Skoltech
Skolkovo Institute of Science and Technology

Thesis Changes Log

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PhD Program: Engineering systems

Title of Thesis: Innovative technological pathway for new commercial applications of Stirling cycle-based systems

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The thesis document includes the following changes in answer to the external review process.

Changes are listed in the chronological order of receiving reports from the members of the Jury. Each chapter section first contains changes related to the content in reply to comments and in the end – minor corrections to the text. Changes in the abstract, list of figures and tables are put in the end of document.

CHAPTER I

In response to comments of Dr. Christophe Goupil and Dr. Lorenzo Ferrari about the technical specification for the Stirling machine:

I extended Section I.2.4 with additional technical information about the Stirling machine and the test rig. The section now includes four subsections "*The structure of the Stirling refrigerator*", "*Technical parameters of the Stirling refrigerator and the thermal chamber*", "*The structure and technical parameters of the test rig*", and "*Operational characteristics of the Stirling refrigerator*". Similar figures and tables in Chapter V and VI were removed to avoid repetition, and the referencing thought the text was corrected. I also made corresponding changes to the chapter list of figures and tables in the beginning of the dissertation.

In response to the recommendations of Dr. Clement Fortin about using masculine and feminine pronouns and about reference format in the text:

In the preamble of the chapter, I added: "As a general note, in the course of the chapters, when referring to designers, I use the masculine pronouns generally and sometimes the feminine form when appropriate. For more than two consequent references, for example [1], [2], [3], I omit the references in the middle and write [1]-[3] for simplicity."

In response to comments of Dr. Ighor Uzhinsky about analysis of market requirements:

In the beginning of section "I.3 Object of study", I added a clarifying sentence that this work focuses on the development of design methods and not on market requirements. The work assumes that the requirements are known and offers a set of design methods that help to choose among alternative design decisions when developing a commercial system according to assumed requirements. In section "I.6.1 Concept development (Chapter II and IV)", I added for clarity to

the first sentence: "…that would satisfy general market requirements supplied as an input to the concept stage." With the same intention, I added in the preamble of Chapter II: "while satisfying the market requirements identified prior to the concept stage during marketing research." In Chapter I, section "I.5 Dissertation structure" beginning from the second paragraph, I added the discussion on methodological limitations of conducting market analysis in this dissertation.

Corrections in the text:

In the preamble to the chapter: "technology push" → "the "technology push" concept"; "The result of such a contradiction is" → "The result of such a contradiction could be"; "systems from energy conversion technologies" → "systems based on energy conversion technologies"

In the section "I.1 Motivation": "essential to the author" → "essential for the author"

Table 2: "mustimeter" → "multimeter"

In the beginning of the section I.2.4, I added: "This technical specification section describes in detail the structure, technical parameters, and operational characteristics of the studied Stirling machine with its test rig."

"through heat exchanger" → "through cold head"

In section "I.2.5 System level definitions": "through different thermodynamic states" → "through four thermodynamic processes"; "These states include isothermal compression, isochoric expansion, isothermal expansion, and isochoric compression." → "These processes include compression with constant temperature, expansion with constant volume, expansion with constant temperature, and compression with constant volume."

In section "I.5 Dissertation structure": "focus on commercial value with the aim to serve market requirements rather than scientific objectives" → "focus on increasing commercial value by fulfilling market requirements rather than following scientific objectives"

In section "I.6 Thesis statement", I edited and further clarified the thesis statement.

In section "I.6.1 Concept development (Chapter II and IV)": "Therefore, there is a need for a method that helps to identify as many alternative design concepts in literature, both scientific and patent, as possible to compare design alternatives and craft a competitive concept design." → "Therefore, there is a need for a method that helps to find high number of alternative design configurations in scientific and patent literature for the comparison and the development of competitive design concepts."

In section "I.6.2 System design (Chapter II)": "This design problem was solved in my MSc thesis with the application of the systems engineering concept "tradespace exploration." → "I developed the objective method during my MSc thesis by adapting the "tradespace exploration" methodology from systems engineering literature."

"However, the use of this method is essential here because it links the concept stage and the detail design stage that are both studied in this dissertation and it forms a coherent and novel life-cycle design methodology for the development of commercial energy conversion systems." → "However, the application of this method in this dissertation is essential, because the method links the concept stage and the detail design stage, which are both studied in this work, in a coherent and novel life-cycle design methodology for the development of commercial energy conversion systems."

In section "I.6.3 Detail design (Chapter III)": "At this decisive design stage of commercial development, the resources a finite." → "The development resources during this important design stage are finite."

"the detailed development" → "a detailed development"

"the management of *designers interplay under finite resources"* → *"*reaching an optimal design outcome for *collaborating disciplinary designers under finite resources"*

"Such factors define the importance of a design method that accounts for the designers' interaction during the design process. This problem was solved with the application of a novel design method based on game theory." → "This problem calls for a design optimization method

that accounts for the designers' interaction during the design process. Such method was developed with the application of game theory."

In section "I.6.4 Testing and refinement (Chapter V)": "Designing a system "on a digital screen" is a relatively simple matter. Building an operational experimental design is far from simple." → "Many technical aspects in the operation of a real system are difficult to predict during the detail design. This limitation poses a question:…"

In section "I.6.5 Production and rump-up (Chapter VI)": "At this stage, the main design challenge is to *scale technology for different applications*." → "The main design challenge at the production stage is how to *scale technology for different applications*."

"It is not difficult to see how similar problem are likely to arise during the development of other science-intensive energy-conversion technologies." → "Similar design challenges may be relevant for the development of other science-intensive energy-conversion systems."

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CHAPTER II

In response to the comment of Dr. Lorenzo Ferrari about the results of the tradespace analysis:

In Section IV.9, I added additional plots (Fig. 21) for Cost-Efficiency and Power-Efficiency tradeoffs with corresponding comments. I also added the plots (Fig. 22) and analysis that demonstrate the effect of bore, stroke, cold temperature and hot temperature on the tradeoff Cost-Power for the alpha-type engine. For additional clarity of effects by design parameters on the cost, I added Fig. 23. To deepen the understanding of the extended results of the tradespace analysis, I added an additional figure (Fig. 19) with schematic views of alpha, beta and gamma engine types and comments to this figure. I made corresponding changes to the list of figures in the beginning of the dissertation.

In response to the recommendations of Dr. Carolina Costa:

Section "III.I United States": In the end of the third paragraph, the incomplete sentence "The research activities were." was removed.

Fig. 11b, in the caption: "Research topics in 65 documents, Japan, 1960-2006" → "Research topics in 65 documents, Japan, 2007-2018"

Fig. 18: The colors of the graph were changed for easier reading.

In response to comments of Dr. Ighor Uzhinsky about usefulness of conclusions for a subsequent work:

In the end of the section "IV.8 Final remarks on selecting design alternatives", I added three paragraphs commenting that based on the review of literature sources there is a need to analyse the performance of alternative engine configurations (alpha, beta, gamma) during the system design stage. I added the figure with schematic views of these configurations and discussed what key metrics, and design parameters should be used during the controlled comparison. I added a point in the conclusion to the chapter that reflects this result.

In the first paragraph of section "IV.9 Downsizing the space of design alternatives", I added for clarity: "For the demonstration example, I selected alternatives for kinematic configurations – alpha, beta and gamma type discussed in the previous section."

In the end of the same section IV.9 before the last paragraph, I added a paragraph-long discussion based on the results of tradespace analysis at the system design stage that the alpha configuration was selected as a requirement for the detail design stage. I added a point in the conclusion to the chapter that reflects this result.

Corrections in the text:

In the preamble: “design configurations” → “design concepts”; “This chapter” → “The present chapter”; “tests this method through the analysis” → “tests this method in the conceptual analysis”; “was to identify” → “was the identification of”; “configuration of competitors” → “configurations of competitors”; “and the leading” → “, leading”; “method that studies” → “method that helps to research”

Fig. 9: “US” → “the US”

Fig. 19: “The consequence of steps to reduce to evaluate concepts” → “The sequence of steps to evaluate conceptual designs”

Section “IV.1.1 Scientific literature”: “automotive application [46, 47]” → “automotive application [46], [47]”; “US Department of Energy” → “the US Department of Energy”

Section IV.9: “The method to solve” → “The proposed method to solve”

“The most common approach to conduct this selection is to optimize a figure of merit – a quantitative parameter of technical performance – for a relevant design element or the whole system.” → “The most common approach to choose among design alternatives is to perform design optimization. This procedure includes the maximization of conflicting figures of merit – quantitative parameters of technical performance – attributed to objective design alternatives.”

In section “IV.9 Downsizing the space of design alternatives”: “These set of input design parameters is supplied to a system model that is capable of evaluating different concepts based on physical relations and estimating the equipment cost.” → “These input design parameters are integrated into a system model with physical relations and cost equations to evaluate different design concepts and their equipment costs.”; “than for bore” → “than for the borehole diameter”; “we selected” → “our team selected”; “This difference” → “This diminishing of efficiency”; “tradeoff” → “trade-off”; “helps” → “help”; “in a contradictory manner” →” in a conflicting manner”; “system configuration” → “system configurations”; “downsized based on the market requirements and using” → “downsized using market requirements and”

In section “IV.10 Novelty and Contribution”: “accurate account how the scientific and patenting activities for Stirling engine developed over the last 58 years” → “accurate account of scientific and patenting activities for Stirling engine over the last 58 years”; “into account” → “into consideration”

In section “V Conclusions”: “is a number one” → " is the number one”; “space explorations” → “space exploration”; “US” → “the United States”; “United States” → “the United States”;

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CHAPTER III

In response to comments of Dr. Lorenzo Ferrari and Dr. Carolina Costa about the modelling equations for the micro-CHP:

I created the Appendix section to the chapter and added the modelling equations with implemented constant parameters and the table with validation results of the model. In Section II.4.1 “System model of micro-CHP” I added the sentence with the reference to the Appendix: “The modelling equations and model validation are in the Appendix to this chapter;” and made corresponding changes to the chapter contents and list of tables in the beginning of the dissertation.

In response to comments of Dr. Lorenzo Ferrari about technical parameters other than power and affordability:

I added a paragraph in the end of Section “IV.1 Game theory in design optimization” with additional comments on bore, stroke, hot and cold temperatures for Pareto-optimal and Nash front optimization.

In response to comments of Dr. Christophe Goupil about Nash optimization:

I added four paragraphs before the last paragraph in Section "IV.1 Game theory in design optimization", where I discussed some key criticism to Nash optimization found in economics literature and how these critical points apply to design optimization.

In response to comments of Dr. Christophe Goupil about too rigid specifications and resulting constrains on design outcomes:

The second paragraph in Section "IV.1 Game theory in design optimization" discusses this limitation. I changed the text to highlight possible limitations for innovativeness of design optimization outcomes with the proposed game theoretic methodology.

In response to the recommendations of Dr. Carolina Costa:

Section "II.2 Analysis of game theoretic assumptions"**:** "Osbourn [29]" → "Osborne [29]"

In response to comments of Dr. Ighor Uzhinsky about usefulness of conclusions for a subsequent work:

In the preamble to the chapter, I added the link between the preceding chapter with the requirement to design an alpha-type system and the present chapter, where I analyse how a group of disciplinary teams would design such system during detail design. In section "IV.1 Game theory in design optimization" in the end of the first four paragraphs, I added practical implications for the detail design stage. These implications were put in the conclusion section as practical recommendations for the detail design stage for future. I also added a point in the beginning of the conclusion section that clarifies how the results of this chapter are applicable for the detail design stage.

Corrections in the text:

In preamble to the chapter: "Multidisciplinary nature of energy conversion systems" → "The multidisciplinary of energy conversion systems"; "Although the proposed in this chapter design methodology was tested only on the model of the Stirling engine system, its principles could be applied to the detail design…" → "Principles of the design optimization method developed in this chapter could be applied to the analysis of the detail design…"; "Unlike the conceptual and system design" → "Unlike the conceptual and system design stages"; "discipline could be counter-productive" → "discipline is not the objective of this chapter"; "represent essential aspects of the design process at this stage" → "are challenging aspects of the detail design process with great potential for improvement"; "Principles of the design optimization method developed in this chapter using game theory could be applied to" → "The principles of this design optimization method could be applied in"; "All these processes" → "Their design"

In section "I Introduction": "[21]–[23]" → "[21]-[23]"

"Furthermore, the implications of reallocating design decisions among discipline designers are not fully understood." → "Furthermore, the effect of different design authority among discipline designers on the system design outcome is not understood in literature."

In section "II Framework": "abowe" → "above"

In section "II.2.1 The design process is a strategic game": "According to this assumption, in the design process exists a set of players." → "According to this assumption, a number of players participate in a design process."

In section "II.2.6 Time is absent from the model": "This assumption allows studying…" → "This is a strong assumption, but it allows studying…"

In section "II.4.1 System model of micro-CHP": I removed the sentence "This object of study was selected because of its high technological potential and technical expertise of the authors in this field."

In section "IV.3 Novelty and Contribution": "Proposed algorithm" → "Proposed an algorithm…the…the design of"

In section “V Conclusions”: “of this question to” → “of this problem for the system”;
Formatted references.

CHAPTER IV

In response to the recommendations of Dr. Carolina Costa:

Fig. 17. The colors of the graph were changed for easier reading.

In response to comments of Dr. Ighor Uzhinsky about usefulness of conclusions for a subsequent work:

In the preamble to the chapter, I added “To formulate the development strategy for the test and refinement stage, it was important to perform a similar analysis of the technical literature for the refrigeration application using big data approach.” In the section “III.1 Maturity of the domain” in the last paragraph, I added a comment that based on results of literature analysis, the requirement for the testing and refinement stage was to maximize cooling capacity of the experimental system to extend possible market applications. I added a point in the conclusion to the chapter that reflects this result.

Corrections in the text:

In the preamble to the chapter: “the process of breaking in the mechanical drive” → “the break-in process for the mechanical drive”; “lead” → “led”; “is crucial” → “was crucial”; “Keeping the focus did not happen” → “However, we did not keep the focus on the engine application”; “the heat transfer system from the external source to the engine” → “the system to transfer heat to the engine from the external source”

“we started in parallel with the initial tests the evaluation” → “in parallel with the initial tests, we started the evaluation”

Section “II.3 China”

“an noticable" → “a noticeable”

“high-cooking capacity” → “high-cooling capacity”

Section “III.1 Maturity of the domain”

“this” → “these”.

Section “III.4 Final remarks on selecting design alternatives”

“design alteratives” → “design alternatives”

In section “III.6 Novelty and Contribution”: “Identified historically accurate account how the scientific and patenting activities for Stirling refrigerators developed over the last 58 years” → “Identified a historically accurate account of scientific and patenting activities for Stirling refrigerators over the last 58 years”; “Most research” → “Most research activities”

Formatted references.

CHAPTER V

In response to the comment of Dr. Carolina Costa about the comparison between the high-tolerance PCP and dry-friction PCP:

I added two paragraphs in the end of section “IV.1 Piston-cylinder sealing in Stirling refrigerators” addressing this comment. The discussion is also supported by a comparison table and a figure with the refrigerator temperature measurements for the dry-friction PCP. I also made corresponding changes in the list of figures and tables in the beginning of the dissertation.

In response to comments of Dr. Ighor Uzhinsky about usefulness of conclusions for a subsequent work:

In the preamble to the Chapter, I added the connection to one of conclusions in the previous chapter: “This knowledge [results in Chapter IV] helped to set the strategy for desired operation of the developed Stirling machine, which is the maximization of the cooling capacity.” In Section “IV.1 Piston-cylinder sealing in Stirling refrigerators” and in the conclusions, I added a connecting sentence to the next chapter: “The operational data for the dry-friction PCP collected during the work reported in this chapter was used in the next chapter to validate the physical model of the Stirling refrigerator system for scaling for different commercial applications.”

Corrections in the text:

In preamble of the chapter: “Existing scientific and engineering literature…” → “The existing scientific and engineering literature…”; “the state of art technical parameters for Stirling refrigerators” → “the state of art for technical characteristics of Stirling refrigerators”; “The main challenge with this element is that it operates under pressure gradients and high piston speeds. These conditions change more than nine times per second. This is why analytical modelling of this component is difficult and require experimental optimization.” → “This element operates under challenging conditions. The piston-cylinder seal experiences pressure gradients over the gap and has high surface speeds. These parameters change more than nine times per second due to typical shaft frequencies from 9 Hz to 25 Hz. The analytical modelling of this component is difficult because the operation of the seal is a complex combination of factors from mechanics, fluid dynamics and tribology. An alternative approach to analyse different design alternatives for the seal or other critical system components is to perform experimental optimization.”; “most stressful conditions” → “most stressful and difficult to model conditions”; “will be low” → “is likely to be low”

In the Nomenclature table “at the be- ginning” → “at the beginning”

In the section “I Introduction”: “Cascade vapor-compression refrigeration (CVCR)” → “Cascade vapor-compression refrigeration, cascade VCR or CVCR”

“[5]-[7], [3]” → “[3], [5]-[7]”

“Empirical studies recently showed significant efficiency improvement (Fig. 1)” → “Empirical studies recently showed significant improvement of coefficient of performance or COP (Fig. 1)”

“in her analysis Legett” → “in her analysis, Legett”

“[8], [9], [10]” → “[8]-[10]”

In section “I.2 High-tolerance seal”: “in-creased sealing length” → “increased sealing length”

“The principal diagram and the external view of our SR test rig was depicted on Fig. 5.” → “The principal diagram and the external view of the SR test rig was depicted in Fig. 8, Chapter I.”

“Earlier findings [11], [12], [13], [14]; [15], [16])” → “Earlier findings [11]-[16]”

“The PCP experiences reduced side forces due implementation of the improved Ross-yoke mechanism [31] (1)” → “The PCP has reduced side forces because the pistons in the improved Ross-yoke mechanism (1) move in parallel to the cylinder walls [31].”

In section “II.6. Static friction moment and friction losses”: “[42], [43], [44]” → “[42]-[44]”

In section “II.3.3 Similarity condition”: “characteristic size d e” → “characteristic size d_e”

In section “V Conclusions”: “…cooling temperature down to −150°C without its increase after 10 hours of cumulative operation.” → “cooling temperature down to −165°C without its increase after 19 hours of cumulative operation.”; “Conducted experimental optimization of the piston-cylinder sealing in a real Stirling refrigerator with the alpha configuration of the Ross-yoke mechanical drive with the improvement of the minimum refrigeration temperature from 173 K to 123 K” → “Studied experimentally the performance of a high-tolerance and dry-friction PTFE seals for the piston-cylinder pair in a real Stirling refrigerator with the alpha configuration of the Ross-yoke mechanical drive;” “The increase of heating load” → “The increase of electrical heating load”;

“function- ality” → “functionality”;

"leak- age" → "leakage", "high- tolerance seal" → "high-tolerance seal";
"operational temper- atures" → "operational temperatures";
"con- ducted" → "conducted", "cylin- der" → "cylinder", "al- lows" → "allows", in Fig. 3 "heat-exchanger" → "heat exchanger", "dis- placer" → "displacer";
"ap- plication" → "application", "con- trolled" → "controlled"
"cross section area" → "cross-section area"
"be- cause" → "because", "F m" → "F_m ";
"be- low" → "below", "friction co- efficient" → "friction coefficient";
"dur- ing three test runs" → "during three test runs", "dur- ing prolonged time" → "during prolonged time";
"bot- tom" → "bottom", in Fig. 5 "our in-house Stirling refrigerator" → "in-house Stirling refrigerator"
"be- cause" → "because";
"average leak- age rate" → "average leakage rate", "lin- ear" → "linear";
"with- out" → "without";
"en- abled higher leakage" → "enabled higher leakage"
in Fig. 8 "af- ter" → "after";
"be- tween test intervals" → "between test intervals"
Formatted references.

CHAPTER VI

In response to comments of Dr. Christophe Goupil about finite time approach:

I added a section "IV.3 Finite time operation of the Stirling refrigerator", where introduced the concept of finite time operation, analysed two strategies to reduce cycle time and increase cooling rates with available experimental data, and commented on integration of finite time principles in modelling and experimental optimization. I added corresponding changes in the contents and list of figures in the beginning of dissertation.

In response to comments of Dr. Christophe Goupil about the strategy "maximized power VS maximized efficiency":

I added in Chapter I a section I.2.4-d with the measured coefficient of performance (efficiency) from charge pressure and shaft frequency. The plot (Fig. 9) also contains cooling powers and temperatures. The plot depicts the difference between maximum cooling power and maximum efficiency for the tested system. The section *"Operational characteristics of the Stirling refrigerator"* comments on the selected strategy.

In response to comments of Dr. Christophe Goupil about optimization of the coupling:

I added a paragraph in the end of the new section "IV.3 Finite time operation of the Stirling refrigerator" with comments on possible technical changes to reduce the resistance of the coupling.

In response to the comment of Dr. Carolina Costa about different approach to calculate cooling capacity:

I added two paragraphs in the end of Section "IV.1 Limitations". The first paragraph discusses the possibility to scale the system using the Otaka number with sufficient accuracy. The second paragraph discusses other methods in literature to calculate cooling capacity and includes comments on the applicability of these methods.

In response to comments of Dr. Ighor Uzhinsky about usefulness of conclusions for a subsequent work:

In the preamble to the chapter, I added the connection to one of conclusions in the previous chapter: "The operational data collected during the test and refinement stage (Chapter V) was used to validate the physical model."

Corrections in the text:

In section "II.1 Object of analysis": "Electromotor" → "An electromotor"; "by the gas, air," → "by the gas and the air,"

"eating loads" → "heating loads"

"to our knowledge" → "to the author's knowledge"

"We also applied the same calculation approach from Table 3" → "The same calculation approach was applied as in Table 3"; "Higher charge pressure allow" → "Higher charge pressure allows";

"the dependence of the specific Otaka number Θ_s and the temperature ratio" → "the dependence of the specific Otaka number Θ_s from the temperature ratio."

In section "IV.5 Novelty and contribution": "To the best of the author's knowledge the present work is the first to propose and experimentally validate a thermal numerical model of the system "Stirling refrigerator – thermal chamber" to predict temperatures in the thermal chamber and refrigerator cooling capacity." → "The present work develops and experimentally validates a numerical model for the system "Stirling refrigerator – thermal chamber" to predict temperatures in the thermal chamber and refrigerator's cooling capacity."

"Developed a physical model validated experimentally of the system "Stirling-refrigerator – thermal chamber" → "Developed and validated experimentally a physical model of the system "Stirling-refrigerator – thermal chamber"

"Discovered the effect of declining value for the refrigeration performance parameter, Otaka number, previously believed to be a constant value." → "It was found that the Otaka number, previously believed to be a constant parameter, is dependent from the temperature of the refrigerator."

"Offered a relatively simple, yet effective approach to scale ECTs using mathematical modeling and experimental validations." → "Demonstrated simple and effective approach to scale ECTs using experimentally validated physical model."

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CHAPTER VII

In response to the comment of Dr. Clement Fortin about literature on design thinking:

In section "IV.1 Relation to other school of design thinking", I extended the analysis of related literature on design thinking and systematized it in a table. I made a corresponding change to the list of tables in the beginning of the dissertation.

In response to the comment of Dr. Carolina Costa about the interactions of sides in the Pentagon model:

I added two paragraphs in the end of the section "IV.1 Pentagon model for the development of ECT" that offer two approaches to represent interactions between the sides of the Pentagon.

Corrections in the text:

In the preamble to the chapter: "the development" → "the commercial development"; "The results show that…" → "The results show how…"; "various factors" → "various commercial factors"; "the commercial development of energy conversion technologies (ECT)" → "the commercial development of Stirling machines from technical literature"; "The methods were validated…" → "The methods for selecting alternative design decisions at different design stages were validated…"; added "The objective of this chapter is to discuss the design methods further and analyze their applicability to the development of other energy conversion technologies (ECT)."

In section "I.1 Bibliometric method to study papers and patents at the concept stage": "…in Stirling machines studied in the literature." → 'in Stirling machines."; "It is interesting to note that scientific and patent literature typically contain different design configurations." → "It is interesting to note that design configurations from scientific and patent literature very often are different from each other." "configurations were different" → "configurations were not always alike"

In section "I.2 Tradespace exploration method at the system design stage": "Another aspect that significantly influences how we make the design decisions is whether we conduct trade studies" → "Trade studies may significantly influence how we make the design decisions".

In section "I.3 Application of game theory at detail design stage": "Most, if not all, engineering works" → "Engineering studies";

In section "I.4 Experimental optimization of critical components at testing stage": "how gradual improvement" → "how gradual experimental improvement".

In section "I.5 Experiment-based model for scaling at scale-up stage": "essential for commercial success" → "essential for evaluation different commercial applications"; "The understanding of these discussed factors allows organizing a useful research and development process of Stirling machines for commercial usage." → "The understanding of factors in section I.1-I.5 and implementing proposed design methods allow organizing an effective research and development process of Stirling machines for commercial usage."

Fig. 1. : "technological pathway" → "the technological pathway"

In section "I.6 Analysis of the thesis statement": "For the concluding discussion in this chapter, it would be interesting to evaluate further the commercial factors that influenced the proposed design methods, to discuss their advantages and disadvantages, and to extend the discussion on the applicability of those methods to the development process of other energy conversion technologies." → "For the concluding discussion in this chapter, it would be interesting to evaluate further the commercial factors that inspired the proposed design methods. I will discuss the advantages and disadvantages of the methods and extend the discussion on their applicability to the development of other energy conversion technologies."

In section "II.1 Commercialization factors in development": "development projects comparing to a scientific project" → "development projects in comparison to scientific projects"; "people management, and other features" → "and people management."

In Section "II.2 Advantages and limitations of design methods": "to critically assess" → "to assess critically";

In section "II.3 Applicability of the technological pathway to other ECT": "I use a simple table" → "I use a table"; "factors that justify and limit their application." → "factors that justify and limit the application of methods to other ECTs"

Section "III.1 Commercialization factors in development": "Figure 5, Chapter I, " → "Fig. 1,"; "…Theses results show that commercial organizations …" → ": commercial organizations…"; "This analysis offers some proof form literature that the selected commercial factors do exist during the industrial development of science-based products." → "This analysis confirm that the analysed commercial factors are relevant for the industrial development of science-based products."; "The satisfaction market requirements" → "The fulfilment of market requirements"; "The framework of Barge-Gil and López states" → "The framework of Barge-Gil and López suggests"; "the detailed development is verified" → "the detailed development is confirmed"; "where" → "with"; "This analysis confirm" → "In summary, the comparison of assumed in the thesis commercial factors with the constraints of real science-based product developments confirms that assumed commercial factors are plausible."; "to confirm the existence of discussed commercial factors further" → "to analysis of real science product developments can be established for further confirmation of assumed commercial factors"

In Table 2: "Any ECY could be modeled" → "Any ECT could be modelled"; "Analysis of most of existing knowledge" → "Representative analysis of all existing knowledge"; "big number" → "large number"

In section “IV.1 Pentagon model for the development of ECT”: “The results of the analysis in this chapter inform the formulation of the Pentagon Model for the commercial development of energy conversion technologies.” → “The results of this work help to formulate a design process model for the commercial development of energy conversion technologies, which I named the Pentagon Model.”

“Fig. 1” → “Fig. 2”

Formatted references.

ABSTRACT

“To solve this problem” → “To cover this gap”

“proposes a design methodology” → “proposes a novel design methodology”

“The novel design methodology” → “The design methodology”

“The third method helps to predict the influence of designers’ decision-making on the design process outcomes during the detail design stage using game theory.” → “The third method helps to improve interactions between designers during the detail design stage and reduce negative influence of designers’ collaborative decision-making on the design process outcomes using game theory.”

“in the commercial development model of other” → “in the commercial development process of other”

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Changed page numbers.

LIST OF FIGURES AND TABLES

Changed formatting of names for figures and tables.