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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Dominik Johannes Knoll

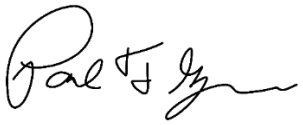
PhD Program: Engineering Systems

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: Paul T. Grogan

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Signature:**  **Date: 30-12-2019**

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

This thesis tackles three interrelated research objectives: 1) formulate a generic methodology for concurrent design, 2) develop a software tool that implements key functions associated with the methodology, and 3) extend the methodology and to technology roadmapping applications. The research follows a design science methodology where the author creates a new artifact and establishes its utility or value through assessment exercises. Review of literature on existing concurrent design efforts along with a questionnaire and interview of subject matter experts establishes and validates key components of the proposed methodology (MoCoDeM: model-based co-located conceptual design methodology). The software tool (CEDESK: concurrent engineering data exchange Skoltech) implements key functions from the methodology and is evaluated using a sequence of nine conceptual space mission design studies with varying objectives. Finally, an application case evaluates how concepts within the MoCoDeM methodology and CEDESK tool can be applied to technology roadmapping exercise.

The overall quality of the thesis is acceptable. It is clear there was significant software architecture and development required to support the broader thesis objectives. The author is careful to explain both the practical contributions of the CEDESK tool but also the more general contributions to knowledge through the synthesis of literature and expert feedback and formulation of the MoCoDeM methodology. The overall quality of the thesis would be improved if the author contributed to or built upon a theoretical framework to explain how MoCoDeM influences key processes during a concurrent design exercise. This approach would mitigate some of the methodological challenges by focusing only on causal factors believed to influence results of concurrent design rather than a holistic evaluation of an entire session. However, this effort is likely out-of-scope for this thesis and would be better addressed in future work.

The content of the thesis is highly relevant to the topic. Chapter 2 also synthesizes the current state-of-the-art of concurrent design to give context for the work. Application case studies in Chapter 7 provide a rich narrative to explain and demonstrate concurrent design activities and reflect an iterative development of CEDESK. The application of concurrent design concepts to technology roadmapping in Chapter 8 is a novel approach that demonstrates broader use of the proposed methodology and tool.

The research follows a design science methodology where the author creates and evaluates artifacts (MoCoDeM and CEDESK) using a combination of expert elicitation and application case studies. Overall, the research methodology is acceptable; however, there remain some areas where the author can strengthen or clarify the arguments. An expert survey in Chapter 4 consisting of 20 respondents characterizes the current state of concurrent design from government and industry organizations as a precursor to artifact development. Results from this chapter would be better represented as a set of key requirements or functions that shall be achieved by the proposed artifacts to be evaluated via validation activities. Expert interviews in Chapter 6 consisting of five experts evaluate the process elements of MoCoDeM and CEDESK. This is the weakest chapter of thesis because the qualitative results are limited to face validation at a high level of abstraction. While a contributing element of validation/assessment, the author should be careful to not overstate the results of this activity. Finally, nine studies in Chapter 7 iteratively demonstrate the use of the CEDESK tool to support conceptual design of space missions. Although the cases use different subjects and timescales than practice, this chapter provides the strongest artifact evaluation of the thesis. Iterative development builds confidence that the CEDESK tool facilitates the activities and data quantify activities during each session. Stronger conclusions from each case about the lessons learned, key insights, or design challenges overcome would help understand how the artifacts support and influence the design activities. Finally, evaluation of the application of the proposed artifacts to technology roadmapping relies on an informed argument in Chapter 8. Most of the chapter provides

narrative to explain how MoCoDeM/CEDESK concepts apply to the new problem domain and a more detailed application case would help demonstrate its use (the chapter feels rushed and unfinished).

The scientific significance of this work focuses on the generalized concurrent design methodology (MoCoDeM) and its implementation in the CEDESK tool. The author shows, despite significant interest from many industry- and agency-oriented organizations, there remains limited general characterization of concurrent design or its supporting elements in literature. The author makes a modest but significant contribution in this thesis to characterize and understand how processes and software tools contribute to concurrent design activities. The research does not provide analytical evaluation of the proposed artifacts in a controlled study (which is not feasible in the current format without an underlying theoretical framework to focus the research questions), rather it builds a justification for how and why the artifacts impact and ultimately improve concurrent design activities drawing from a set of studies.

The results of this thesis are highly relevant to the applications of conceptual concurrent design and technology roadmapping. The primary audience of this thesis is the practitioner community along with the applied academic community charged with advancing new methods and tools. Demonstration of the MoCoDeM/CEDESK artifacts in the set of space mission studies provides evidence for general applicability. Furthermore, the extension of the artifacts to technology roadmapping exercises shows how concepts drawn from systems engineering can contribute to strategic management and technology development.

The author reports contributions to two published articles (*Concurrent Engineering* and *Acta Astronautica*) with a third in revision (*IEEE Access*) and four conference papers (*International Systems Engineering Symposium*, *IEEE International Systems Conference*, and *Conference on Systems Engineering Research*). Given the thesis topic, *Concurrent Engineering* and *Acta Astronautica* are appropriate and high-quality journals to disseminate results. The conference publications expose an international audience to the work but do not have as much permanence or impact. This publication record represents a modest contribution to literature and could be strengthened with additional journal publications to, for example, report synthesized results of concurrent design sessions to the design engineering audience (although this is not without challenges to distill key insights). In general, there is interest in design session data sets and software such as CEDESK may have a role to capture and record such data for further research.

In summary, please consider the following points:

1. Artifact assessment/validation based on expert elicitation could be supported by a clear set of key requirements or functions resulting from the expert questionnaire in Chapter 4 and expert interview in Chapter 6. Its current form reports feedback results but does not distill or synthesize key qualities related to the proposed artifacts beyond broad categories of "expert availability" and "integrated tool chain." Taking this perspective helps distinguish more significant contributions to broader research goals from the particular implementation selected in this work.
2. Similar to the above comment, the case studies in Chapter 7 largely report results of the conceptual design activities without relating to assessment or evaluation of specific functions or capabilities of the proposed artifacts. A lot of data is presented related to the number and type of changes and resulting dependencies; however, it is not clear to the reader how this relates to the proposed artifacts. Does it characterize the design problem or how the design team used the artifact? There is only limited value in demonstrating the participants completed a design activity (existence proof). A richer discussion or synthesized narrative would help understand what key insights or lessons learned could be acquired from each case. The "Observations" subsection in the first set of pilot studies is a good start but should be synthesized into a cogent evaluation.

3. Some of the automatically generated N-squared diagrams in Chapter 7 are very difficult to read due to overlapping text (especially in Figure 7-19). Building on the above point, what should the reader obtain from these visualizations? Does it characterize the design problem or provide insight about how the design team used the proposed artifacts? Are there certain dependency structures beneficial for applications of concurrent design?
4. Chapter 8 tackles a large research objective to transfer the work developed for applications of conceptual design (specifically but not exclusively space systems) to other areas of strategic management and technology roadmapping. The introductions in 8.1-8.3 are sufficient to explain how concepts can be generalized; however, section 8.4 is insufficient to characterize an application and should be expanded. It is understood that some details cannot be disseminated due to confidentiality issues; however, the thesis must provide comprehensive assessment to better justify the utility or value of the approach to technology roadmapping.
5. There are numerous typological errors throughout, especially in Chapter 8. Note that "it's" is a contraction of it is (not common to use contractions in technical writing) and "its" is possessive.

Provisional Recommendation

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☐ *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*