combining both design methods could have benefits for creating better axiomatic designs and better system models leading to a better physical system together with a digital representation of that same system (a digital twin).

Keywords: Axiomatic Design, Diamond Model, Digital Twinning, Model-based engineering.

1 Introduction.

The Unified Modeling Language UML [1] has been a software modeling standard since 1987 and has been used for decades as a graphical language to represent software designs. At the time of the development of SysML [2] the term Model Based Systems Engineering (MBSE) [3] or in short Model Based Engineering (MBE) or Model Based Design (MBD) was created. In the last decade MBE has become a common method for engineering large scale (complex) systems. In recent years digital twinning [4] has also become popular. A digital twin is a virtual model of a system. A digital twin is more than a simulation because it uses real-time data from the physical system as input and can also provide real time input to the physical system (and hereby control the physical system). INCOSE has identified MBE and Digital Twinning as key the key technologies required for systems engineering in its vision for 2035 [5]. To unify MBE with physical system development and digital twinning in one model, Boeing defined the diamond model in 2018 [6][7]. The diamond model is a visualization of the MBE process. The models are used for digital twinning purposes via a so called digital thread which is the infrastructure for data sharing between physical system and model(s).

Axiomatic design is an elegant method for engineering systems [8]. Research in linking MBE to AD is scarce. Previously, Farid defined a mapping between AD domains and SysML diagrams [9]. Wang et. al map their MBSE design methodologies to

AD [10], in doing so creating a new AD domain called the behavioral domain defining Behavioral Entities (BE) between FR and DP.

In this paper a model is presented for integrating MBE with AD, inspired by the diamond model. In contrast to Farid and Wang we do not take SysML as starting point for our model. Instead we take the V-Model itself as starting point because this was also the starting point for the Diamond. Combining AD with the MBE (and the Diamond model) may benefit both. AD may strengthen MBE because explicitly attention is paid to creating decoupled designs and elegant designs (by applying the information axiom). MBE may strengthen AD because it gives insight (information) to the AD that is otherwise overlooked. Models can also be used to (in part) virtually verify the AD parameters and constraints [11] instead of performing time consuming real life experiments. Proving these benefits is not part of this paper.

This paper is organized as follows. In chapter 2 background information is given on the V-Model, MBE, digital twinning, and the diamond model. In chapter 3 first a mapping is made between the left side of the V-Model and AD, after which this mapping is extended with a mapping to the Diamond model. In chapter 4 the diamond model combined with AD is presented. In chapter 5 the conclusions and future work are discussed.

2 Background Information

2.1 The V-Model

The V-Model has been a commonly used process for engineering a system for decades. Many different definitions exist of this model. In this paper the definition of the V-Model according to the VDI 2206 guideline is used as reference [12].

In the VDI model, development is started by defining the requirements. After these requirements are defined the system design is made. The system specification describes the requirements of the system from a system perspective, e.g. “the system should be able to carry goods packed in boxes”. Via a creative process, different concepts of the system are generated that lead to a high level system design (system architecture). In this architecture the different system components are already distinguished but not specified. Detailed design consists of defining the requirements for these individual components (component specification) and creating the detailed design of each component. In the VDI definition of the V-Model this is called domain-specific design. After this step the system is built and integrated. First each component is assembled and tested. When all tests are passed the components are integrated end the integration of components is tested. After this step the system is tested against the system requirements. The difference between integration testing and system testing is that in integration testing it is only tested whether components are connected as required while in system testing it is tested that the system functions according to the system specification. Finally the system is validated by the customer, on the customer site. When testing fails at some level and a redesign needs to be made the process falls back to making adaptations in the corresponding design phase and following the steps of the model again. Tests for each phase are defined in the design phases to guarantee the system is testable.

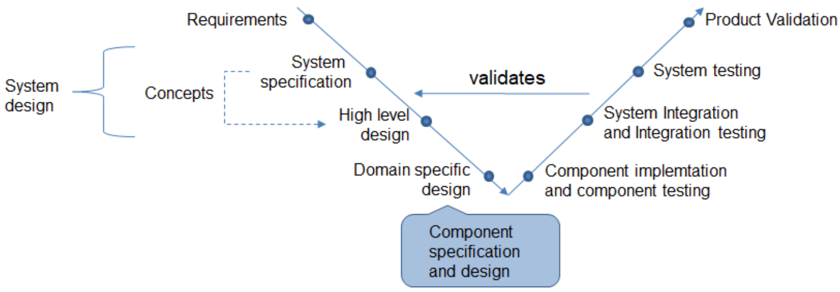

Fig. 1. The V-Model

In theory this is a very rigid model. In practice often a design is made iteratively by moving from requirements down to domain specific design and (e.g. because it turns out a requirement could not be satisfied within certain hidden constraints) the system architecture and even requirements are adapted and a new version of the design is made.

2.2 Model Based Engineering

In classical engineering different teams are working mostly separately and specifications are made on paper. Verification is done by having design reviews. The system is tested based on test plans and test cases defined on paper. In model based engineering (MBE) virtual models are made throughout the engineering process. Engineers from different disciplines collaborate to design and redesign the system through a shared digital environment. The customer is involved in the process giving feedback on virtual models and simulations of the design. The system is tested by test cases generated automatically from the models and correctness is validated against the models. Tool support is used to validate e.g. whether a system architecture is complete with respect to the system specification. In the model based engineering definition used in this paper models are graphical representations of a system on different levels such as UML models, SysML models, but also cad designs and simulations.

2.3 The Diamond Model

In 2018 the diamond model (Fig. 2) was first presented by Daniel Seal of Boeing during the Global Product Data Interoperability Summit (GPDIS) [13] . Boeing was looking for a methodology for MBE represented by something as recognizable as the systems engineering V. The Diamond Model in essence adds a mirrored V shape on top of the regular V resulting in a diamond shape representing the design phases for the virtual system. This makes the Diamond model applicable for both MBE as well as digital twin development. The connection between the top half and bottom half of the diamond is the so called digital thread, which is the data-driven architecture that links together information during the product life cycle [14]. The Diamond Model also incorporates the modeling and virtual realization of the production system, which is a deviation from the V-Model.

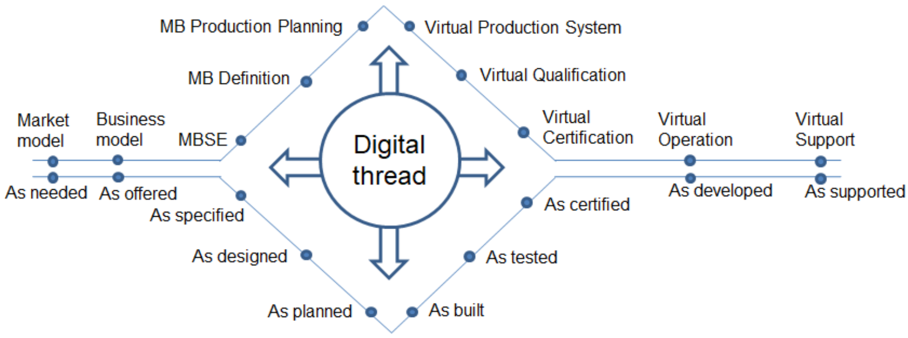

Fig. 2. The Diamond Model as defined by Boeing

Within the diamond model, the virtual models on the left side specify the physical system and the right hand side allows validation of the physical system. The top side and the bottom side not necessarily have to stay in sync. On the top side it is allowed to move faster through phases and go back to earlier phases when redesign is needed.

In the top part of the diamond, the market model defines the customer needs and the business model defines the business needs. MBSE stands for Model Based Systems Engineering and defines the system specification (requirements) and concept of operations (concepts); and the Model Based Definition stands for the high level (system) design and the detailed design . The MB Production Planning defines how the system is built. The virtual production system is the digital twin of the actual production system. Virtual Qualification allows to partly validate the quality of a solution in a virtual environment so that less qualification needs to be done on the real system. Virtual Certification allows to validate whether the system meets the proper standards in a virtual environment. Virtual operation allows monitoring the system while it is in operation. Virtual support allows to trouble shoot a system virtually when problems occur.

The bottom part of the diamond is defined in terms of milestones. On the left hand side, 'As needed' marks that the user requirements are defined. 'As offered' marks that the scope of the project is defined and product will be delivered as agreed with the customer. Note that it may be that not all initial customer needs will be satisfied by the offer. 'As specified' marks the system requirements are specified for the physical system. 'As designed' marks that the physical system is designed. 'As planned' marks that that the production environment is ready and building can start. On the right hand side 'As build' marks the physical system has been built, 'As tested' marks the physical system functions as tested, and 'As certified' marks the physical system is certified as required to the applicable regulations. 'As develops' marks that the system functions as desired and 'As supported' marks that the system is supported as how it is supposed to be supported.

Vertically and horizontally the design stages, virtual system, and physical system milestones are linked. E.g. production is supposed to be planned as designed in the virtual production system and the system is build using that production system.

3 Model Mapping

Fig 3. presents a mapping of the V-Model to AD. The Customer needs in our V-Model directly map to customer needs in axiomatic design. The System specification maps to system level functional requirements in AD (FR). Through the concepts the system design is acquired (DP). The system design (architecture) already defines the physical system itself (and not what the system should do) and is therefore in our view a representation of the design parameters. The domain specific design leads to new requirements (FR') and from those requirements a component design is defined (DP').

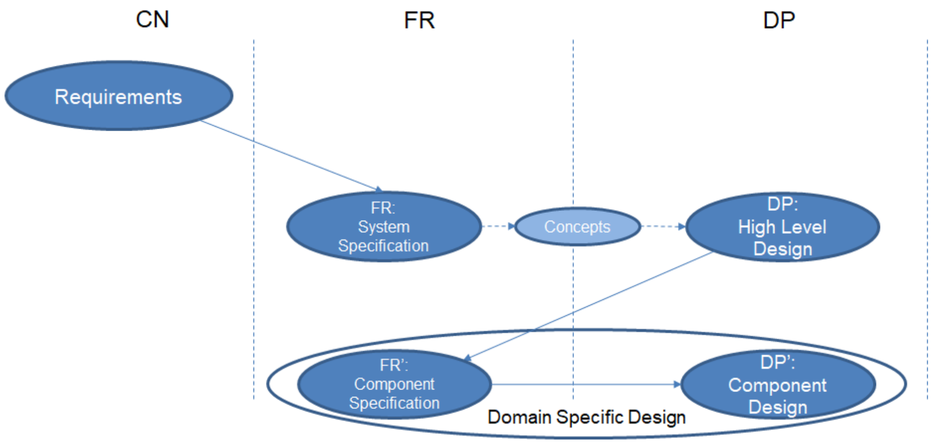

Fig. 3. A mapping of the V-Model to AD

Farid defines the process of design synthesis to generate detailed DP [9]. Our process is similar (but different) in that we first generate new FR after which we generate new DP. Similar to Farid we can also apply design analys to validate the FR and DP and change them if required. This is in line with how the V-Model is applied in practice: creating a more and more detailed design (design synthesis) after which the correctness and completeness are checked (design analysis) and if needed the requirements and designs are adapted.

The MBE phases in the diamond model can now direclty be mapped into the mapping described in Fig. 3. The customer needs correspond to the market models and business models of the MBE Diamond. The System specification and concepts correspond directly to MBSE. High level design, component specification and component design correspond directly to MBD (Fig. 4).

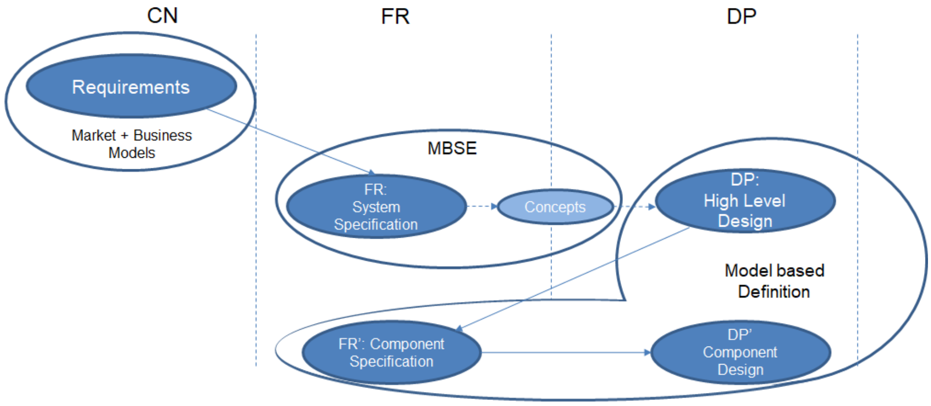

Fig. 4. A mapping of the V-Model, AD, and the Diamond model

4 Combining the Diamond model with Axiomatic Design

With the mappings made in section 3, AD can be combined with the Diamond model. The combination is made by creating a new model in which the lower left side of the diamond is replaced by AD (Fig. 3).

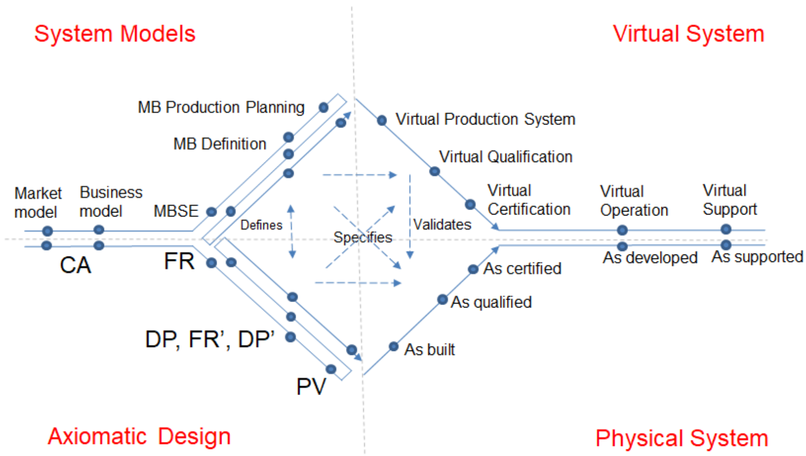

Fig. 5. Combining AD and the Diamond model

The Market model and Business model deal with customer attributes (CAs). The MBSE specifies the system level FR as described in section 3. The MB Definition consists of DP, FR' and DP' which are defined initially in that particular order. The MB Production Planning corresponds to the process variables.

In practice a design is often made in multiple iterations of design synthesis and design analysis, meaning working towards a more detailed design and checking whether this design meets the requirements or should be adapted for other reasons (e.g. not meeting constraints). In MBE models are also made in multiple iterations. These process has been explicitly added to our Diamond model by zigzagging back and forth on the left hand side of the diamond. This is done both for the modelling and the AD. Note that in Fig. 5 the placing of the dots purely reflects the order and not the time between different iterations.

On the right hand side the model still functions as described in the diamond model. The data thread is left out of this representation but is still the glue between AD, system models, virtual system and physical system.

5 Discussion

5.1 Usefulness

This paper described a model combining AD with the diamond model. Up to now the usefulness of this approach has not been discussed. The AD and the system models both specify the virtual system as well as the physical system. The AD and models could strengthen each other and contribute to the correctness and completeness of both models and eventually lead to a better design (compared to taking only one of the two design approaches). Combining the Diamond model with and AD could have the following benefits:

- the models created in MBE can serve as input for the AD;
- AD stimulates decoupling (because attention is paid to the independence axiom) which would lead to a decoupled model based design;
- AD stimulates creating elegant solutions (because attention is paid to the information axiom) which would lead to an elegant model based design;
- virtual executable models provide input for the validation of an AD
- virtual executable models give new insights for optimization of the AD; and
- the AD provides the specification and can be used for validation of the model based design.

5.2 Future Work

The usefulness of the model has not been proven. In order to do so case studies need to be performed. Wang et. al performed a case study with their proposed methodology in which engineers both applied AD and MBE to come up with a design for a system. Designers where not convinced, however one case study is not sufficient to prove the added value and applicability of using both AD and MBE together. A tool to support this methodology would greatly help in this respect. Unfortunately that tool does not exist yet. This tool could generate an AD from system models or the other way around, and incorporates all the system analysis and optimization possibilities of AD, create virtual systems from models and serve as digital twin environment for the physical system.

Farid proposes the detailing of the DPs through the process of design synthesis and validating the DPs through the process of design analysis. In this paper design synthesis is proposed on the system level DP leading to both new FR and new DP on component level and a design analysis process in which the detailed FR and DP are verified with respect to the system level DP. These two processes need to be redefined in the context of the model proposed in this paper.

6 Conclusions

MBE more and more becomes (if not already is) the preferred way of engineering complex systems. The Diamond model presents an elegant model for linking MBE to physical systems. In this paper a new model was presented that links MBE to AD inspired by the diamond model. This model consists of four parts: the system models, the AD of the system, the virtual system and the physical system. It incorporates zigzagging between AD domains which is also mirrored in the design of the system models. This model brings together both the strengths of MBE and AD to create a virtual system (digital twins) and the physical system.

7 Acknowledgements

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