Skoltech
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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Dominik Johannes Knoll

PhD Program: Engineering Systems

Title of Thesis: Model-based Processes and Tools for Concurrent Conceptual Design of Space Systems

Supervisor: Associate Professor Alessandro Golkar

Date of Thesis Defense: 31 January 2019

Name of the Reviewer: Professor Imre Horvath

I confirm the absence of any conflict of interest	**Signature:** **Date: 21-12-2019**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.

Reviewer's Report

First of all, thank you for trusting me with this responsibility. Upon your honoring request I studied the dissertation and tried to form an objective and constructive assessment. I relied on my expertise related to both design/research methodology development and application, and to cognitive engineering of smart cyber-physical systems. I have discussed my major findings with the PhD candidate in a videoconferencing session.

- ***Brief evaluation of the thesis quality and overall structure of the dissertation.***

The dissertation consists of altogether 275 pages, out of which 224 pages belong to the core and the rest is to the appendices. Figure 1-5 presents the overall structure of the dissertation, which contains nine chapters, including the Introduction chapter and the Conclusion chapter. Chapter 2 provides an overview of the scientific and engineering domains and background knowledge that are the most relevant for the presented work. Chapter 3 provides information on the three-fold objectives of the dissertation and the guiding research questions. Chapter 4 presents an expert survey in order to identify requirements and create a framework for the methodology development. Chapter 5 presents the design methodology proposed for model-based concurrent conceptual design of space systems. Chapter 6 discusses the conduct and the results of the expert interviews, which were done to reflect on the proposed methodology from an industrial use context. Referred to as pilot studies, Chapter 7 presents nine conceptual design studies that contributed to the finalization of the model-based concurrent conceptual design methodology. Chapter 8 focuses on the reuse of the MoCoDeM methodology for technology road mapping in the context of conceptual design of space systems. Finally, Chapter 9 revisits the research questions and presents the findings of the research work related to these questions.

The second chapter identifies (i) systems engineering and product lifecycle, (ii) model-based system engineering, (iii) modeling engineering processes, (iv) conceptual design, (v) solution- and trade-space exploration, (vi) concurrent/collaborative conceptual design and engineering, (vii) multidisciplinary design optimization, (viii) concurrent conceptual design of space missions, and (ix) technology road mapping as relevant foundational concepts and domain knowledge for the work. While the presented overview is quite comprehensive, the trends and the emerging technologies/approaches are not exposed and evaluated. Moreover, the last developments such as digital twins-based engineering and issues of knowledge engineering/availing are not specifically addressed.

If read and interpreted literally, many parts of the text in Chapter 4 can be ambiguous for the reader, for instance, due to lack of terminological definitions or interchanged use of specific terms. This chapter introduces the Design Research Methodology of Blessing and Chakrabarti as an appropriate methodological framing of the presented research work. The selection of this methodology can be approved, but its operationalization was found incomplete. Namely, the role and completion of the second descriptive study are not explained clearly, whereas it is misleading to associate it with model-based technology road mapping.

Chapter 4 refers to a literature study, whose reasoning model, conduct, findings and takeaways are not discussed. It is supposed to be a different study than the general survey presented in Chapter 3, since that was not driven by the three research questions. Chapter 4 concentrates on the conduct and the outcomes of the completed expert survey. However, there are no details provided about the strategy and measures of sampling (criteria and requested size). The interrogation dealt with various aspects of teamwork, benefits, challenges, tools, trends, models, process, duration, infrastructure, capacities and features of facilities, and evaluation criteria of concurrent conceptual design (CCD) studies. This multiplicity implies the need for a stratified systematic sampling. No statistical significance analysis was applied on the outcome of the survey.

The discussion of the essence and ingredients of the model-based concurrent conceptual design methodology MoCoDeM) in Chapter 5 is in general informative and well argued. However, it presents the methodology from a use perspective (as exemplified by Figure 5-26 and section 5.6.8 'Tradespace exploration'), rather than from a research and/or a computational implementation perspective. The chapter is overloaded with chunks of use, system and computational information. Therefore, is would perhaps be better to separate it into a methodology presentation part and a tool specification and implementation part. On the other hand, it is not stated that the proposed methodology applies only to those space systems that are fully specified in the design stage (i.e. it does not apply to self-adaptive and self-evolving systems). Explanation on why the mentioned five pillars (i.e. facility, team, processes, tool, and model) have been preferred and were considered sufficient is not included. Clarification is also needed on why the actual features of the space system and its working context should not be considered at conceptualization of the methodology. Popular nowadays, dislocated collaboration is not included in the developed MoCoDeM methodology. The description of the integrated system model is restricted to capturing certain characteristics. The well-known thinking scheme of the so-called V-model is not considered as a standard and generic process model of realization of space systems. Figure 5-12 does not show the concurrency of events as they are shown in Figure 5-15. The title of Subchapter 5.6. is 'Collaboration tool', while a set of tailored tools was the subject of the actual software development.

As a first step of presenting the set of tools (CEDESK), it would be useful to start with its overall computational functionality. Based on the description given in the development/implementation driven Chapter 5, it is not evident how the prescriptive study part of the adopted research methodology has been operationalized from a research perspective. While integration of trade-space exploration and parametric modeling can be accepted as true novelties of the CEDESK, understanding of the related argumentations is made complicated by some vague sentences such as: "In the case that the system to be designed can be associated to a bigger family of products (e.g. communication satellites), the new design is compared with other planned or existing solutions." It is mentioned that a unique feature of the CEDESK is 'consistency checking', which reveals possible mistakes in the constructed parametric models. However, the principles, mathematics or algorithms of this important functionality are not disclosed. Likewise, the computational implementation of the 'coordination' functionality, that is based on an automatic generation of DSM, remains hidden.

Having a descriptive flavor, Chapter 6 informs about the conduct and the results of expert interviews, which were done to validate and enhance the results, according to the view of the reviewer. However, the relationship of the expert interviews to the second descriptive study is not clear based on the available description. It is mentioned that the objective was 'verification of the process guideline', rather than validation of the entire methodology (including its specific procedures, methods and tools). Considering the fact that five experts were involved, it is a case of under-sampling in which no statistical significance can be explored.

With the objective of generated practical information about the proposed MoCoDeM methodology and providing answers to the research questions, Chapter 7 presents conceptual design studies of space missions, referred to as pilot studies. Students enrolled in the Satellite and Mission Design course were the participants in the nine design studies, which were conducted in the Skoltech laboratories. It is clarified that the student teams followed the common research – or probably system conceptualization – methodology, but with a different purpose in mind. Obviously, it is an indication of potentials of the MoCoDeM methodology, if it is applicable to a large number of different projects. Nevertheless, a comprehensive validation of the impacts of the methodology could have been assessed better in a different set up. For instance, the increase of the efficiency of system conceptualization can be analyzed deeper by solving conceptualization tasks by groups without and with the use of the methodology. This could be extended with the assessment of the differences in the achievements of groups of unexperienced designers and experienced designers applying the MoCoDeM methodology. It is an issue how much realistic industrial situations, contexts and constraints were represented in the pilot studies, and, depending on this, what can be predicted for space system developer companies. From a research point of view, it is an important fact that the methodology was evolving during the three and half years, over which the nine design studies were completed by the students and the tools developed by the researcher(s). The impression is that presented conceptual design studies were meant to be continuation of the methodology development part, rather as case studies for functionality, performance, usability, or utility assessment.

Chapter 8 reuses the MoCoDeM methodology for technology road mapping in the context of conceptual design of space systems. Obviously, the evolution of technologies has a significant effect on conceptualization of new generation of space systems, and technology road mapping is important for innovation oriented companies. However, this part of the dissertation raises at least two important questions: (i) why should a methodology which is tailored to the requirements of co-located concurrent conceptual design serve equally good for model-based technology road mapping, and (ii) how does the road mapping by using the MoCoDeM methodology contribute to the second descriptive study of the applied research methodology? Chapter 8 does not give explicit answers to these questions. It is explained that: ”Applying the concurrent design method in technology road mapping aims to achieve two goals: 1) provide engineering rationale for roadmap targets, 2) explicitly account for interdependencies between all involved participants”. In the literature, road mapping is typically seen as the front-end activity of system conceptualization processes, which can be included in a structured methodology as such. However, toward this end, the requirements of this particular application as well as the functionality needed for road mapping should be taken into consideration at the time of developing the conceptual framework and the underpinning theory of the MoCoDeM methodology.

- ***The relevance of the topic of dissertation work to its actual content***

The principal assumption of the PhD candidate was that an established methodology for supporting CCD of space systems does not exist yet and each organization has its own interpretation of the best practice. The proposed MoCoDeM methodology is intended to be a formal model-based approach, which provides guidelines for a concurrent design process and supports the teamwork by dedicated tools. The dissertation seems to be focused exclusively on co-located multi-disciplinary teamwork. The issue of dislocated (on-line) teamwork, which is already a daily-practice in many industries nowadays, is not addressed with sufficient detail. The intention of the research was to develop a CCD methodology that is underpinned by a sufficiently robust theory, and that provides a process model, a pool of problem-solving and collaboration methods, a set of interrelated computer-based tools, and measures for assessment of the application and the results, and eventually lends itself to an efficient support for CCD of space systems. The underpinning theory has been constructed based on a generalization of specific practical experiences and needs of real life stakeholders.

Though the structuring of the dissertation seems to be quite logical, there are some uncertainties concerning the actual contents of the chapters, and in particular, their relationships with the chosen research methodology. The Introduction plays a crucial role in the notional and conceptual clarification of the fundamentals, backgrounds and objectives of the research. It provides sufficient insight and analyses the major issues of designing space systems, the essence of model-based systems development, the chain of design inter-dependencies, and the epistemological and methodological aspects (five pillars) of CCD. As far as balancing the extents of the chapters is concerned, it was felt that Chapter 5 is somewhat overloaded with information (this presents the prime contributions of the research work). The impression has been that the discussion of the processes, the methods and the tools associated with the developed methodology might have been arranged more purposefully in separate chapters.

- ***The relevance of the methods used in the dissertation***

The methodological framing of the work is based on a research methodology that is well known from the literature. Selecting this methodological framing for this work is correct, but its consistent application is an issue. Namely, the research methodology of Blessing and Chakrabarty identifies three major phases on research: (i) first descriptive study, (ii) prescriptive study, and (iii) second descriptive study. According to the best knowledge of the reviewer, the latter is about justification, validation and consolidation of the research work and the results. Considering the structuring and contents of the dissertation, it is evident that Chapters 3 and 4 are about the activities that belong to the first descriptive study, and Chapter 5 represents the prescriptive study. Chapters 6, 7 and 8 are presented in the dissertation as parts of the prescriptive study. However, if this understanding is correct, then what is associated with the second descriptive study is the completed work (and in the dissertation)? This remains a kind of puzzle after reading the whole dissertation.

- ***The scientific significance of the results obtained and their compliance with the international level and current state of the art***

Model-based concurrent conceptual design of complicated and complex systems is a frequently addressed, important, but only partially known research phenomenon. This dissertation has offered a meaningful and valuable contribution to this. Interesting in the approach is that it started out from concrete need of industrial stakeholders and aggregated knowledge from the academic literature to synthesize a possible solution for this problem. It is a fact of the matter that both the methodological approaches and the support environments are in the focus of systems scientists and engineers, and both are rapidly developing. The attention of research is rapidly shifting from one issue to the next, without a full comprehension or an exhaustive exploration of the space of possible solutions. New developments and opportunities, such (i) networked communication and knowledge engineering technologies, (ii) intuitive/heuristic and systematic/computational idea generation methods, and (iii) the appearance of self-managing smart systems have to be taken into consideration. Comprehensiveness of the approaches is also a scientific issue, and this dissertation provides a good example for the possibilities in this context. Repeatability is an important expectation for scientific works and results. In the dissertation, there are at least two parts which need further attention: (i) the information about the applied sampling strategy and minimum sample size in the case of the interrogative studies, and (ii) specification of the logical assumptions, computational algorithms, data constructs, and software architecture of the support tools.

- ***The relevance of the obtained results to applications (if applicable)***

Though the proposed model-based methodology can be further enhanced, it can be seen as a remarkable contribution to the industrial understanding of the whole of concurrent conceptual design of space systems and to the facilitation of its systematic and computational tool enabled cooperative execution in the industry even in its current form. This is evidenced by the variety of conceptual design tasks which have been considered at the time of development, and at the time of assessing its applicability in industrial contexts. It is argued in the dissertation that the use of models in road mapping is not common – therefore, it proposes an extension of the model-based concurrent conceptual design approach to road mapping. If road mapping is used as input information to ideation and conceptual design, this can indeed be an effective means for generating next generation solutions in industrial contexts.

- ***The quality of publications***

The list of own publication of the PhD candidate includes four first-authored items and one co-authored item. Each of the mentioned publications are co-authored by multiple researchers. The quality of the studied publications is on the level of international peer reviewed contributions. Unfortunately, the first journal article, entitled 'Concurrent engineering process model of conceptual design studies' was not accessible for the reviewer at the time when the dissertation was studied.

The second item on the list, a paper presented at the IEEE's System engineering symposium under the title 'Review of concurrent engineering design practice in the space sector: State of the art and future perspective', is actually a short review paper. This review summarizes the learnings from concurrent design practice and describes open challenges to be addressed in future research.

Likewise, the third first-authored paper, entitled 'A concurrent design approach for model-based technology road mapping', is a 6-page long paper presented at an IEEE international systems conference. This work describes an approach, where experts build and run models in a concurrent design environment allowing the evaluation of potential product architectures according to a defined set of figures of merit and at different time horizons, with the intention to inform the planning of technology investment and development. The process is illustrated using the example of a solar-electric aircraft technology roadmap.

The fourth item, entitled 'A coordination method for concurrent design and a collaboration tool for parametric system models', is a full-length article published in the Concurrent Engineering journal. The paper proposes a method and a tool for conducting conceptual design studies for space exploration and satellite constellation projects in a time and space concurrent manner. This publication directly contributes to and delivers useful content for the CCD methodology discussed in the dissertation.

The co-authored paper, entitled: 'Study of data structures and tools for the concurrent conceptual design of complex space systems' was published in the Proceedings of the 14th IFIP WG 5.1 International Conference on Product Lifecycle Management and the Industry of the Future, argues that the data generated in concurrent design studies essentially describes behavior with a limited set of information about the geometry. The authors investigated the SAPPhIRE causality model as a potential data structure to support conceptualization and other phases of the product lifecycle. Though useful publication in general, this paper is not in the very kernel of the dissertation.

Issues to be addressed before/during the defense:

- The presentation of the work suggests a multiyear and intensive teamwork. Explanation on the own contribution (independent research work and genuine scientific achievements) of the PhD candidate to the laboratory development, theory forming, and implementation of the software tools.

- More concrete information about the literature review of the current state of the art of model-based concurrent conceptual design should be included in Chapter 3.
- Higher clarity should be achieved with regard to the second descriptive study of the chosen research methodology. Its objectives and contents should be specified.
- It is recommended to divide the current Chapter 5 into two chapters that are dedicated to the specification of the overall methodology and the development of the tools, respectively.
- Higher clarity should be achieved in terms of the relationship of Chapters 6, 7 and 8 to the second descriptive study of the chosen research methodology, and the performance validity of the proposed methodology and the set of tools.

Technical issues:

- Additional definitions and systematic use of the terms can facilitate clarity and understandings. The text can benefit from a proof-reading and local brush-ups.
- Certain figures (e.g. 1.1) are too small for a convenient reading in printing. Readability of figures should be improved by using proper font sizes.

Provisional Recommendation
☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense. Since the findings of the reviewer have been discussed with the PhD candidate in due time, and the introduction of the recommended changes means only structural and textual modifications (rather than a need for additional research), it is believed that the revision can be completed according to the initial schedule.*
☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report.*
☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*