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Methodologies for Mechatronic Systems Design: Attributes and Popularity

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ABSTRACT

The number of connected elements in engineering are greatly increasing with problems getting harder, broader, and deeper. These problems are multidisciplinary thus require an engineering systems approach which is multidisciplinary in nature to solve them. Such modern multidisciplinary systems are called mechatronics systems. The V-model, its variants and the hierarchical design method has brought about a number of benefits in the design of complex mechatronic systems and also provide an effective way of presenting macro level and micro level collaboration. This paper seeks to evaluate and expose the level of adoption of these methodologies as used in the design of mechatronic systems. A review of the VDI 2206, RFLP method and the hierarchal design method was carried out. Google scholar was then used to identify publications within the custom range of period 2003 to 2016, where the methods were adopted. An evaluation of the pros and cons of each method was then carried out in addition to an analysis of the publications. A statistical presentation of publications where these methods were applied was then presented. Possible reasons were outlined and explained for the observed trends. In conclusion, a methodology is recommendation that can be best suited in solving some of the current design challenges.

Keywords: Mechatronics,V-model, VDI 2206, RFLP Method, Hierarchal Design Method.

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1. INTRODUCTION

The demand for innovative products has resulted in advancement of information technology and decision making as well as the synergetic integration of different fundamental engineering domains (Jürgen and Stefan 2003). Modern products are mechatronic in nature since they are comprehensive mechanical systems with fully integrated electronics, intelligent control system and information technology. Mechatronic engineers are required to design engineering systems characterized by high levels of synergy between engineering domain and integration with intentions of achieving constrains such as efficiency, higher performance, precision, speed and lower costs by being immediate, innovative, integrative, conceptual, and multidisciplinary. The use of the sequential design processes which still remains a standard in many industries is proving to be unsuitable for modern mechatronic designs as it introduces design challenges by increasing design costs, development leading-time and high levels of effort without reaching high product quality (Christoph Kilger 2014; Zheng et al. 2014). Bradley (2010) in his exploration of mechatronic systems states that some of the reasons for design failure are due to;

- A misunderstanding of the relationships between system technologies particularly software related and others,
- Problem complexity and communications between disciplines,
- An overemphasis on core disciplines.

The mechatronic system design process should address these challenges by following an interdisciplinary design procedure, which includes evaluation, integration, and optimization of the system and its sub-systems and components as a whole concurrently. The design process should also enable all the design discipline teams to work in parallel and collaboratively throughout the design and development process so as to produce an overall optimal design with no after-thought add-ons allowed(Farhan 2013). The need for soft control algorithms is also ever increasing in the context of modern interdisciplinary product development. All this makes it essential to increase the transparency between domains within the design process by expanding the design methodology towards methods that are compatible with software engineering. (Eigner et al n.d). To meet the requirements for collaboration when designing mechatronic systems, many design methods have been developed. These design approaches have been derived from traditional sequential design, concurrent engineering or lean product development. However many design methods still remain poor in support of technology integration and the multidisciplinary perspectives in mechatronic systems design (Zheng et al., 2014). Of the proposed methodologies those based on the V-model variants have brought about a number of solutions that are required in the design of mechatronic systems. This paper focuses on the design processes based on the VDI 2206 guidelines, RFLP method and Hierarchal design method as these methods have attracted much interest within the scientific community (Hofmann et al. 2010) (Zheng et al. 2014) .

2. THE VDI 2206 GUIDELINES

The VDI 2206 represents guidelines for mechatronic systems design worked out by the committee of the Association of German Engineers (VDI) in the year 2003. These guidelines provides a framework for mechatronic specific design procedures, methods and tools which are flexible for adaptation in individual design tasks, supplementing existing guidelines with the latest findings of design research(Jürgen and Stefan, 2003). The main elements that are presented for the procedural method as a part of the new guidelines for the VDI 2206 are:

- A general cycle of problem solving on the micro-level,
- V-shaped model on the macro-level,
- Macro-cycles according to the degree of maturity
- User-specific process modules for recurring operation steps.

The design process distinguishes between the problem solving process of the individual designer (micro-level) which comes from systems engineering and the generic process related to design phases and corresponding product states (macro-level). At micro-level the designer is supported in an action-oriented way: alternating between systematic and associative ways of proceeding or reacting from unforeseen situations whilst structuring design sub-tasks. The macro-level aids in survey of the total design process: setting of milestones, planning and controlling the design progress etc.

2.1. The V-model

The V-model is well established in the domain of software engineering which was adapted to mechatronics as it clearly adopts the top-down-approach (system design) and the bottom-up-approach (system integration) (Nabil and Govardhan, 2010, Farhan 2013, Jürgen and Stefan 2003).

It also allows pointing out the need of permanent verification/validation between the requirements/specified functions (left hand side) and the actual (virtual and/or real) system (right hand side).

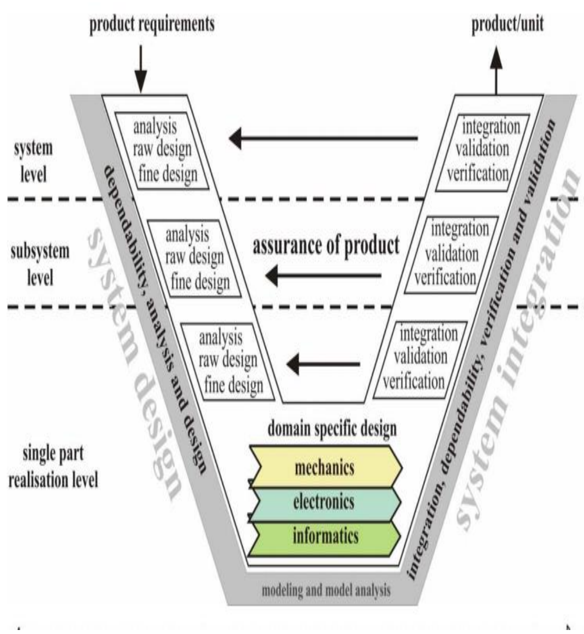

Figure 1- V-model (Vasilije and Lazarević, 2008)

The requirements define and clarify individual design tasks aiming at establishing a cross-domain solution and also provide a system test plan for evaluation of the product later. The test plan focuses on evaluating and validating the functionality specified during the requirements gathering. This also includes an integration test plan for evaluating the combined elements of the system. System design defines a cross-domain solution concept, which describes the essential physical and logical characteristics of the future product. The overall function of a system is divided into sub-functions to which suitable working principles and/or solution elements are assigned, fulfilling the functions regarding the overall system context. Domain specific design allows the solution concept to be developed conjointly by the involved domains and worked out in detail mostly separately in the concerned domains. The described phases are flanked by the modeling and analysis of the system characteristics with intentions of investigating system properties with the aid of models and computer-aided tools for simulation. Finally the designs from the specific domains are integrated in to an overall system analyzing the interrelations.

The “end product” is the result of a macro-cycle successfully passed through. It does not exclusively mean the finished product but an ongoing creation of the future product in terms of product maturity. Degrees of maturity are, for example, concept model, functional model, physical prototype etc. The introduced v-shaped model on the macro-level is a generic procedure pattern, however a complex mechatronic product will normally not be finished within one macro-cycle but several passes (macro-cycles) and increasing product maturity (Vasilije and Lazarević 2008).

The main phases in the V-model are not specified in detail as the individual designer or team does this. Design procedures, which occur regularly during the design, can be described in terms of partly predefined process module representing procedures and methods for different design tasks. According to the individual design task the designer can choose the appropriate process modules meeting his requirements and adapt them or alternatively, create new ones.

2.2. Evaluation of the VDI 2206

These guidelines provide a simple and easy to use procedure where each phase has specific deliverables. It has a high chance of success due to the early development of test plans during the development life cycle and works well for projects where requirements are easily understood. The VDI 2206 has been successfully implemented in the design of a number of mechatronic systems which include (Pawel et al. 2009, Marek and Ralf 2008, Vasilije and Lazarević 2008).

Studies have shown that the development process described by the V-model can lead to problems when applied in the development of highly integrated systems within the domain specific development phase due to the occurrences of deviations from the common solution concept (Roland and Reiner 2013). There is neither communication nor analysis of these deviations for cross domain effects which results in late detection of the cross-domain consequences that is detection during the integration phase. This delay in communicating or analyzing these effects calls for additional iterations within the domain specific development phase resulting in late integration and finally the procedure becomes costly and time inefficient. To tackle these problems approaches where there is early consideration of the possible cross-domain dependencies have to be applied and such methods are usually based on the concepts of systems theory. This basically involves identifying individual components within a complex system then considers their relationship to one another. It is also important to identify additional methods to control system and model complexity. There is also need to focus on how to improve collaboration between the different domains during the domain specific design phase and to offer solutions where integration of specialized domain-specific tools is considered.

3. RFLP METHOD

This method was introduced by Dassault Systèmes in 2008 and developed according to Model Based System Engineering (MBSE) view or viewpoint approach (Beckmann-Dobrev et al. 2015) (Sirin et al. 2015). A viewpoint describes how a set of stakeholders perceive a particular interest , while a view is a fixed package that is said to conform to the viewpoint (Sirin et al. 2015). The RFLP (Requirements/ Functional/ Logical/ Physical) method is a specific V-model adapted to design of mechatronic system (Zheng et al. 2014). It focuses on the left-hand descending branch of the "V-model" dividing it into 4 views: Requirement engineering view, Functional view, Logical view and Physical view.

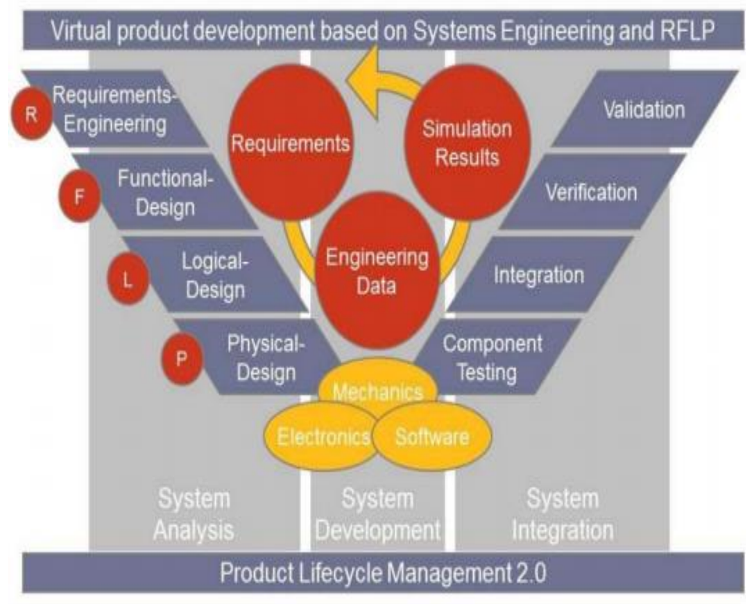

Figure 2 The RFLP design method

By following this design process the RFLP allows concurrent engineering to coordinate the individual activities and views of distributed design teams. The requirement engineering view allows clarification of users' requirements. In the functional view, the intended use of the mechatronic system is defined. In the logical view, the logical architecture, connections, the behavior (discrete behaviors, physics behaviors, and hybrid behaviors) of mechatronic systems will be defined. Finally the physical view defines a virtual definition of the real world product. The RFLP method is implemented in the CATIA System v6 software and so can be considered as a commercial mechatronic design approach. Since this method is integrated in the CATIA application it allows storage, share and exchange of information and data such as sharing MCAD or E-CAD data type among engineers of different disciplines,

3.1. Evaluation of the RFLP method

Researchers upheld the provided solutions to challenges in the V-model through the integration of expert know-how, interoperability of CAx applications. The

RFLP help in formalising the customer needs , technical requirements and also in performing global product traceability across the whole product definition. The method also provides a means to use multi domain modeling methods in support of the macro level collaboration. The integration of multidisciplinary fields through simulation applications and the limitation of the number of design loops improve design time management and quality of data exchange. However the integration of the software domain still remains a challenge (Zheng et al. 2014). Since RFLP is just the descending side of the V-model, it has been overshadowed by the V-model making it difficult to highlight its significance.

4. HIERARCHICAL DESIGN METHOD

The hierarchical design method considers the integration of the mechatronic disciplines from the very beginning of the design process. This design method helps in describing product models and data from different viewpoints. The proposed models may represent structural knowledge, behavioral knowledge or functional knowledge. By following this method, the mechatronic system is broken down into mechatronic modules, which are further broken into discipline-specific subsystems with each subsystem characterized by a model pillar. These models allow the system to have different degrees of detailing and views, which in turn translates from a hierarchy of models to a hierarchy of design parameters. Figure 3 shows an example of a mechatronic module.

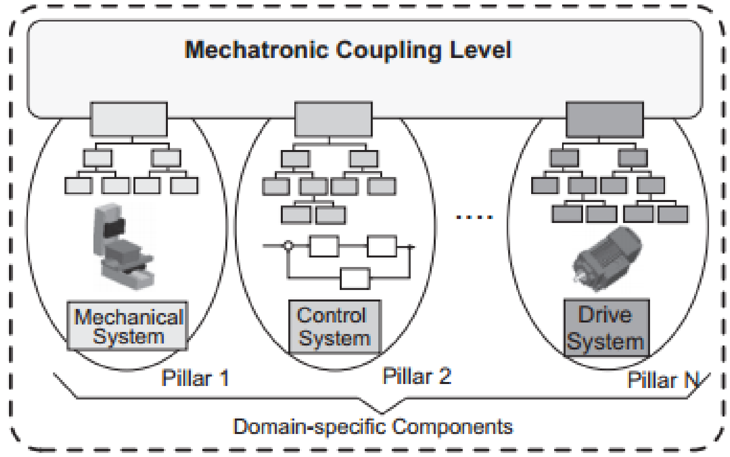

Figure 3-Mechatronic module (Hehenberger et al. 2010)

This approach meets the modeling challenge by following a modular design. The interfaces within a modular design should be well defined and are shared only with a few other subsystems, which in this case are the other mechatronic modules. A technical system’s physical behavior is determined by the properties of the subsystems and their internal or external interactions, which describe the connection between the elements or represent the connections across the system boundaries respectively. The axiomatic design approach can be applied to minimize the component and subsystem dependencies.

Classification of design models is based on the four design stages, which are problem definition, conceptual design, preliminary design, and detailed design. A general description of these stages is given by Pahl and Bates (2006). An interdisciplinary definition, description, and presentation of product information is required for successful product development.. Solution principles from different disciplines should be properly combined and utilized so as to create an extended and quality principal solution. Hierarchical models serve as very important tools for complex design tasks. The conceptual design phase is where most of the design aspects such as hierarchy of parameters and modularity of the design are analyzed. This phase is where the largest part of the later resulting product structure ad costs is predetermined or even fixed. The conceptual design phase is divided into functional design, principle design and architectural design. The hierarchical design method can thus be said to constitute of six stages, namely, requirement design, functional design, principle design, architectural design, preliminary design and detailed design (Follmer et al. 2011). The expanded conceptual design phase is of great importance since most design aspects are considered here and as a result the scope for design is limited to merely smaller changes in the subsequent design stages. To fully understand the hierarchical design method the problem definition (requirements design) and conceptual design (functional design, principle design and architectural design) have to be discussed.

The requirements design stage focuses on the definition of the initial information related to the system and the system subdivision into modules. Analyzing the initial requirements spawn further requirements, and creates a hierarchy of system objectives. Analysis of the requirements is carried out once they are classified into groups either globally, cumulatively, specific or interconnected. These requirements also contain the definition of the system boundaries and the expected system behavior. Consequently, the requirements apply to the overall system, every single subsystem and individual subsystems. A requirements model and a method for tracking implementation of the requirements is set with high priority requirements determined (Hehenberger 2014). The information gained at this stage has great influence on the original product idea. Requirements should always be re-evaluated, properly selected, specified in detail and finally structured according to the relations between them.

Functional modeling provides an abstract method for understanding and representing an overall product focusing on the flows of material, energy and signals. The primary task is to support the procedure of finding suitable solutions in design by creating discipline-independent functional models of the product. A functional model contains an abstract description of the main goal of a product by stating its overall function. Functional models with the addition of a functional basis, provide design teams with a solution to simplify design problems and to make critical decisions early through the realization of modules. Combining sub-functions from a functional model creates a modular architecture. Applying concept generation techniques where the modules identify opportunities for function sharing by components results in a number of alternative solutions. The created functional structure must fulfill the specified requirements. If it is assumed that for complex technical systems a certain number of elementary functions exist, then this functional structure is as a result of cooperation between these elementary functions. Analysis of the interconnections between functional parameters allows easy structuring of the design procedure reducing unnecessary iteration loops.

Principle design focuses on defining a solution that specifies the operating principles of the system under consideration. The solutions will however be defined very roughly because detailed dimensions are not available at this stage. The important properties of a technical system, which include functions, structure, and behavior, have to be evaluated. Since systems characteristics are drawn from these properties, they also form the basis for assessing the system. Simulations can also be used to check whether all requirements have been translated into significant properties of the principle solution. Selecting the principle solution gives the fundamental estimations of the significant properties of the system that are defined by the selected technologies.

The architectural design stage focuses on combining the solutions that have already been proposed into workable modules. The modules are then arranged within the solution environment with the interfaces (connections, ports, geometry, etc.) of the individual modules being defined whilst putting into consideration the possible alternatives. The interfaces must be such that there is minimum dependency and interaction between the modules.

4.1. Evaluation of the Hierarchical design Method

The hierarchical structure allows reflection of the nature of the tasks involved at each individual level within the overall system. There is a move away from the detailed design and operation of the design components to the management of the information infrastructures required to achieve overall system functionality and performance early in the design process. This approach also makes it possible to design innovative mechatronic systems with high flexibility and speed and that provide answers to non-routine design questions by relying on a modular design architecture. Modularity allow managing a large number of interfaces and this is important for structuring design knowledge, complexity management, upgrading, evolvability, parallel working of teams, and replacement of parts of the system (Whitfield et al. 2002; Baldwin and Clark 2006; Holmqvist and Persson 2003). Good modularization is a requirement from the start of product development. The ability to decompose a design task provides the basis to achieving creative design solutions (Komoto and Tomiyama 2012).

The hierarchical design method also allows utilization and proper combination of solution principles from different mechatronic domains extending the quality and variety of the principal solution. There is minimization of the number of iteration loops, which are prevalent in many design methods. These loops are however, time consuming and require intense communication across domain boundaries. Though the iteration loops cannot be avoided completely, they are shifted from the mechatronic level down to the intra-domain level. The hierarchical design model is thus very effective for the micro level collaboration.

5. TRENDS ON THE ADOPTION THE OF DESIGN METHODS

A survey on the literature where the design methods were cited was also carried out. In order to gather the statistics of the cited works, google scholar was used to search out the literature by inputting key words in the search tool bar which included “VDI 2206”, “hierarchical design + mechatronics”, “RFLP + mechatronics”. Since the VDI 2206 guidelines were published in 2003 only literature obtained from the period 2003 – 2016 was used. It should also be noted that the RFLP method was introduced in the year 2008. Figure 4 was then generated to show the appearances of the VDI 2206, RFLP method and Hierarchical Design Method in period 2003-2016

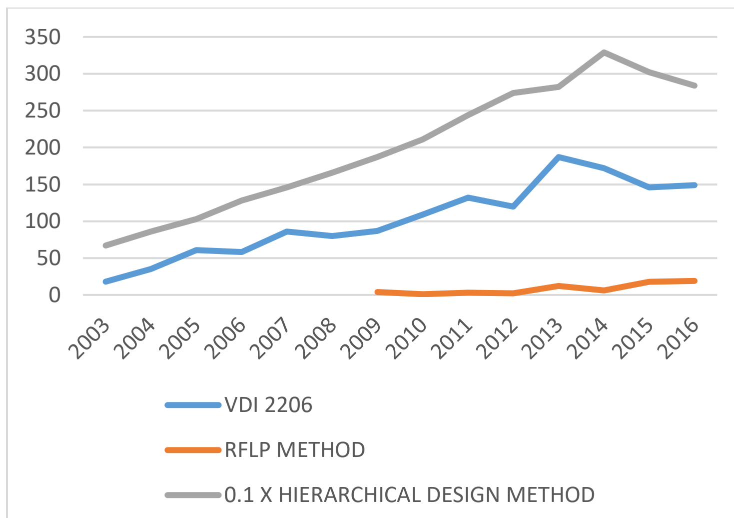

Figure 4- Appearances of the VDI 2206, RFLP method and Hierarchical Design Method in period 2003-2016

A relatively increasing trend of the citation of all methodologies was observed. A total of 15700, 1470, and 65 appearances in literature were observed for the hierarchical, VDI 2206 and RFLP guidelines respectively. The literature gathered demonstrates a very high popularity of the hierarchical design method with the research community with the least popular being the RFLP method. It was also observed that the period between 2003-2009 an number of design were carried out using the VDI 2206 design methods, however thereafter the appearances of the method were related to solving some of the challenges it provided. The RFLP method got the least popularity. Though the method integrated systems engineering tools and aimed at minimizing cross domain communication it still had challenges between software and other domains thus very few designs attributed to its application. This low uptake by designers can also be attributed to the fact that is just the descending side of the V-model thus it has been overshadowed by the V-. As has already been discussed the general upward trends in the acceptance of the hierarchical design method can be attributed in it being a method which facilitates the design engineering systems solving problems of increased complexity and communication between domains without an overemphasis on core disciplines. The hierarchical design methods also shows high acceptance as it facilitated systems decomposition, minimizing number of iteration loops and also provides possibility in the design of low cost systems which is fundamental in modern designs.

6. CONCLUSION

The hierarchical design method has been observed to be a powerful approach in solving the design challenges of modern mechatronic systems. Within the research community it has the greatest popularity in the design of mechatronic systems. However the level to which the V-model defines an integrated design process, represents concurrent engineering and unifies domain specific design with macro level collaboration cannot be ignored. It is therefore recommend to consider methods that integrate both design methods so as to harness the advantages of each individual method. Such cases has been be observed in the design methods presented by (Follmer et al. 2011) and (Zheng et al. 2017) as show in figure 4 and figure 5 respectively.

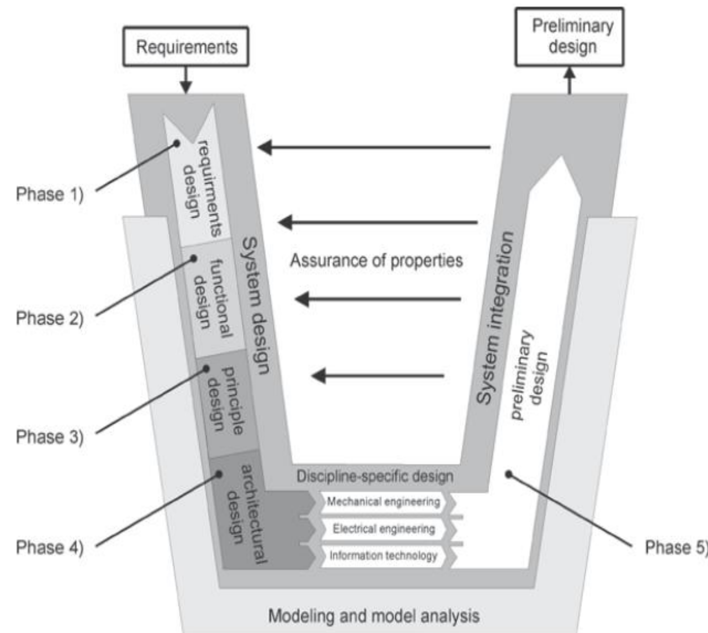

Figure 5-Integration of the hierarchal design phases into the V-model (Follmer et al., 2011)

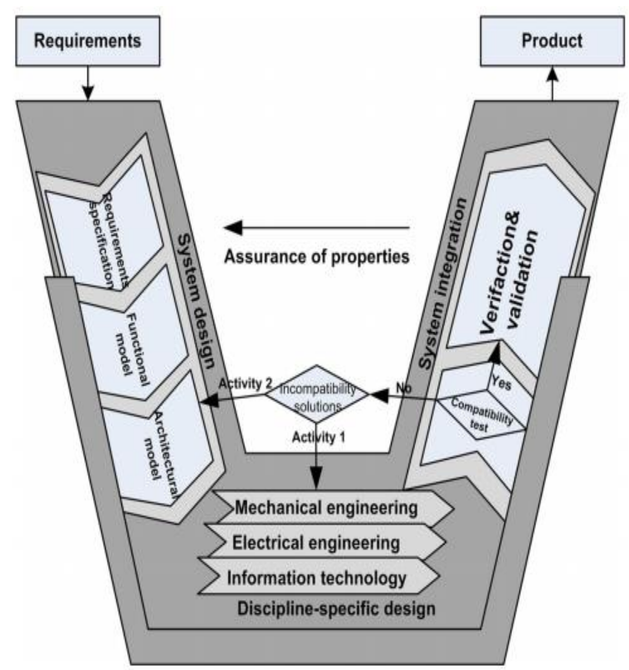

Figure 6 Macro-level process: an extended V-model based on VDI 2206 (Zheng et al., 2017)

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