Skoltech
Skolkovo Institute of Science and Technology

Thesis Changes Log

Name of Candidate: Eldar Shakirov

PhD Program: Engineering Systems

Title of Thesis: Integrated Engineering and Manufacturing Change Management in the Additive Manufacturing Context

Supervisor: Prof. Ighor K. Uzhinsky, Skoltech

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

The thesis document includes the following changes in answer to the external review process. The changes description is given according to their location in the final thesis version. The respective review comments and comment codes are given in Appendix A.

Thesis title

Change #1.1
Thesis title update to make it concise and clear for a broader audience.

Location: pages I and III of the final thesis version.

In response to the review comment from Professor Edward Crawley (C10).

Chapter 2.

Change #2.1
Adding the comment on a possible need to measure the company's success based on other indicators related to, e.g., sustainability.

Location: Section 2.1, page 14 of the final thesis version.

In response to the review comment from Professor Alain Bernard (B4).

Change #2.2
Table 2.1 update for inclusion of ceramic materials. The selection of the commercially available technologies for advanced ceramics manufacturing is based on Lakhdar, Y. et al. (2021) 'Additive manufacturing of advanced ceramic materials', *Progress in Materials Science*. Elsevier Ltd, p. 100736. doi: 10.1016/j.pmatsci.2020.100736.

Location: Section 2.2.1, page 29 of the final thesis version.

In response to the review comment from Professor Alain Bernard (B6).

Change #2.3
Figures 2.8-2.9 (Figures 2.8-2.9 in the previous thesis version) color scheme and font size update for better figures consistency throughout the document.

Location: Section 2.2.2, pages 34-35 of the final thesis version.

In response to the review comment from Professor Michael Zäh (Z2).

Change #2.4
Expanding the discussion on build orientation after reviewing the article by Zhang, Y. et al. (2017) 'Build orientation optimization for multi-part production in additive manufacturing', *Journal of Intelligent Manufacturing*, 28(6), pp. 1393–1407. doi: 10.1007/s10845-015-1057-1.
The paragraph following this discussion has been revised for better narration flow.

Location: Section 2.2.3, page 36 of the final thesis version.

In response to the review comment from Professor Alain Bernard (B7).

Change #2.5
Elaborating the discussion on design for AM (DfAM) challenges following the review of the article by Vaneker, T. et al. (2020) 'Design for additive manufacturing: Framework and methodology', *CIRP Annals*, 69(2), pp. 578–599. doi: 10.1016/j.cirp.2020.05.006.
Additionally, a cross-reference to this discussion is now given in section 3.2.2, p. Z.
Furthermore, this discussion has been complemented with a material-structure-performance concept recently presented by Gu, D. et al. (2021) 'Material-structure-performance integrated laser-metal additive manufacturing', *Science*, 372(6545), p. eabg1487. doi: 10.1126/science.abg1487.

Location: Section 2.2.3, page 37 of the final thesis version.

In response to the review comment from Professor Alain Bernard (B5).

Change #2.6
Adding the comment clarifying the hypotheses on the company's maturity level when introducing the primary research question (RQ) of the work.

Location: Section 2.4 (after RQ formulation), page 47 of the final thesis version.

In response to the review comment from Professor Alain Bernard (B10).

Chapter 3.

Change #3.1
Revision and edit of the change scenario steps and of accompanying Figures 3.5-3.7 (Figures 3.5-3.7 in the previous thesis version) for the addition of the change validation by the customer. Also, a corresponding remark has been made at the end of a paragraph before Figure 3.4 (Figure 3.4 in the previous thesis version).

Location: Section 3.1, pages 53-60 of the final thesis version.

In response to the review comment from Professor Alain Bernard (B11).

Change #3.2
Figures 3.4-3.7 (Figures 3.4-3.7 in the previous thesis version) enlargement and reorientation for better readability. Change scenario animation update (available at tiny.cc/ICM_scenario).

Location: Section 3.1, pages 54-50 of the final thesis version.

Own edits.

Change #3.3
Addition of the comment on mutual necessity between ICM and AM. The necessity of adopting an ICM procedure is further driven by the need to use AM, and, at the same time, AM needs ICM for better coordination during technology deployment and operation!

Location: Section 3.3, second paragraph (in the final thesis version), page 68 of the final thesis version.

In response to the review comment from Professor David Hardt (H1).

Change #3.4
Revision of the fourth paragraph in section 3.3 to clarify the explanation of the numerical evaluation necessary for roles distribution analysis.

Location: Section 3.3, page 69 of the final thesis version.

In response to the review comment from Professor David Hardt (H4).

Chapter 4.

Change #4.1

Revision of the first paragraph in section 4.1. The edit specifies an Artificial Neural Network (ANN) technique used in the referenced thesis of Bashir (2000) - the General Regression Neural Network (GRNN) - and refines the reasoning based on sections 6.2, 6.5, and Table 9.1 of the referenced thesis. Appendix B of the changes log provides Section 6.5 from Bashir (2000) for reviewers' convenience. Thus, the ANN acronym has been removed from the list of abbreviations, and the GRNN acronym has been added to it.

Location: Section 4.1, page 72 of the final thesis version.

In response to the review comment from Professor David Hardt (H5).

Change #4.2

Figure 4.5 (Figure 4.5 in the previous thesis version) update for consistent use of the terminology: using "change lead time" instead of "change duration."

Location: Section 4.1.2, page 81 of the final thesis version.

In response to the review comment from Professor David Hardt (H6).

Change #4.3

Addition of the clarification remark in footnote #33: "this work assumes that an engineer's salary does not depend on the type of product to work on."

Location: Section 4.1.4, page 88 of the final thesis version.

In response to the review comment from Professor Alain Bernard (B13).

Change #4.4

Figure 4.9 (Figure 4.9 in the previous thesis version) enlargement and content refinement for better readability. The accompanying description at the beginning of section 4.2.3 is revised as well.

Location: Section 4.2.3, page 95 of the final thesis version.

In response to the review comments from Professors Alain Bernard (B16), Edward Crawley (C3), David Hardt (H2), Michael Zäh (Z1).

Change #4.5

Addition of Figure 4.10 describing the major objects used in the modeling framework and aiming to aid readability of Figure 4.9 (Figure 4.9 in the previous thesis version).

Location: Section 4.2.3, page 96 of the final thesis version.

In response to the review comments from Professors Alain Bernard (B16), Edward Crawley (C3), David Hardt (H2), Michael Zäh (Z1).

Change #4.6

The model background in Figure 4.11 (Figure 4.10 in the previous thesis version) has been updated to match the model configuration in Figure 4.9 (Figure 4.9 in the previous thesis version).

Location: Section 4.2.3, page 97 of the final thesis version.

Own edit.

Change #4.7
Color scheme update in Figures 4.11 and 4.13 (Figures 4.10 and 4.12 in the previous thesis version) for better color consistency throughout the document.

Location: Section 4.2.3 of the final thesis version, pages 97 and 103 of the final thesis version.

In response to the review comments from Professor Michael Zäh (Z2).

Change #4.8
Figure 4.12 (Figure 4.11 in the previous thesis version) enlargement and resolution increase for better readability.

Location: Section 4.2.3.3, page 101 of the final thesis version.

In response to the review comments from Professors Alain Bernard (B16), Edward Crawley (C3), David Hardt (H2), Michael Zäh (Z1).

Change #4.9
Clarification that the values presented in Table 4.13 (Table 4.13 in the previous thesis version) are based on the simulation results.

Location: Section 4.2.4, page 118 of the final thesis version.

In response to the review comment from Professor Alain Bernard (B19).

Change #4.10
Addition of Table 4.14 to define the parts catalog used in the first and second exemplary studies enabled by the manufacturing modeling framework.

Location: Section 4.2.4, page 118 of the final thesis version.

In response to the review comment from Professor David Hardt (H7).

Change #4.11
Color scheme update in Figures 4.15-4.17 (Figures 4.14-4.16 in the previous thesis version) for better color consistency throughout the document.

Location: Section 4.2.4 of the final thesis version, pages 117, 119, and 120 of the final thesis version.

In response to the review comments from Professor Michael Zäh (Z2).

Change #4.12
Figure 4.18 (Figure 4.17 in the previous thesis version) enlargement on a separate page for improved content readability.

Location: Section 4.3, page 122 of the final thesis version.

In response to the review comments from Professors Alain Bernard (B16), Edward Crawley (C3), David Hardt (H2), Michael Zäh (Z1).

Change #4.13
Revision and elaboration of section 4.3, which includes the additional explanation of the proposed integrated approach (in the paragraph before Figure 4.18) and revision of the first stage description (in the paragraph after Figure 4.19) for better clarity. Addition of Figure 4.19 illustrating the proposed approach for integrated simulation across the product development and manufacturing activities.

The purpose of Figure 4.18 (Figure 4.18 in the previous thesis version) is to show how does the implemented framework look; also, the newly added approach diagram in Figure 4.19 is based on Figure 4.18.

Location: Section 4.3, pages 121-125 of the final thesis version.

In response to the review comments from Professors Alessandro Golkar (G2) and David Hardt (H8).

Chapter 5.

Change #5.1
Revision of the first sentence to emphasize the AM context.

Location: Chapter 5, page 126 of the final thesis version.

In response to the review comment from Professor David Hardt (H1).

Change #5.2
The term "prototyping" (especially concerning step 6 of the ICM reference process) is replaced with the terms "production" and "manufacturing." This change aims to emphasize a reference to the latter stage of the change management process since the term "prototyping" may attribute to early prototyping iterations happening during conceptual and detailed design stages.

Location: Chapters 5 and 6.

In response to the review comment from Professor David Hardt (H15).

Change #5.3
Addition of Table 5.1 to facilitate the reader's understanding of the studies composition and interrelation.

Location: Section 5.2, page 131 of the final thesis version.

In response to the review comment from Professor Edward Crawley (C4).

Change #5.4
Addition of Table 5.2 to define the retrospective indicators used in Study #1.

Location: Section 5.3, page 133 of the final thesis version.

In response to the review comment from Professor David Hardt (H9).

Change #5.5
Revision and elaboration of the introductory and concluding paragraphs for each study discussed in Chapter 5. In introductory paragraphs of the corresponding sections, this change adds the references to the process of study shown in Figure 5.5 (Figure 5.5 in the previous thesis version) to clarify the object of study and references to the manufacturing system configuration used in the studies and shown in Figure 5.12 (Figure 5.12 in the previous thesis version). In concluding paragraphs of the corresponding sections, this change revises and complements the summary of the study results for completeness.

Location: Sections 5.3-5.9.

In response to the review comment from Professor Edward Crawley (C4).

Change #5.6
Clarification of the third sentence of the first paragraph in section 5.4. The duration multiplier for the Spiral process architecture – that equals 0.5 – has been taken as an abstract example since there is no tracked reference for this parameter from the use case data.

Location: Section 5.4, page 136 of the final thesis version.

In response to the review comment from Professor David Hardt (H10).

Change #5.7
Figure 5.12 (Figure 5.12 in the previous thesis version) enlargement for improved content readability. The accompanying description on page 137 is complemented with the comments on the dimensional restrictions for layout generation and the reference to Figure 4.10 definiting the major objects used in Figure 5.12.

Location: Section 5.4, page 138 of the final thesis version.

In response to the review comments from Professors Alain Bernard (B16), Edward Crawley (C3), David Hardt (H2), Michael Zäh (Z1).

Change #5.8
Elaboration of textual interpretation of Figures 5.13-5.14 (Figure 5.13-14 in the previous thesis version) given in two paragraphs preceding these figures.

Location: Section 5.4, page 139 of the final thesis version.

In response to the review comments from Professor David Hardt (H11).

Change #5.9
Figure 5.13 (Figure 5.13 in the previous thesis version) enlargement and reorientation for better readability and color scheme update for better consistency.

Location: Section 5.4, page 140 of the final thesis version.

In response to the review comments from Professors Alain Bernard (B16), Edward Crawley (C3), David Hardt (H2), Michael Zäh (Z1).

Change #5.10
Figure 5.13 (Figure 5.13 in the previous thesis version) update for consistent use of the terminology: using "change lead time" instead of "change duration." Figure caption update to improve comprehensibility.

Location: Section 5.4, page 140 of the final thesis version.

In response to the review comments from Professor David Hardt (H6 and H11).

Change #5.11
Elaboration of the explanatory comments for Figures 5.16, 5.17, and 5.22 (Figures 5.15, 5.16, and 5.21 in the previous thesis version), along with the addition of an explanatory Figure 5.15.

Location: Section 5.4, pages 141-142 of the final thesis version.

In response to the review comment from Professor Edward Crawley (C5).

Change #5.12
Color scheme update in Figures 5.8-5.11, 5.14, 5.16-5.17, 5.19, 5.21-5.27 (Figures 5.8-5.11, 5.14-5.16, 5.18, 5.20-5.26 in the previous thesis version) for better color consistency throughout the document.

Location: Sections 5.3-5.9 of the final thesis version.

In response to the review comment from Professor Michael Zäh (Z2).

Change #5.13
Adding the comment on the trend of changes in manufacturing iteration cost and total change cost in Figure 5.21 (Figures 5.20 in the previous thesis version).

Location: Section 5.6, second paragraph, page 145 of the final thesis version.

In response to the review comment from Professor David Hardt (H12).

Change #5.14
Correction of the number reporting an increase in the manufacturing cost: a double increase in the masses of all components led to a 1.7 times increase in the manufacturing cost (and not to a 2.3 times increase). The incorrect number reported in the previous thesis version (2.3) has been mistakenly derived as a ratio between the costs at mass change fraction equal to 2 and the costs at mass change fraction equal to 0.5, i.e., for a four times increase in the masses of all components.
The same corrections have been done in section 5.8.

Location: Sections 5.7, second paragraph (p. 148); section 5.8, second paragraph (p. 149).

In response to the review comment from Professor David Hardt (H13).

Change #5.15
Elaborating the comment on the slope and linear trends of the manufacturing total duration and manufacturing total cost lines in Figure 5.24 (Figures 5.23 in the previous thesis version). Because of this, the first paragraph of this section (section 5.8) has been revised and expanded as well.

The same explanation has been added in section 5.7 for the same lines in Figure 5.23 (Figures 5.22 in the previous thesis version).

Location: Sections 5.7, second paragraph (p. 148); section 5.8, second paragraph (p. 149).

In response to the review comment from Professor David Hardt (H14).

Change #5.16
Figures 5.26-5.27 (Figures 5.25-5.26 in the previous thesis version) enlargement and reorientation for better readability.

Location: Section 5.9, pages 152-153 of the final thesis version.

In response to the review comments from Professors Alain Bernard (B16), Edward Crawley (C3), David Hardt (H2), Michael Zäh (Z1).

Change #5.17
Expanding the fifth recommendation point (section 5.10) with the conclusions on a linear correlation of the manufacturing total cost and manufacturing total duration with the variable parameters of the studies ##5-6, i.e., part mass and support to part mass ratio.

Location: Section 5.10, the fifth conclusion point, page 155 of the final thesis version.

In response to the review comment from Professor David Hardt (H16).

Chapter 6.

Change #6.1
Re-emphasizing the comment on mutual importance between ICM and AM, which was also highlighted in section 3.3.

Location: Section 6.1 (paragraph two), page 157 of the final thesis version.

In response to the review comment from Professor David Hardt (H1).

Change #6.2
Adding the comment on the extension of the presented framework for the analysis of the set-based concurrent engineering (SBCE) practice.

Location: Section 6.3 (paragraph four, last two sentences), page 162 of the final thesis version.

In response to the review comment from Professor David Hardt (H17).

Change #6.3
Text edit for consistent use of the engineering change and manufacturing change terms.

Location: Section 6.3 (paragraph five, last two sentences), page 162 of the final thesis version.

In response to the review comment from Professor Edward Crawley (C1).

Change #6.4
Elaboration of the paragraph discussing the limitation in validation of the proposed approach. It acknowledges that the thesis can claim for contribution to knowledge but not to practice. Also, it specifies the validation steps proposed for future work.

Location: Section 6.3, pages 163-164 of the final thesis version.

In response to the review comments from Professors Alessandro Golkar (G4-G5), Alain Bernard (B20), Edward Crawley (C9), and Alexey Nikolaev (N2).

Change #6.5
Addition of the paragraph discussing the necessary validation of the value anticipated from integrating Engineering Change Management and Manufacturing Change Management into Integrated Change Management.

Location: Section 6.3, page 164 of the final thesis version.

In response to the review comment from Professor Edward Crawley (C7).

Change #6.6
Refinement of the paragraph discussing the limitation in considering the conventional manufacturing context. The framework extension proposed therein would allow us to compare Integrated Change management in the conventional and additive contexts and, hence, study the additional benefit of AM.

Location: Section 6.3, page 164 of the final thesis version.

In response to the review comments from Professors Edward Crawley (C8) and David Hardt (H1).

Change #6.7
Addition of the paragraph acknowledging the limitation of the considered AM context. Since the interview-based study described in section 3.2 has been conducted only with one manufacturer, within one industrial sector, and on one specific AM process, the generality and transferability of the obtained insights is limited.

Location: Section 6.3, page 165 of the final thesis version.

In response to the review comment from Professor Michael Zäh (Z8).

Change #6.8
Addition of the paragraph acknowledging the contextual limitation related to applicability of the approach. Since the proposed model-based approach has been demonstrated only in one industrial context, its applicability and simulation robustness and sensitivity to other sectors requires further validation.

Location: Section 6.3, page 165 of the final thesis version.

In response to the review comments from Professors Alessandro Golkar (G5), Alain Bernard (B21), and Alexey Nikolaev (N1).

Change #6.9
Addition of the paragraph acknowledging the limitation of the work in consideration of other KPIs for a more systemic analysis of AM and ICM impact. For example, the KPIs related to environmental sustainability that are discussed by Chandrakumar, C. and McLaren, S. J. (2018) 'Towards a comprehensive absolute sustainability assessment method for effective Earth system governance: Defining key environmental indicators using an enhanced-DPSIR framework', *Ecological Indicators*, 90, pp. 577–583. doi: 10.1016/j.ecolind.2018.03.063.
Also, this paragraph acknowledges that the "make or buy" consideration was not addressed extensively and that it is an important aspect in the quantitative study of the process planning alternatives.

Location: Section 6.3, page 165 of the final thesis version.

In response to the review comment from Professor Alain Bernard (B12 and B3).

Change #6.10
Revision of the last sentence in the paragraph discussing the limitation in addressing the impact of other new technologies. Defining more clearly the current scope of applications addressed by the framework. This paragraph aims to underline that the presented framework, currently, is not suitable to analyze any new manufacturing technology; such an extension would require a further population of the model libraries. Having them, it is expected that the framework can be applied to the analysis of other new manufacturing technologies.

Location: Section 6.3, page 166 of the final thesis version.

In response to the review comment from Professor David Hardt (H18).

Change #6.11
Addition of the paragraph acknowledging limited user-friendliness of the approach and, hence, its practical applicability.

Location: Section 6.3 (penultimate paragraph), page 166 of the final thesis version.

In response to the review comments from Professors Alain Bernard (B22), Alexey Nikolaev (N1), and Alessandro Golkar (G6).

Change #6.12
Addition of the figure summarizing thesis contribution (Figure 6.2).

Location: Section 6.6, page 173 of the final thesis version.

In response to the review comment from Professor Edward Crawley (C6).

Changes in Bibliography

Change Bib-1
Completing the reference: Schmid, M. and Levy, G. (2012) 'Quality management and estimation of quality costs for Additive Manufacturing with SLS', in. ETH-Zürich. doi: 10.3929/ETHZ-A-010335931.

In response to the review comment from Professor Alain Bernard (B23).

Location: Page 188 of the final thesis version.

Miscellaneous clarification and error correction edits

Multiple grammar corrections have been made in response to the review comments from *Professors David Hardt (H3)* and *Alessandro Golkar (G1)*.

Following the comment of *Professor Michael Zäh (Z3)*, the convoluted sentences found along the thesis have been split for better readability (the references to paragraphs are given according to the final thesis version):

- In the paragraph after Figure 2.10, p. 36.
- In the first paragraph of section 4.1, p. 72.
- The sentence before Figure 4.2, p.75.
- In the second paragraph of section 4.2.3.4, p. 102.
- The sentence on setup times definition in the first paragraph of section 4.2.3.6, p. 105.
- The sentence explaining the assignment of AM capital costs in section 4.2.3.6, after formula (12), p. 107.
- In the paragraph before Figure 4.18, p. 121.
- In the paragraph after Table 5.3, p. 133.

Following the comment of *Professor Michael Zäh (Z4)*, citations have been revised to avoid linking multiple sources to one paragraph or sentence. This is necessary for a more transparent assignability of the sources. The changes include (the references to pages are given according to the final thesis version):

- Splitting the reference to Esmaeilian et al. (2016) and Conner et al. (2014) on p. 28.
- The reference to Thompson et al. (2016) and to Meisel et al. (2017) on p. 37. The reference to Meisel et al. (2016) has been removed as redundant and used later in illustration of post-processing challenges (p. 38) and in the example of supports' volume minimization (p. 67).

- Splitting the reference to (Jarratt, Clarkson and Eckert, 2005; Hamraz, Caldwell and Clarkson, 2013) and (Koch, Gritsch and Reinhart, 2016; Koch, Michels and Reinhart, 2016) on p. 51.

The thesis still includes citations with several references if one of two cases takes place:

- If each source is considered to be a reference to a given statement; e.g., the citation to (Barricelli, Casiraghi and Fogli, 2019; Jones et al., 2020; Trauer et al., 2020) on p. 3, where each reference reviews various definitions of the digital twin concept.
- If the citation represents a chain of references that build the final argument consequently on each other. For example, in the citation to (Krishnan and Ulrich, 2001; Pahl et al., 2007; Ulrich and Eppinger, 2011) on p. 14, Pahl et al. (2007) and Ulrich and Eppinger (2011) rely on the work of Krishnan and Ulrich (2001). We might have omitted the citation to Pahl et al. (2007); however, the thesis considers Pahl et al. (2007) being a critical reference for a discussion of the product development process and therefore adds it into this multi-source citation.

Other minor changes include:

- Revision of the paragraph after Figure 4.14, pp. 112-113.
- Edits in the captions of Figures 5.1-5.3 (Figures 5.1-5.3 in the previous thesis version), pp. 127-128.
- Revision of the second paragraph of section 5.4, p.137.
- In Figure 5.18 (Figure 5.17 in the previous thesis version), correction of the sequence number for step seven of the right matrix, p. 144.
- Edit in the caption of Figure 5.20 (Figure 5.19 in the previous thesis version), p. 146.

Comments on the rest of the feedback received from the Jury, which was considered but addressed indirectly or not addressed through the changes in the thesis final version:

- The “toy problem” suggestion has been addressed via the improvement of the use case explanation in Chapter 5. The development of the “toy problem” scenario is considered for future work.
- Moving the discussions on chapter-specific state of the art has been considered. It was concluded that keeping the reviews closer to the proposed approach can provide a more in-depth look into the problem and facilitate understanding.
- Introducing the research methodology after presenting the research questions has been considered. It was concluded that presenting the methodology early in the work is important to explain the thesis structure, even though the methodology refers to the research questions that the reader would learn later.
- The research work related to the application of discrete event simulation to value network analysis has been reviewed and considered relevant to the topic. However, an in-depth consideration including the comments on this topic along the thesis has been considered out of the scope of this work.

Appendix A. The coded summary of the review comments provided by the Jury.

The summary of the review comments from Professor Alain Bernard	
Chapter 1 B1	It would have been better to introduce it [DRM] 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
B2	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.
Chapter 2 B3	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".
B4	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.
B5	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)
B6	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
B7	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.
B8	Some incoming papers about ABC method applied to costing for AM are to be published by Qussay Jarrar et al.
B9	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…
B10	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.
Chapter 3 B11	On Fig. 3.5, it would be interesting to "close the loop with the customer" and moreover, with "the trigger" of the change process. .. 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.

B12	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.
Chapter 4 B13	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.
B14	... the proposed approach is to be considered carefully because this [the approach] 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.
B15	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.
B16	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.
B17	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.
B18	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
B19	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)
B20	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.
Chapter 5 B21	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.
B22	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
Bibl. B23	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 ???????
Publ. B24	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 the review comments from Professor Edward Crawley	
General C1	Need to consistently use engineering change and manufacturing change (or product change and manufacturing change) but not a mixture

Chapter 2 C2	"consider writing a survey paper to capture and codify this literature"
Chapter 5 C3	There are a number of figures, for example Manufacturing system configuration figure 5.12, that need to be larger for readability
C4	In the Chapter 5 studies – each study should have a summary of objective, and a summary of result (I see results are in compiled into section 5.10). To the extent practical, each study should have a: Figure like 5.17 at the beginning of each study – somewhat of a roadmap in DSM form Figure like 5.18 and/or 5.21 at the end summarizing the study outcomes
C5	The colormaps in Figures 5.15, 5.16, 5.21 need to have a comprehensive explanation
Chapter 6 C6	Suggestion to add a figure summarizing the contribution.
Suggested additional work C7	The development of a case with a task that is done in an integrated way, and then the exact same task is redone, but with EC and MC separate, so that we can see benefit of the integration.
C8	The development of a case with AM and conventional manufacturing, so that we can see the additional benefit of AM in integrated EC/MC.
C9	The development of a "physical validation case" – to match to either previous EC/MC models or real data.
C10	Shorten the thesis title to make it concise and clear for a broader audience
The summary of the review comments from Professor Alessandro Golkar	
General G1	It is recommended that the candidate checks once again the manuscript for occasional typos and English mistakes (example: 5.5 The context of a the use case à use case context).
Chapter 4 G2	While the approach has been comprehensively described in the document, a potential way to improve its understanding to the reader is the introduction of an approach diagram. In such a diagram, the approach would be decomposed into macro steps, with appropriate references to the sub-sections of chapter 4, which is presenting the approach.
Chapter 5 G3	The case study is convincing and well structured. However, the case study is also difficult to grasp for non-experts of the aeronautical sector. In order to improve the clarity of the manuscript, I recommend the author to develop a simple "toy problem" (for instance, for which model calculations could be performed by hand), and discuss it.
G4	The development of a toy problem will also help the candidate to address one of the key limitations of the thesis, which is the lack of comprehensive validation. The candidate itself discusses the issue of validation as a limitation of the work. However, such a limitation could be overcome (albeit in part) through validation on a "toy problem" for which analytical results could be derived (by hand, or by simple spreadsheet calculations for example).
Chapter 6 G5	Another key limitation of the thesis is the demonstration of the generalization of the approach. Ideally, the thesis would have had at least two case studies in two different sectors, in order to provide convincing evidence of its broad applicability in industrial engineering. Perhaps the author will not have time to do so during his thesis process, but I highly recommend him to think at a new case study, perhaps in future work. A brief discussion of such opportunity of future work could perhaps be expanded in the text.

G6	Perhaps Eldar could think as well to develop the innovation component of his work, in order to unlock its commercialization value, for example through the development of a patent.
Publ. G7	I believe Eldar will have an opportunity to publish at least one paper in a Q1 international journal based on the results of his work.
The summary of the review comments from Professor David Hardt	
General H1	Make very clear that the ICM framework that is developed is general, but is driven by the needs of using an AM process, and that the case study is for that process. At times it is not clear how general the work is. Is it always driven by the characteristics of AM? This is important to the generalization discussion in Chapter 6
H2	A number of the figures of the integrated system are not useful as presented. For example, Figure 5.12 shows a manufacturing system diagram with more than 100 symbols and none are either readable or defined. Whether this is a standard format or not, it should be legible and fully explained.
H3	Other comments sent with the manuscript include clarifications, grammar suggestions and error corrections
Chapter 3 H4	Unclear explanation of the numerical evaluation necessary for roles distribution analysis in section 3.3.
Chapter 4 H5	"The ANN-based method does not depend on a presumed function yet still requires the historical relationship patterns between effort and other independent design variables, the effort drivers." -- does it not?
H6	On the reference to Figure 4.5 in the first sentence of section 4.1.4: where is this [major output of the model is an estimation of the EC lead time] shown in the figure?
H7	On Figure 4.15: define the part types 1-9
H8	On Figure 4.17: what does this Figure tell us? What is the message?
Chapter 5 H9	On the use of retrospective indicators in Table 5.1 of the previous thesis version: need a table to define in on place
H10	Why [the duration multiplier] is 0.5?
H11	On the explanatory paragraphs before Figures 5.13-5.14 and figures themself: please explain more fully how to interpret the figure. What does the numbering mean? Does it refer to the process steps? What does the shading mean?
H12	On the trend of a change in manufacturing iteration cost with reduction of the unrecyclable fraction: looks linear?
H13	On the increase in manufacturing cost in result of part mass increase (section 5.7): but why greater than 2? No scale efficiencies?
H14	On the line showing the change in manufacturing total duration in section 5.8: this reflects the ratio of (support mass / part mass)? The effect is small?
H15	Suggestion to use the term "production" instead of "prototyping" (section 7)
H16	For point 5 of recommendations given in section 5.10: suggesting to make a comment on the "mass ratio effect" observed in study 6 (related to comment H13).
Chapter 6 H17	Can your framework be extended to SBCE? (a comment to the fourth paragraph of section 6.3)

H18	Does your work, therefore, lend itself to analysing new manufacturing technology? (a comment to the penultimate paragraph of section 6.3)
H19	Great idea, need to do (on the proposal of a Process Twin concept in section 6.4)
The summary of the review comments from Professor Alexey Nikolaev	
General N1	At the same time, even though the author discusses the framework validation (Chapter 5), to make the framework a real tool used and recognized by practitioner's community, further research as well as pilot deployments, case studies, etc. are required.
N2	Additional validation of the applicability of the framework to real change management processes used in real organizations (accounting legacy processes and frameworks, organization culture, decision making practices, technological, market and organizational features across various industries and particular organizations etc.) as well as adequacy and reliability of the results predicted by simulation are required.
N3	This is something to be addressed during the thesis defense or to be considered as possible suggestion for further research of the author.
The summary of the review comments from Professor Michael Zäh	
General Z1	Not all figures are of high quality
Z2	They [Figures] display an inconsistent color scheme as well as variations in text size and font style
Z3	Long and convoluted sentences impede the reading flow at some points
Z4	Citation: Linking multiple sources for one paragraph should be avoided because otherwise the assignability of the sources to the contents is not clear
Chapter 1 Z5	The main aspects of the research motivation are addressed in a condensed form.
Chapter 2 Z6	At this point, a clearer separation of the fundamentals from the state of the art would further clarify the need for research.
Chapter 3 Z7	The state of the art on the chapter-specific topics is given, which should, however, have been moved to the beginning. [refers to Chapters 3-4]
Z8	It should be noted that the [interview-based case] study was conducted with only one manufacturer in the energy sector. It appears that the results have a limited generality and thus transferability to different industries. ... Overall, it is unclear to what extent the results can be applied to other AM processes as new metal-based technologies gain importance. ... few important issues are not addressed, such as transferability to other AM processes and industries.
Publ. Z9	The author's publication list could, however, have been supplemented by a scientific paper in a journal with a higher impact factor.

Appendix B. The excerpt from Bashir (2000).

6.5 Summary

Unlike traditional regression analysis, a general regression neural network (GRNN) is based on the probability density function of the observed data rather than on a presumed function. In this chapter, general regression neural network (GRNN) estimation models were constructed for the data from CMC and GE. The input variables were the same as those used by the multivariable parametric estimation models described in the previous chapter.

The results clearly show that the artificial neural networks can be considered as a good tool for estimating design effort. Within the limited data sets, the developed models produced good results. A comparison between the GRNN estimation models with parametric models based on traditional regression analysis showed that both models had about the same accuracy. This conclusion should not be generalized; some models may perform well on certain data, others may not. However, the sole purpose of this work was to demonstrate the capabilities of ANNs as an alternative method for estimating design effort. ANNs can be more practically utilized for cases where a mathematical relationship is not easily established.