Skoltech
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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Eldar Shakirov

PhD Program: Engineering Systems

Title of Thesis: Integrated analysis of engineering and manufacturing change management in the additive manufacturing context: a simulation-based modeling framework

Supervisor: Professor Ighor Uzhinsky, Skoltech

Co-supervisors: Professor Clement Fortin, Skoltech; Professor A. John Hart, MIT

Name of the Reviewer: Professor Alain Bernard

I confirm the absence of any conflict of interest 	**Date: 15 June 2021**

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

Reviewers report should contain the following items:

- Brief evaluation of the thesis quality and overall structure of the dissertation.
- The relevance of the topic of dissertation work to its actual content
- The relevance of the methods used in the dissertation
- The scientific significance of the results obtained and their compliance with the international level and current state of the art
- The relevance of the obtained results to applications (if applicable)
- The quality of publications

The summary of issues to be addressed before/during the thesis defense

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

The thesis relates to "**INTEGRATED ANALYSIS OF ENGINEERING AND MANUFACTURING CHANGE MANAGEMENT IN THE ADDITIVE MANUFACTURING CONTEXT: A SIMULATION-BASED MODELING FRAMEWORK".**

The structure of the dissertation is classical with a general introduction, a second chapter providing a state of the art review, ended with a definition of the research problem statement, two chapters of propositions, a chapter of applications (seven case studies are proposed) and a final section with discussions and conclusions, including some perspectives. A list of literature references is also proposed as well as five appendixes (very interesting, with detailed complementary elements). The three lists of Abbreviations, Figures and Tables are provided at the end of the document.

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

The proposed topic is relevant with respect to the actual evolution of the market, taking more and more benefit of Additive Manufacturing technologies and integrating these technologies and related practices into the evolution of manufacturing means of the companies. Engineering Change Management (ECM) in the field of AM is really relevant and needs some innovative approaches based on a very dynamic and evolving knowledge.

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

The PhD candidate adopted the Design Research Methodology (DRM) from Blessing and Chakrabarti. The four stages of the methodology are explained in the context of this thesis at the end of the Chapter 1. It would have been better to introduce it after giving the different research questions and sub-questions at the end of chapter 2. The explanations are based on the acronym of those questions but the reader does not know yet the content of those questions. So, this is quite difficult to evaluate the relevance of the proposed method without knowing the questions of research.

Some of the research questions are not research questions but they are goals to be achieved. Achieving goals does not always need research, this could be a pure engineering task, based on already well known theories and practices.

Concerning the state of the art, it is very extensive about all the different issues that have been considered in the Thesis. However, it would have been interesting to read some papers related to "make or buy" strategies. Another topic that should have been investigated more in depth is "value sharing" and "value management". Cost and time are considered as the main KPIs but other issues could be considered, such as sustainability (including cost but also social and environmental issues) in particular when speaking about changes related to AM, for design, for AM-based manufacturing chain and logistic solutions (changing to digital logistics instead of physical logistics). All benefits but also all investments have to be balanced before and during the evolution of practices. They have to be included in the engineering change management practice.

Concerning more especially ECM, a standard exists concerning the complete process of analysis related to the adoption (or not) of AM. It relates to the global Design for AM process. The candidate would have benefit to refer to this standard that has been adapted in a practical way in a recent CIRP keynote (VANEKER et al., 2020): *https://www.sciencedirect.com/journal/**cirp-annals**/vol/69/issue/2* "Design for additive manufacturing: Framework and methodology". Tom **Vaneker**, Alain Bernard, Giovanni Moroni,

Ian Gibson, Yicha Zhang. Pages 578-599.

Table 2.1 is very informative. Maybe an addition could be introduced with ceramics. Ceramics do not appear in this table even if some very interesting technologies exist (in particular there is a 3DCERAM French machine in Skoltech labs).

Concerning the second research gap, the candidate would have read some papers published by Yicha Zhang et al. related to some original approaches on process planning for AM, including build orientation, placement optimization for multi-part production, support generation, etc. Some incoming papers about ABC method applied to costing for AM are to be published by Qussay Jarrar et al.. Many other models have been published during the last 20 years (even more) which show that costing depends on production context which means that defining the cost of a given part is not relevant without giving the complete conditions of the study/context and of the delivery conditions, including emergency, size of batch, etc… All the KPIs are directly linked to the complete AM-based process planning issues, including design engineering, post-process and control operations (even characterization ones, if needed for some certifications). The candidate also mentions quantitative assessment of AM impact. This is a very important and relevant issue that is very critical to be evaluated because it relates to many factors, not only during manufacturing stage (packaging, if any, is also impacted, for example).

The third research gap is also relevant and some needs exist to provide complete learning systems based on the total experience all along the projects.

Concerning the "global" research question, the candidate should clarify if some hypotheses have been proposed related to maturity level of the company about the different skills and means within the company. The "AS-IS" situation of the considered context is one important input factor of the proposed approach.

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

The proposed results have been constructed based on both literature review (an extensive one) and on interviews and case studies.
The candidate proposes two levels of decomposition of the targets considered in the PhD work (level 1: engineering change management, manufacturing change management, integrated change management, product creation practice; level 2: engineering activities planning and execution, manufacturing system design and activities planning and execution, integrated change management, product creation practice). This mostly corresponds to two kinds of fields of interest: AM impact on the integrated change management practice, transformation in the product creation practice.

A remark concerning the representations used by the candidate: for example on Fig. 3.5, it would be interesting to "close the loop with the customer" and moreover, with "the trigger" of the change process. As commented by the candidate, triggers could be any stakeholder of the global process and if a change is initiated, the stakeholder who asked for this change has to validate that this change fits the new requirements. This is supposed to be demonstrated on Fig. 3.6 but it would be important that this process would be commented and justified during the defense because it does not seem that there is a final validation by the customer after step n°26. The advantage of the chosen graph representation is to highlight the inter-domain collaboration between the stakeholders.

In order to characterize the most important factors related to what is called by the candidate "AM-driven transformation of a product creation process", some interviews are organized and analyzed in

order to identify the influence of what is called “transformation points”. Some analytical instruments are proposed in Chapter 4 to help in adapting these considerations to a specific context. Two main evaluation/comparison factors are introduced: cost and lead time with respect to decision making during the integrated change management process. A real systemic vision is absolutely necessary to be taken into account to evaluate the major impacts at global level of the adoption of AM.

In Chapter 4, the candidate introduces a framework to evaluate cost during the product development process and to propose alternative solutions for manufacturing process planning. At that stage, it may be considered that the salary of the designers is paid and does not depend on the different products they design. For manufacturing this is not the same. Machines work only when manufacturing products, so the manufacturing time ratio is very important to be considered when addressing a strategic decision to change for AM practices, the consequence will be visible at the end of the year when compiling cost and expenses… This means that the proposed approach is to be considered carefully because this should allow considering direct costs and also context costs (with priority jobs for example, or with the optimization of production batches). What is interesting is that the candidate is aware of such issues when commenting about those concerns page 71 and that the proposed approach is supposed to take such particular points into account. The main conclusion is to adopt DSM and a Discrete-event-simulation technique to achieve the expected goal of the research. A first model is proposed in Fig.4.4. As usually, the main issue is not to propose a model, this is to be sure to be able to populate this model with relevant and coherent data. With respect to Fig. 4.5, the candidate would have benefit to read the PhD work and the papers published by Joanna DAABOUL et al. which relate to discrete-event simulation models in the field of mass customization, which is to be considered as a possible context of integration of AM. In the following paragraphs ending section 4.1, the candidate clearly describes and comments the different parameters of the proposed model, which is interesting and helpful.

In section 4.2, the framework is constructed and commented. The content is relevant. It is not possible to read Fig. 4.9 that should appear over a complete page, this would clarify it and help the reader appreciate the different elements that are presented. Fig. 4.10 resumes the complete process flow of the manufacturing modeling framework. A detailed definition of each parameter is proposed with respect to sets of part-related and process-related parameters. What would have been interesting is to define the most influencing factors with respect to different categories of parts. A generic approach is interesting but needs to be adapted with qualitative factors for example. Another concern is the process planning with respect to the availability of machines. This remark relates to the availability of machines when the production will be achieved and to eventual adjustments that would be necessary with respect to a new context of production. In addition, it is not clear if the values of Table 4.13 are based on “average values” of real production or on simulations based on hypotheses (the term “average” appears in the legend of Fig.4.16).

The section 4.3 is based on an integrated change management scenario in a context of service bureau. The demonstration of the proposed solution is based on different scenarios, hypotheses and information. The application of the demonstrator is not completely clear with respect to the validation of the chosen solution. It seems that it is based on a trial/error approach which is not realistic, but this may not be the case and this has to be clarified during the defense.

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

In Chapter 5, the candidate proposes some application case studies. It appears that the use of the model is mostly for strategic decisions, in fact it relates to the relationship between the redesign of the system and the re-structuration of the manufacturing solutions. Being able to early evaluate such impact is very important.

So the obtained results, highlighted by the case studies, clearly demonstrate the relevance of the proposed model and framework.
What is important is to consider the sensitivity of the different factors and the robustness of the simulation results with respect to real contexts and systems. This will have to be commented during the defense.
The user-friendless is also one important issue and the demonstrator will have to be industrialized before being used by a company. The proposed figures/copies of screens will have to be commented during the defense with respect to the progress of the proposed methodology.

The comments in the last Chapter (discussions and conclusions) show that the candidate is aware of the limit of the PhD work and the proposed perspectives are interesting. As in many fields, the concept of Twin is introduced as relevant. This is a perspective for the future that has to be considered but some limits actually exist and many research works will have to be achieved based on a global and systemic vision.

- **The quality of publications**

The publications have been mostly proposed in conferences, one has been published in IJPLM journal. More attention should be addressed to additional publications in international journals. It is important in order to share more widely the proposed results and to be well-known from the scientific community.

The summary of issues to be addressed before/during the thesis defense

The following modifications will clarify the content of the document:

In section 4.2, the framework is constructed and commented. The content is relevant. It is not possible to read Fig. 4.9 that should appear over a complete page, this would clarify it and help the reader appreciate the different elements that are presented.

Concerning the "global" research question, the candidate should clarify if some hypotheses have been proposed related to maturity level of the company about the different skills and means within the company. The "AS-IS" situation of the considered context is one important input factor of the proposed approach.

The following reference has to be completed:

Schmid, M. and Levy, G. (2012) 'Quality management and estimation of quality costs for Additive Manufacturing with SLS', in ???????

In addition to the different remarks appearing in my previous comments that could help in preparing the defense, here are some questions that appear after reading the dissertation and that will be discussed during the defense.

Q1: The proposed thesis provides a framework to guide in change management process related to the use of new technologies. What is the real and practical trigger to start the process of adoption of a new technology? Is this the market demand? Is this an economical pressure? It seems that the main issue is to evaluate if the company has a real capability to be successful when adopting the proposed framework.

Q2: Is the proposed method only useful for change management or is this also possible/relevant to use it daily in order to minimize the risk of failure when addressing a new project? It seems that this is more

for long term decision but maybe this is not the case.

Q3: Is the company supposed to already know all the capabilities of AM before adopting it? Is design stage sufficient to be transformed and adapted? Different scenarios are proposed that let the reader think that the potential production means are already known.

Q4: Many companies suffer of not controlling the design and manufacturing processes and the main question is the "make or buy" decision making process. Cost is not the unique factor of decision. This decision seems to be "context dependent". Is there any generic definition that is proposed in terms of requirements, context, etc… as part of the foundations of the proposed approach?

Q5: Many experiences show that some companies start with a "buy" strategy for two main reasons: investments capabilities and lack of skills. How do you consider the trigger to switch from a "buy" strategy to a "make" one? What are main KPIs to be considered?

Q6: Product/Process/Organisation complexity issues are mentioned as the base of the modeling. The PPO concept and approach are more than 20-year old. On these three dimensions, did you define a "minimum level of completeness of knowledge" before applying the proposed ECM approach? Is there any priority order: Product before Process before Organisation? All together jointly?

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*