Skolkovo Institute of Science and Technology

CONCEPT SELECTION OF INNOVATIVE COMPLEX ENGINEERING SYSTEMS CONSIDERING SYSTEMS EMERGENT PROPERTIES

Doctoral Thesis

by

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DOCTORAL PROGRAM IN ENGINEERING SYSTEMS

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I hereby declare that the work presented in this thesis was carried out by myself at Skolkovo Institute of Science and Technology, Moscow, except where due acknowledgement is made, and has not been submitted for any other degree.

Candidate (Mikhail Nikolaev)

Supervisor (Full Prof. Clement Fortin)

ABSTRACT

The current thesis is devoted to improving the concept and architecture selection design decision making in innovative complex engineering systems. It addresses the problem of the need to consider innovativeness and complexity for the development of such systems. The absence of this consideration for innovative complex engineering systems has the potential to result in the development of unsuccessful systems. This problem is highly relevant nowadays and continues to become more urgent as the number of technological innovations and the complexity of new engineering systems increase. The thesis proposes a solution for the indicated problem with a focus on design decision making. It integrates systems engineering, systems analysis, key elements of the design of complex systems, and elements of the innovation theory to propose a new decision-making framework.

The proposed decision-making framework constitutes the combination of the contributions for the current thesis. Firstly, the thesis provides an ontological model of systems emergent properties based on the systems thinking approach. It represents a schematic model that divides all systems emergent properties on strategy- and engineering-level properties and provides their link to systems values. Secondly, it proposes a new decision-making approach to design decision making in innovative complex engineering systems. The proposed approach represents an extension of the well-known Value-Based Decision-Making approach and reaches systems values through systems emergent properties using the developed ontology. Finally, two decision-making models, which use the developed ontology and are based on the proposed decision-making approach, are developed and successfully tested on four case studies from the oil and gas industry. Industrial case studies include one case study for supporting operations of oil and gas fields, two case studies for rock core research laboratory systems, and one transportation system of global significance.

The proposed framework of the thesis uses fundamental systems attributes to improve design decision making instead of solely focusing on a mathematical approach.

PUBLICATIONS

1. **[Indexed in WoS and Scopus, Q1] M. Y. Nikolaev,** A. V. Kazak. Liquid saturation evaluation in unconventional organic-rich reservoirs: A comprehensive review // Earth-Science Reviews. – 2019. – Vol. 194. – pp. 327-349. – DOI: 10.1016/j.earscirev.2019.05.012
2. **[Indexed in WoS and Scopus] M. Y. Nikolaev,** C. Fortin. A literature review of design decision making in disruptive technological innovations of new products // Proceedings of ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference / American Society of Mechanical Engineers. – 2020. – Vol. 6. – 9 p. – DOI: 10.1115/DETC2020-22093
3. **[Indexed in WoS and Scopus, Q4] M. Y. Nikolaev,** C. Fortin. Systems thinking ontology of emergent properties for complex engineering systems // Journal of Physics: Conference Series. – 2020. – Vol. 1687. – 9 p. – DOI: 10.1088/1742-6596/1687/1/012005
4. **[Recommended by the Higher Attestation Commission] M. Y. Nikolaev,** C. Fortin, E. E. Baraboshkin, D. A. Koroteev. Concept selection of automated rock core description system based on the systems emergent properties // XXI Century: Resumes of the Past and Challenges of the Present Plus. – 2021. – Vol. 10, № 1 (53). – pp. 63-68. – DOI: 10.46548/21vek-2021-1053-0011 [in Russian]
5. **[Indexed in WoS and Scopus] M. Y. Nikolaev,** C. Fortin. The emergence approach to design decision making in innovative complex engineering systems // AIP Conference Proceedings. – 2022. – Vol. 2559. – 8 p. – DOI: 10.1063/5.0099043

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LIST OF ABBREVIATIONS

AFT – Alternative-Focused Thinking

ALTS – Arctic LNG Transportation System

ARCDS – Automated Rock Core Description System

ASME – American Society of Mechanical Engineers

CDMM-1 – Level-One Combined Decision-Making Model

CDMM-2 – Level-Two Combined Decision-Making Model

DSM – Design Structure Matrix

DSS – Decision Support System

HoQ – House of Quality

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical and Electronics Engineers

ILPS – Innovative Laboratory Petrophysical System

INCOSE – International Council on Systems Engineering

IRTA – Innovative Robotized Tropospheric Airship

ISO – International Organization for Standardization

LNG – Liquefied Natural Gas

MAUT – Multi-Attribute Utility Theory

MBSE – Model-Based Systems Engineering

MCDM – Multi-Criteria Decision Making

MHoQ – Modified House of Quality

MIT – Massachusetts Institute of Technology

MDM – Multi-Domain Matrix

NASA – National Aeronautics and Space Administration

NMR – Nuclear Magnetic Resonance

OPM – Object-Process Methodology

QFD – Quality Function Deployment

RAND Corporation – Research and Development Corporation

Skoltech – Skolkovo Institute of Science and Technology

SoS – Systems of Systems

STG – Systems Thinking Group

SysML – Systems Modeling Language

STOEP – Systems Thinking Ontology of Emergent Properties for Complex Systems

TODIM – Interactive and Multi-Criteria Decision Making (acronym from Portuguese)

TPU – National Research Tomsk Polytechnic University

TRIZ – Theory of Inventive Problem Solving (acronym from Russian)

VFT – Value-Focused Thinking

VOF – Value of Flexibility

VOI – Value of Information

INTRODUCTION

Relevance of the research topic. Innovations have been playing a considerable role in global technological progress, starting from the 1st Industrial Revolution in 1708 until the current-day 4th Industrial Revolution (digital transformation) [1]. The Russian Federation occupies one of the world's leading positions in the development and adoption of innovations. Many official governmental documents emphasize the importance of innovation policy for the strategic development of our country [2]. A considerable number of innovations, called technological, emerge in the engineering-technical domain. A significant part of technological innovations belongs to innovative complex engineering systems, the object of this dissertation's research. Such systems, also called technological innovations of new complex systems, possess both characteristics of complex engineering systems (many elements, many relationships, complex behavior) and technological innovations (invention, economic value, novelty). The development of successful innovative complex engineering systems must be based on design research methods and represents a current-day relevant engineering problem. On the one hand, the development of such systems requires considering their innovative character (innovativeness). On the other hand, it faces the challenge of systems increasing complexity. There is a global trend nowadays that new engineering systems are becoming more complex [3].

By successful complex engineering systems, one assumes systems, in which anticipated systems emergent properties occur. This important point was noted by Crawley et al. in their book "System architecture: Strategy and product development for complex systems" and adopted in the thesis due to the solid credibility of the source [4]. The explanation of successful systems by Crawley et al. uses the term "systems emergent properties," which needs to be clarified from the beginning as it constitutes one of the key points of the dissertation's research. The definitions are analyzed in Chapter 2, but its primary explanation can be given through the related term "systems emergence" applied in an example (Figure 1).

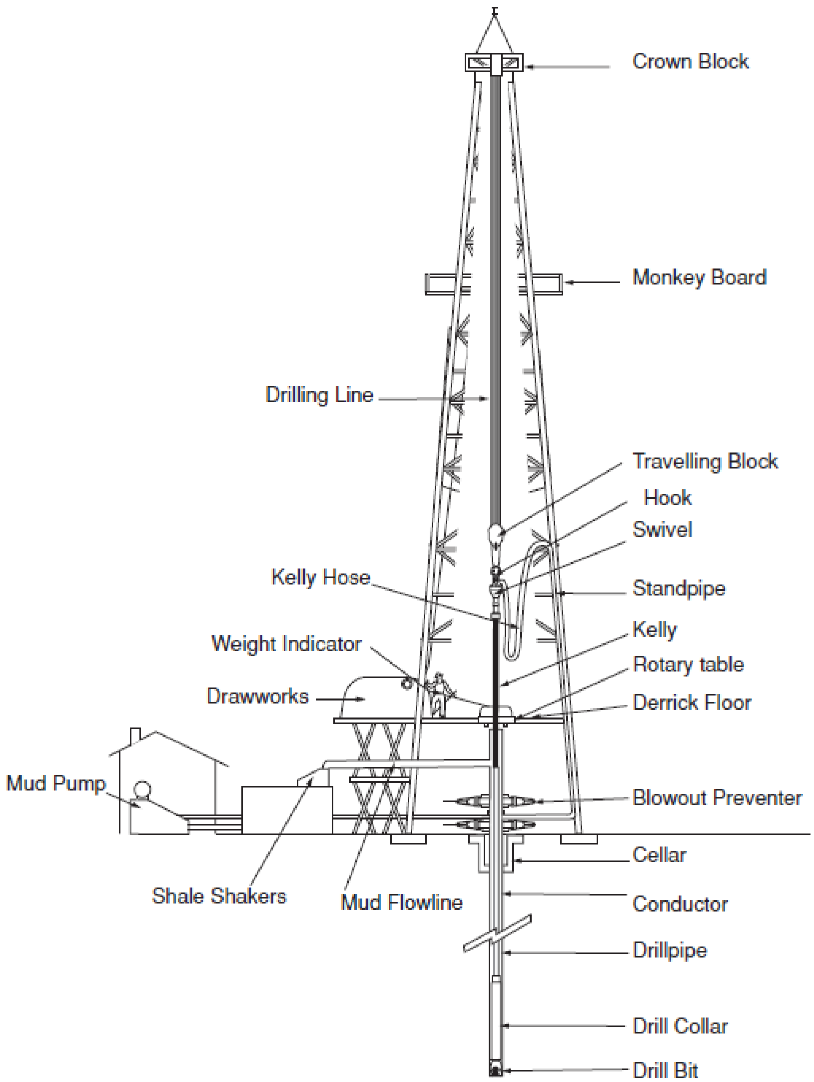


Figure 1 – Drilling rig components ([5]).

As shown in Figure 1, a drilling rig (a complex system) consists of more than 20 components (elements, subsystems). Each element has its own functionality: the drill bit breaks the rock, the mud pump fills the system with the drilling mud, etc. Only when united in a system, can these elements become capable to drill a well. The ability to drill a well constitutes the emergence of the drilling rig as a system and is characterized by function, performance, usability, etc., which are called systems emergent properties. Thus, systems emergent properties represent attributes of a system characterizing its greater functionality than the sum of functionalities of its separate elements [4,6]. Other definitions are given in Chapter 2.

One of the key aspects in the design of innovative complex engineering systems is design decision making for systems concept selection, the subject of the dissertation's research. The National Aeronautics and Space Administration (NASA), Urlich, and Eppinger specified systems concept selection as one of the most critical design decisions for new engineering systems as it stays in the early beginning of their life cycle [7,8]. Good systems concept selection leads to the development of a successful complex engineering system. It allows preserving significant energy, human, time, and financial resources. The Russian Federation and the whole world nowadays encounter the need to be energy-efficient for its successful socio-economic development [9,10]. The development of complex engineering systems intensively consumes energy resources: fuel for transportation needs, electricity for the use of equipment, heating for manufacturing from materials, etc. The consumption of this type of resources is also associated with spending human, time, and financial resources: the longer engineers devote their time to work, the more energy they consume on lighting, transportation, computer work, and other needs that possess additional financial cost. Parnell and West defined the term "decision" as an irrevocable allocation of resources [3]. Hence, any decision results in the loss of resources if it needs to be re-made. Systems concept selection, which is the earliest design decision, allows preserving more resources on the development of innovative complex engineering systems compared to other design decisions.

Design decision making in innovative complex engineering systems possesses its specifics. Similar to technological innovations of new products and systems, it requires the consideration of the high degree of uncertainty and associated market and technological risks brought by innovations [11]. This type of uncertainty is often considered by applying mathematical operations. Aspirations to improve design decision making in technological innovations may lead to applying more complicated mathematical calculations [12]. It may result in a poor understanding of the decision-making methodology by all decision-makers, which can include non-technical specialists (economists, lawyers, project managers, etc.). Instead of focusing on mathematical solutions, the current thesis uses systems emergent properties as fundamental systems attributes to improve design decision making. It considers the combination of innovativeness and complexity in technological innovations of new complex systems, while leveraging mathematical calculations. This way, the decision-making approach and models developed in the thesis favor a good-level of understanding of the decision-making methodology by decision-makers, which aligns with a similar current-day tendency that appeared in companies and organizations. The use of systems emergent properties is built upon achieving systems values, which are extensively used for design decision making.

The adopted research approach of focusing on using fundamental systems attributes to improve design decision making is supported by the decision-making domain, in which this thesis operates. It is displayed within the domains of the Cynefin framework (Figure 2).

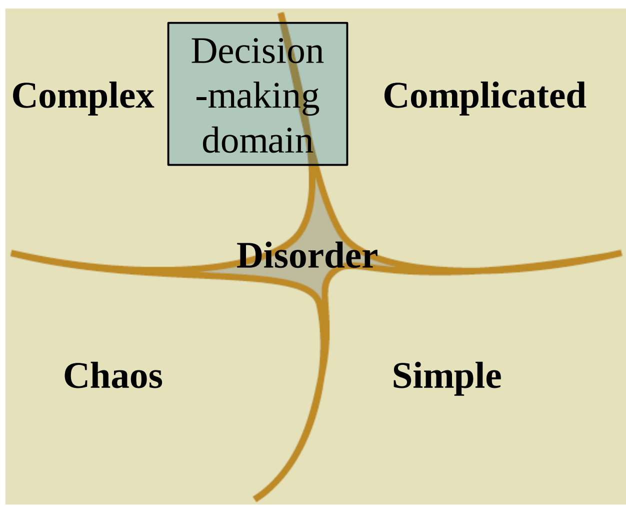


Figure 2 – The sense-making Cynefin framework (adapted from [13–15]).

According to Figure 2, the Cynefin framework represents five decision-making domains: right-hand domains of ordered (simple and complicated), left-hand domains of unordered (chaos and complex), and the central-field domain of disorder. The decision-making domain of the thesis, representing innovative complex engineering systems, is located on the boundary of the complex and complicated domains, representing complex and complicated systems, respectively. Interactions between systems elements in complicated systems are governed by fixed relationships and can be predicted using mathematics. Opposite to them, interactions between systems elements in complex systems demonstrate self-organization, which cannot be predicted using mathematics, and need, for example, experiments for prediction [4,13,14,16]. As design decision making in innovative complex engineering systems tends to be more on the complex domain side, it becomes reasonable in the thesis to focus on using fundamental systems attributes and leveraging mathematical calculations.

Thus, the research topic of the thesis is highly relevant nowadays due to its orientation on solving the current-day engineering problem concerning the development of more complex engineering systems, which are technological innovations. The research focuses on the enhancement of existing design decision-making techniques and tools. It correlates with the innovation policy for the strategic development of the Russian Federation, the global trend of the increasing complexity of engineering systems, the need to save energy resources, and the tendency of favoring a good-level understanding of decision-making methodologies.

As a well-defined systems concept evolves to systems architecture, as emphasized by Crawley et al. [4], the author of the thesis under the term "systems concept selection" assumes the selection of systems concept or systems architecture depending on a particular case study. For conciseness, the terms "complex system," "concept," "architecture," "value," "emergent property" are used in the text of the thesis assuming "complex engineering system," "systems concept," "systems architecture," "systems value," and "systems emergent property," respectively. By the term "value," principles used for evaluation (e.g., educational value, overall value, etc.) are considered [17]. For case studies, innovative complex engineering systems were taken from the oil and gas industry that intensively implements technological innovations of national and global significance. Nowadays, the industry experiences depletion of "easy-accessible" oil and gas reserves and applies technological innovations for reaching them from the unconventional reservoirs, Arctic region gas fields, etc. It also aligns with the recently risen interest of "Gazprom Neft" in systems engineering.

Level of prior studies of the research topic. The dissertation's research focus falls within the systems engineering and systems analysis fields of knowledge, including the key aspects of complex systems design and touching on elements of innovation theory (Figure 3). By systems analysis, the author of the thesis assumes the discipline existing in the contemporary Russian Federation, historically the national analog of systems engineering.

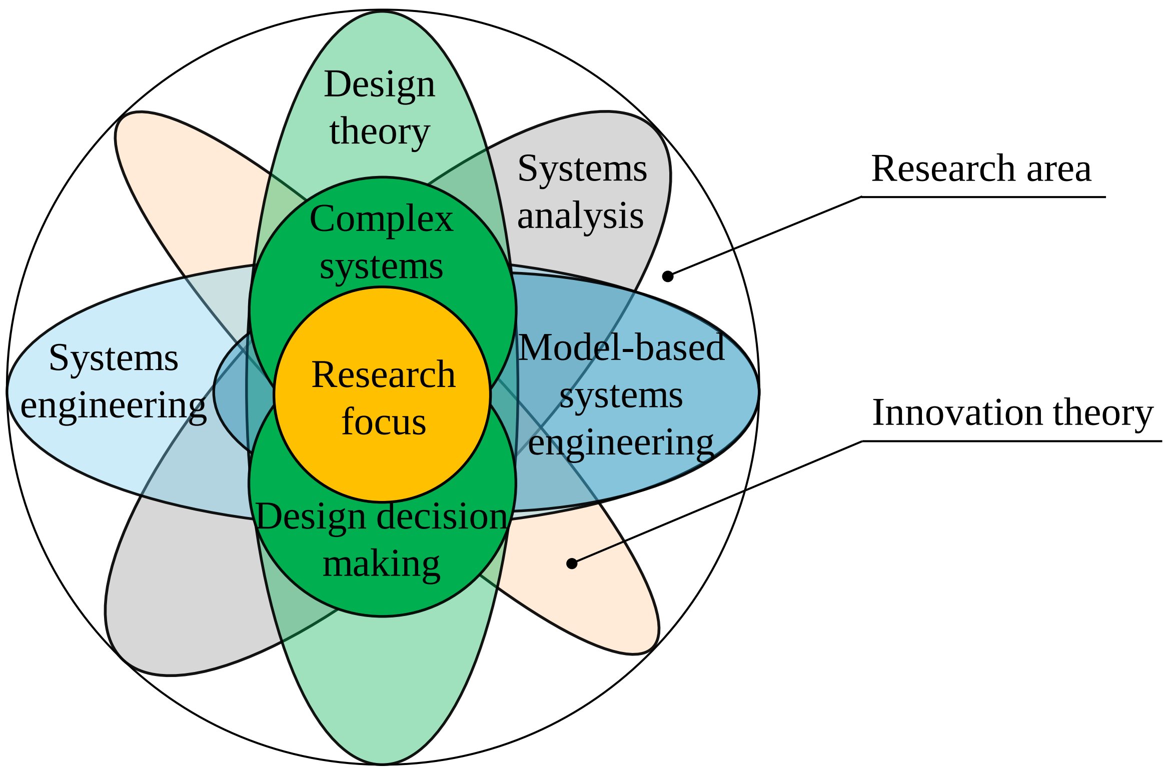


Figure 3 – Dissertation's research focus within different fields of knowledge.

According to Figure 3, the focused research area considered the fields of knowledge of the four aforementioned disciplines. Design theory, systems engineering, and systems analysis are depicted with bigger-sized shapes to reflect the higher significance of their roles in the research than the innovation theory. For design theory, the research was limited to complex systems and design decision making. The focus of systems engineering stayed within model-based systems engineering (MBSE) and touched on systems architecture (not shown in Figure 3). Systems analysis was focused on its aspects close to systems engineering and decision theory. For the innovation theory, only the general elements of defining technological innovations and their design decision making specifics were considered. As innovative complex systems for case studies in the thesis were taken from the oil and gas industry, the conducted research also touched on oil and gas engineering aspects (omitted in Figure 3). Systems engineering was chosen as the primary approach for the research due to its successful and extensive use for engineering complex systems design by NASA, "Statoil" (currently "Equinor"), "Gazprom Neft," and other companies and institutions [18–20].

Many researchers in systems engineering, systems analysis, and the design of new products raised questions about decision making in complex systems and how to improve it. Among them are the following foreign and national scientists and engineers: S.R. Hirshorn et al. from NASA [7,18], E. Crawley, S.D. Eppinger, W.L. Simmons, et al. from the Massachusetts Institute of Technology (MIT) [4,8,21], A. Kossiakoff et al. from the Johns Hopkins University [22,23], R.B. Bratvold from the University of Stavanger, and S.H. Begg from the University of Adelaide [24], A.A. Sannikov and N.V. Kutsubina from the Ural State Forest Engineering University [25], S.S. Semenov, E.M. Voronov, A.V. Poltavsky, A.V. Kryanev, V.N. Volkova et al. from other leading Russian institutions [26,27], etc. Typically, scientists and engineers improve design decision-making techniques and tools in complex systems, not specifying them as innovations or focusing the research only on concept selection design decisions. These specific features serve as options that could be considered and not emphasized in the research. Among the researchers who intentionally considered design decision making in technological innovations are F. Petetin and J.-C. Bocquet from École Centrale Paris (currently a part of CentraleSupélec) [28,29].

In 1960, Simon developed a decision-making process-based model that still serves as the basis for most contemporary decision-making techniques [30]. It consists of three phases: "Investigation," "Design," and "Choice." The "Investigation" phase (referred as "Intelligence" by Corner et al.) assumes information-gathering activities on the decision problem.

The “Design” phase represents decision problem structuring: identifying alternative decision problem solutions (alternatives), criteria, and others. The “Choice” phase consists of the selection between alternatives. This model has been developed based on the later decision-making models and techniques created by other researchers over time. However, the design stage, or decision problem structuring stage, remained a task of primary importance, as noted by Mintzberg et al. in 1976 [31,32]. In 1992, Keeney formulated two underlying philosophies for contemporary decision making: alternative-focused thinking (AFT) and value-focused thinking (VFT) (Figure 4) [17].

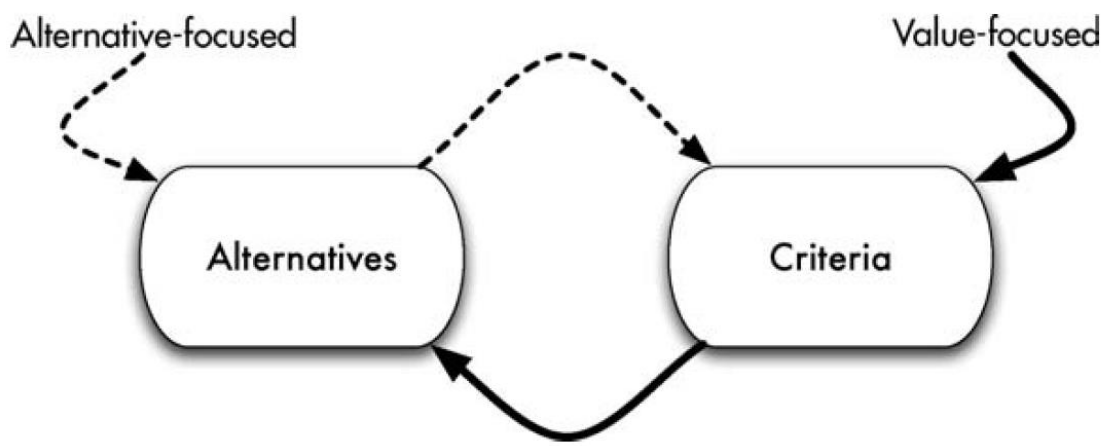


Figure 4 – Difference in decision problem structuring between AFT and VFT [3,31].

As illustrated in Figure 4, VFT puts criteria (values) for the decision first, and then alternatives are identified via the values. AFT does vice versa. The success of VFT, also called the value approach, was proven by its continuous application for design decision making of space missions and systems by NASA [7,18]. Petetin et al. later used it for design decision making in disruptive technological innovations, one of the key types of contemporary technological innovations, considering its specifics [29]. Nikolaev and Fortin reviewed existing design decision-making techniques and tools applied to disruptive and radical technological innovations of new products and systems and concluded that the most successful techniques and tools were those based on the use of the value approach [11]. A specific review on the subject is provided in Chapter 1 of the thesis.

Kossiakoff et al. for systems engineering and Sannikov, Kutsubina for systems analysis noted that the fundamental approach underlying decision making in complex systems is systems thinking [22,25]. Parnell and West presented decision making in systems as a problem-solving process [3]. Crawley et al. defined systems thinking as an approach that considers problems as systems and noted the identification of emergent properties as one of its tasks [4]. No prior works were found to consider emergent properties for design decision making in innovative complex systems, which leaves opportunities to use systems thinking and emergent properties for further research in this field.

Research purpose and tasks. The described above facts on the research relevance and the level of prior studies of the research topic determined the following research purpose: "Development and approbation of a modified decision-making approach for good concept selection of innovative complex systems from systems engineering and systems analysis perspectives." By "good concept selection," the author assumes the type of concept selection design decision that leads to the development of successful complex systems. It is the type of a "good decision" – the one that is consistent with its objectives, alternatives, and available information (see 1.1.5. Decision, design decision, and design decision making). Approbation, which means checking for workability, assumes the development of a related decision-making model or models and their application in practice (case studies). The realization of the research purpose required the fulfillment of the following tasks:

1. To provide clarification of the core research-related terms: "system," "complex systems," "systems thinking," "concept/architecture," "decision," "design decision making," "technological innovations," and others – based on the analysis of information obtained from the literature sources on systems engineering and systems analysis.

2. To prepare a specific literature review of design decision-making techniques and tools applied to technological innovations of new products and systems: conduct an associated literature search, analyze the information from the selected publications, and identify the most successful contemporary decision-making approach.
3. To develop an ontology of emergent properties for complex systems by conducting a supplementary literature search on emergent properties and possibly other related terms in systems, analyzing semantics and relationships of emergent properties based on the information from the selected publications.
4. To formulate the principle that reflects the possibility to consider the combination of innovativeness and complexity as complementary features of innovative complex systems using emergent properties for design decision making and modify the most successful contemporary decision-making approach using this principle and the ontology.
5. To develop a decision-making model (or models) based on the modified most successful decision-making approach and appropriate decision-making techniques and tools, test in case studies from the oil and gas industry, and conclude the results.

Scientific novelty. Scientific novelties brought by the thesis are as follows:

1. For the first time, emergent properties were used for design decision making in complex systems and served as its foundation.
2. For the first time, systems thinking was used as the primary approach of the developed ontology for complex systems.
3. For the first time, the house of quality (HoQ) was modified for making design decisions in complex systems based on emergent properties, enhancing the applicability of HoQ for the conceptual design stage.
4. For the first time, the principle of complementarity for design decision making in innovative complex systems was formulated.

Provisions to be defended (scientific contributions). Provisions are as follows:

1. The systems thinking ontology of emergent properties for complex systems (STOEP). It represents an ontological model that uses the systems thinking approach, unites strategic and engineering-level emergent properties, and is based on analyzing the semantics and relationships of emergent properties.
2. The emergence approach to design decision making. It is based on reaching values through emergent properties and includes the principle of complementarity for design decision making in innovative complex systems, which reflects the possibility to consider the combination of innovativeness and complexity through emergence using emergent properties.
3. Level-one combined decision-making model (CDMM-1). It represents an essential model, which enables the practical application of the emergence approach, and uses the prior knowledge analysis, the design structure matrix (DSM), the modified house of quality (MHoQ), and expert interviews from the Delphi method at different stages.
4. Level-two combined decision-making model (CDMM-2). It represents the modernization of CDMM-1 and includes several phases based on quality function deployment (QFD) that allow expanded correlation of stakeholder needs with emergent properties.

Theoretical and practical significance of the work. The theoretical significance of the thesis consists of enhancing the scope of application for systems thinking and emergent properties. The dissertation's research demonstrated the possibility to use systems thinking not only as an approach to architect complex systems and manage their complexity but also as the foundation for the development of an ontological model that was not done before [6]. With the help of the developed STOEP, emergent properties served as the basis for the modified decision-making approach and subsequent decision-making models. No prior works described the use of emergent properties for design decision making. According to the literature sources on systems engineering, systems thinking and emergent properties occur at the conceptual design stage of complex systems [4,12]. However, they are also applicable to complex systems development at other design stages. Therefore, the proposed decision-making models can be applied to making design decisions at other design stages (not only those for concept selection), considering their further proper adaptation.

The practical significance of the thesis consists of introducing decision-making models that consider systems complexity and innovativeness for design decision making while favoring a good-level understanding of decision-making methodology by decision-makers. Decision-making models were developed of two levels: essential CDMM-1 and modernized CDMM-2. The emergence approach to design decision making was applied by the "WARPA" (World Advanced Research Project Agency) company (France). Its use assisted in understanding the necessity to consider emergent properties for concept selection of the hull envelope subsystem for the innovative robotized tropospheric airship (IRTA), which allowed to save ≈ 1 month of the company's resources on the design of this complex system (Appendix A). The abridged version of CDMM-1 was applied to concept selection of the automated rock core description system (ARCDS) developed by the "Digital Petroleum" company (Russian Federation). Its use allowed to save ≈ 1.5 months of the company's resources on developing this medium-complexity system (Appendix B).

Research methodology and methods. The dissertation's research followed the design research methodology by Blessing and Chakrabarti [33], as listed in Table 1. This type of methodology requires defining a research question that was formulated the following way: "How to modify existing design decision-making techniques and tools using emergent properties for good concept selection of innovative complex systems?" The defined research question complies with the earlier identified research purpose and tasks.

Table 1 – Stages of the design research methodology applied to the dissertation's research.

№	Study	Input	Output	Section
1	Research clarification	Literature analysis	Clarification of the focus, tasks, terms, etc.	Introduction, Chapter 1
2	Descriptive study I	Empirical data analysis	Specific literature review	Chapter 1
3	Prescriptive study	Assumption	Ontology, approach, models	Chapter 2
4	Descriptive study II	Empirical data analysis	Case studies	Chapter 3

According to Table 1, the dissertation's research consisted of four stages: research clarification, descriptive I, prescriptive, and descriptive II studies. Firstly, research clarification was performed through the initial literature analysis to identify the primary aspects of research (focus, purpose, tasks, etc.) and the core research-related terms. Secondly, descriptive study I was carried out by preparing the specific literature review for the review-based empirical data analysis to understand the current state of the art of the research topic. Thirdly, STOEP, the emergence approach, CDMM-1, and CDMM-2 were proposed, constituting the prescriptive study. Finally, descriptive study II was performed through the empirical data analysis based on the results of case studies that supported answering the defined research question. Case studies are decomposed on their own internal stages of research clarification, descriptive and prescriptive studies.

The author of the thesis used the following methods of scientific research [34]:

1. Methods of empirical study: observation, comparison.
2. Methods of combined empirical-theoretical study: analysis, abstraction, modeling.
3. Methods of theoretical study: ascent from abstract to concrete, historical method.

Observation and comparison were used for research clarification, the specific literature review of descriptive study I, and case studies. Analysis, abstraction, and modeling were implemented predominantly for prescriptive study. Ascent from abstract to concrete and the historical method were used for case studies in descriptive study II.

Validity and reliability of the research results. Decisions made using the proposed approach and models were successfully validated by experiments for ARCDS, operations for the Arctic liquefied natural gas (LNG) transportation system (ALTS), inspection by the experts in the field for the innovative laboratory petrophysical system (ILPS) and IRTA.

Approbation of the research results. Research results were presented at the 25th Design for Manufacturing and the Life-Cycle Conference of the American Society of Mechanical Engineers in 2020 (Saint-Louis, USA, online), the International Conference on Engineering Systems in 2020, and the International Conference on Engineering Research in 2021, both organized by the People’s Friendship University of Russia and the Society of Academicians of Fundamental and Applied Sciences (Moscow, Russian Federation, online).

Personal contribution. The contribution of the author to the thesis is as follows:

1. The author played the main role in preparing the review. He personally performed the literature search, initial literature analysis, and initial identification of existing approaches, processes, models, and decision support tools. He played the main role in further literature analysis and further analysis of identified decision-making techniques and tools, which he worked on in collaboration with his research supervisor.
2. The author played the predominant role in developing STOEP, a new ontological model of emergent properties. He personally conducted an extensive literature search, analyzed the semantics of emergent properties, and built the initial ontological model. He carried out on his own the analysis of relationships, of the semantics of associated terms, and the development of the final ontological model.

3. The author played the predominant role in proposing the emergence approach. He personally performed an initial analysis of complementarity of innovativeness and complexity in innovative complex systems, and formulated the associated principle. Further analysis of complementarity in innovative complex systems and correction of the principle were done by him in collaboration with his research supervisor. As the basis for his work, he used research results kindly provided by his colleagues from the Systems Thinking Group (STG): C. Fortin, Y.A. Brovar, and Y.A. Menshenin.
4. The author developed two decision-making models (CDDM-1 and CDMM-2), which use the developed ontology and proposed decision-making approach, and tested them in four case studies. He played the main role in the development of the level-one model (CDMM-1) and personally developed the level-two model (CDMM-2). The author managed decision making and played the role of a decision-maker in all case studies.
5. The author played the predominant role in preparing publications for the dissertation's research and participating in research-related conferences. He served as the first author in the publications, personally summarized all the results, and prepared this thesis.

Publications. Key results of the thesis are reflected by five publications. Four papers were published in the Web of Science/Scopus indexed journals and conference proceedings. One journal paper was published in the journal recommended by the Higher Attestation Commission under the Ministry of Science and Higher Education of the Russian Federation.

Structure and volume of the thesis. The thesis consists of an introduction, three chapters, a discussion, a conclusion, five appendices, and 184 pages of text, 29 figures, and 19 tables.

CHAPTER 1. LITERATURE ANALYSIS AND REVIEW

Understanding the research topic of design decision-making for concept selection of innovative complex systems requires a certain level of knowledge for general and specific research-related questions. General questions include identification of research focus, purpose, tasks, etc., and clarification of the core research-related terms like "complex systems," "design decision making," "technological innovations," and others. Identification of research focus, purpose, etc., was covered by the previous section of the thesis, Introduction. Clarification of the core research-related terms is provided by the literature analysis described in the first subsection of Chapter 1. Specific research-related questions include searching and identifying design decision-making techniques and tools applied to technological innovations of new products and systems, including innovative complex systems. It is provided by the prepared specific literature review described in the second subsection. The core information of Chapter 1 was published by Nikolaev and Fortin in the related review paper [11]. The information from this paper was modified for the thesis: updated, enhanced, and complemented by clarifying essential terms. Chapter 1 partially represents the research clarification and entirely the descriptive study I stages of research.

1.1. Literature analysis: Clarification of the core research-related terms

The clarification of the core research-related terms plays a significant role in understanding the current state of the art on design decision making in innovative complex systems. Its value for the dissertation's research consists of an adequate understanding of the theoretical fundamentals to assist in identifying the keywords for the literature search, the initial step in the preparation of the specific literature review. The clarification starts by explaining the basic terms (system, concept, etc.), continues by clarifying more specific terms (e.g., design decision), and finishes by describing technological innovations (Figure 5).

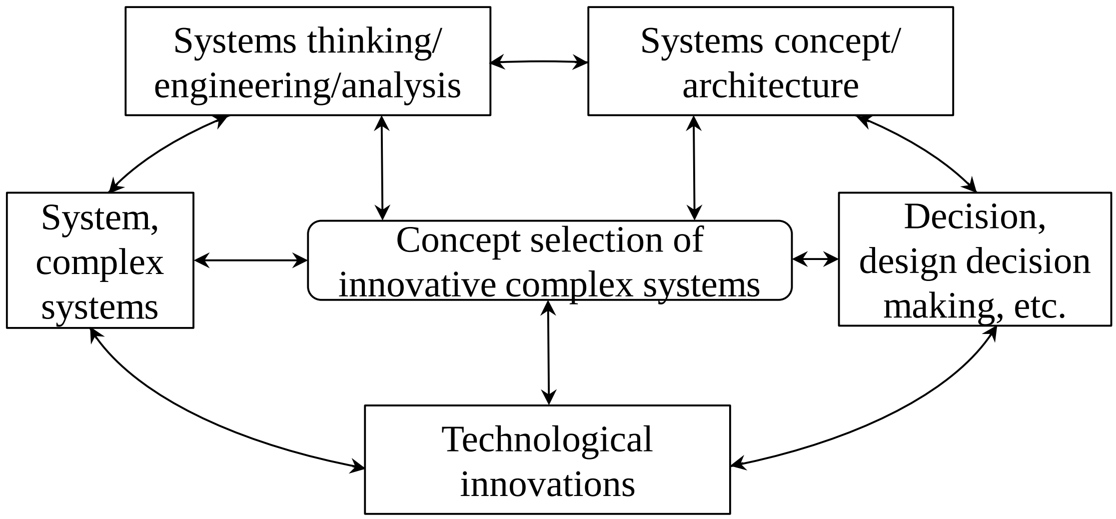


Figure 5 – Correlation among the clarified research-related terms and the research topic.

As shown in Figure 5, the research topic correlates with a variety of research-related terms. They all concurrently contribute to the knowledge of the research topic and each other. The correlation among the terms is direct or through other terms. For example, complex systems directly correlate with systems thinking and technological innovations. However, their correlation with design decision making occurs through the knowledge of systems engineering, concept, architecture, etc. Thus, the knowledge of all terms from Figure 5 is critical for understanding the state of the art of the dissertation's research topic.

1.1.1. System

The notion of a system plays a key role in the whole dissertation's research. It constitutes the primary part of the research object and serves as a path to understanding emergent properties. The term "system" originated from philosophy. Volkova noted that several dozen of its definitions exist [26]. Semenov et al., based on philosophical principles, defined a system as an internally organized wholeness in which all elements are closely linked with each other [27]. Magee and de Weck explained it as a set of interacting elements possessing defined behavior or purpose. Different classifications of systems exist. One of the primary classifications of systems differentiates them on engineering, natural, human, etc. [6,35]. Technical sciences mainly focus on the research of engineering systems as such systems are developed and managed using engineering-technical disciplines: mechanical engineering, instrument engineering, petroleum engineering, and others. Engineering systems in a broader sense include technical and technological systems.

The term “engineering system” similar to “system” also possesses several definitions. The International Council on Systems Engineering (INCOSE), invoking on ISO/IEC/IEEE 15288 international standard, defined an engineering system as a combination of interacting system elements or entities united to accomplish one or more declared tasks [16]. Crawley et al. identified it as a set of entities and their relationships possessing greater overall functionality than the sum of functionalities of separate system entities [4]. Close to Crawley et al., NASA defined an engineering system as a construct of system elements that together reach results not obtainable individually by its elements [18]. All these definitions identify the following general features of engineering systems: they possess elements or entities, relationships between those entities, the purpose for which they were united, and greater overall functionality. Successful engineering systems are those that best satisfy customer needs: meet systems requirements, achieve target goals, and lead to successful industrial exploitation [22]. The greater overall functionality of systems and systems success is associated with their emergent properties and is discussed in Chapter 2 of the thesis.

1.1.2. Complex systems

Since the 1940s, the increasing complexity of engineering systems raised the interest of scientists and engineers to research complex systems. Specific disciplines, systems engineering in the USA and systems analysis in the USSR, were created to assist in developing them [23,26]. From the perspective of systems engineering, Crawley et al. generalized the definition of complex systems as engineering systems that possess many interrelated and interconnected entities and relationships between those entities [4]. From the perspective of systems analysis, Volkova summarized the notion of complex systems as systems with many elements built to solve multi-object, multi-aspect problems and characterized by complex behavior [26]. These points of view combine the complex behavior of multiple elements and relationships in complex systems. Magee and de Weck noted the complex behavior of complex systems by emphasizing that the relationships in them are difficult to describe, predict, and manage [35]. Thus, the development of complex systems requires considering their complexity.

Similar to systems, different classifications of complex systems exist. Magee and de Weck, and Volkova prepared informative overviews of the existing types of complex systems classifications [26,35]. Among all described classifications of complex systems, those based on the degree of their complexity are essential for the dissertation's research. Semenov et al. generalized all existing classifications of complex systems by the degree of their complexity from the perspective of systems analysis and identified the following four main groups: multi-object multi-criteria systems, hierarchical systems, polyhierarchical systems with a rhomboid structure, polyhierarchical systems with the hierarchical multi-agent penta-structures [27]. No generalized classification from the perspective of systems engineering was found in the publications. Among all classifications of complex systems based on the degree of their complexity, the one described by Crawley et al. was adopted for this thesis due to its clarity, apparent simplicity, and credibility of the source. According to it, systems can be differentiated into simple, medium-complexity, and complex. Simple systems represent systems that can be entirely described by a one-level decomposition of 7 ± 2 elements. Systems of medium complexity require two-level decomposition and possess a maximum of $(7 \pm 2)^2 = 81$ elements. Complex systems allow three and more levels of decompositions with a maximum of $(7 \pm 2)^3 = 729$ systems elements. Such a detailed level of decomposition in complex systems is often only assumed and rarely used in practice [4].

Very close to complex systems are complicated systems. In complicated systems (e.g., an automobile), the relationships between the entities are fixed and do not lead to the appearance of emergent properties. In complex systems (e.g., an air transport system), the relationships between the entities exhibit self-organization and result in systems emergent properties [16]. Due to the complexity of complex systems, the research associated with them requires considering systems thinking, systems engineering, and systems analysis.

1.1.3. Systems thinking, systems engineering, and systems analysis

As mentioned earlier, systems engineering and systems analysis were created as specific disciplines to assist in developing complex systems [23,26]. These two disciplines are based on the use of systems thinking. Crawley et al. defined systems thinking as an approach that considers problems as systems [4]. From the systems engineering perspective, it is a holistic approach used to architect engineering systems and manage their complexity [36]. From the systems analysis perspective, systems thinking was specified as a holistic approach orienting on the disclosure of the wholeness of complex systems, identification of their diverse internal and external relationships, and comprehensive description of complex systems of interest [26,27]. As systems thinking serves as the foundation simultaneously for systems engineering and systems analysis, the aforementioned points of view are similar.

Systems engineering is defined as an interdisciplinary approach aimed to guide the design and development of successful complex systems [7,16,23]. Systems analysis is understood as a combination of methods aimed to analyze complex systems [37]. These two formulations describe two related but different disciplines. The term “systems engineering” initially appeared at the beginning of the 1940s in the works by Bell Telephone Laboratories in the USA [38]. In 1948 newly established American non-profit RAND Corporation (abbreviation from “Research and Development”) introduced systems analysis [26]. In the 1960s in the USA, systems engineering evolved to a separate discipline that covers design and development aspects of the whole life cycle of complex systems, and systems analysis became one of its essential parts [37,38]. At the end of the 1960s, after the translation of the book entitled "Systems analysis for business management" by Stanford L. Optner into the Russian language, systems analysis entered the Soviet scientific community [26]. The new foreign discipline was widely disseminated among engineers and scientists in the USSR. Over time, it evolved to a separate discipline, different from systems engineering in the USA but still related to it. Systems analysis in the USSR became a combinatory discipline, the correlation of which with systems engineering is visible from Figure 6 below [37].

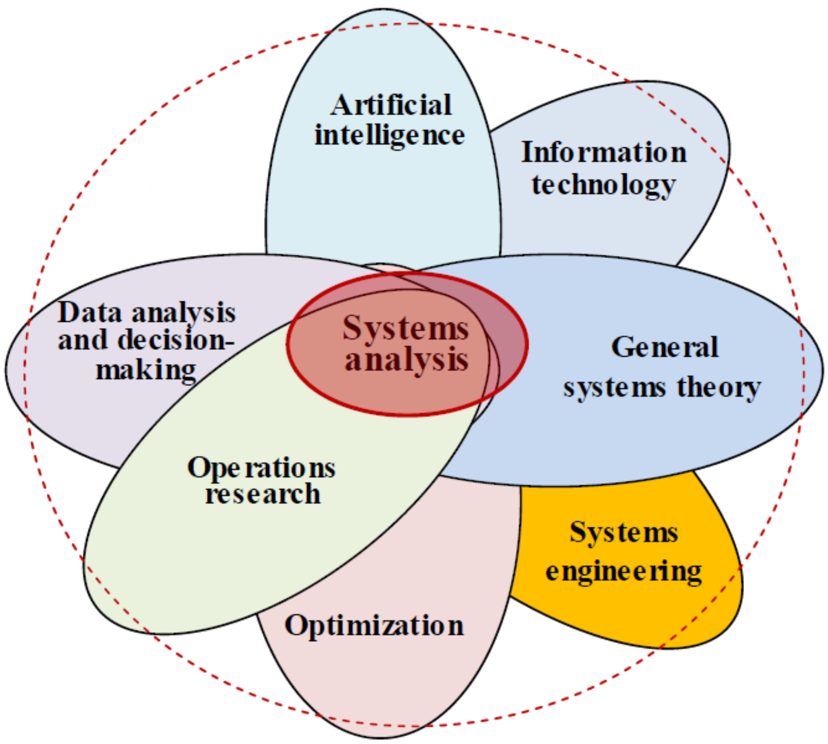


Figure 6 – Composition and structure of systems analysis [37].

According to Figure 6, systems analysis combines different aspects from systems engineering, operations research, decision theory, and others. This point of view on systems analysis originated in the USSR. Nowadays, many scientists in our country still understand it as a combination of the disciplines depicted in Figure 6 [37]. Thus, it can be concluded that systems analysis in the contemporary Russian Federation predominantly followed the traditions of the Soviet scientific school. In our country, it now serves as the national analog to systems engineering. Although systems engineering overlaps systems analysis in Figure 6, these disciplines are not equal and only correlate with each other. However, systems engineering and systems analysis, which are based on systems thinking, are very close to each other in design decision-making in complex systems, including making such critical design decisions as concept or architecture selection.

1.1.4. Systems concept and architecture

There is no single definition of a concept related to its application in complex systems. Menshenin identified several definitions suggested by top-level scientists (Table 2) [39]. Formulation of the definitions in the table below was adapted for the additional conciseness.

Table 2 – Definitions of a concept by top-level scientists according to Menshenin [39].

№	Definition	Source	Citation
1	A concept is a product or system vision that maps function to form and represents an abstraction of a system form and how the system will operate	Crawley et al.	[4]
2	A concept is an approximate characterization of the technology, operating principles, and form of the product	Urlich, Eppinger	[8]
3	A concept is a design proposal that is sufficiently detailed to prove whether it well replies to the task and intention	Andreasen et al.	[40]

According to Table 2, all definitions unite the following two general features specifying the concept: the concept is an abstraction, and maps function to form. Concept identification stays at the beginning of the design of complex systems. It is, therefore, one of the essential steps in the development of new complex systems, describing how a product or a system assumes to meet customer needs [8,18]. The concept results in its high-level mapping from function to form. Its further development for a complex system leads to the appearance of an architecture for a system, an abstract description of systems elements and the relationships between them. Concept guides building the architecture. A separate eponymous discipline within systems engineering was developed for systems architecture [4,41]. Concept or architecture selection constitutes the specific type of design decision.

1.1.5. Decision, design decision, and design decision making

Clarification of the terms “decision,” “design decision,” and “design decision making” is the path to understanding the criticality of concept selection for the design of complex systems. Many scientists explained these subjects in their publications. The following authors stand out by having provided detailed explanations in application to systems engineering and systems analysis: Bratvold and Begg, Parnell and West, Kossiakoff et al., Crawley et al., and Semenov et al. [3,4,22–24,27].

Crawley et al. defined a decision as a targeted selection from mutually exclusive alternatives (alternative solutions for the decision problem) [4]. Parnell and West emphasized that any decision is an irrevocable allocation of resources, which means that it requires resources that would be lost if the decision needs to be re-made [3]. Bratvold and Begg clarified that allocating resources in the decision aims to achieve desired objectives, which links definitions of a decision given by the aforementioned scientists [24].

Thus, all decisions possess objectives and alternatives. Together with the information required for the decision to be made, they form the so-called “decision basis” [42]. A good decision is one that is consistent with its objectives, alternatives, and available information. Decision objectives may bring ambiguity to the decision due to the lack of clarity about the real goals. The information available for decision making may be uncertain and serves as a source of uncertainty in the decision. Decisions are, therefore, influenced by ambiguity, uncertainty, or both [24].

Decisions can be analyzed (decision analysis), made (decision making), and supported (decision support). Decision analysis assumes clarifying decision problems [42]. Decision making means selecting an alternative that best fits decision objectives [24]. Decision support implies assisting decision-makers in making decisions [4]. Kossiakoff et al. combined decision analysis and support in complex systems as decision making and identified the technology level required to make different decisions: information systems for structured decisions, decision support systems (DSSs) for semi-structured decisions, and expert systems for unstructured decisions [23]. Structured decisions are also called programmed, unstructured decisions can be titled as non-programmed [4,30]. Although different classifications of decisions exist, the one developed by Kossiakoff et al. results from a combination of several frameworks and is reasonable to use for systems engineering and systems analysis purposes.

The terms “design decision” and “design decision making” refer to decision making within the aspects of design theory. Design decisions are the decisions that occur in planning, managing, and problem-solving procedures during the design of new products and systems [43]. Many design decisions are determined in design reviews [44]. Design decision making is the type of decision making focusing on making such decisions. Decision making in design theory, similar to other engineering disciplines, occurs in various forms and within multiple contexts [22]. Its activities are complex and influenced by the actually made decisions, which are methodologically supported [43,45]. Supporting design decision-making techniques and tools facilitate the increase of the quality of design decisions and consist of decision-making processes, models, and decision support instruments: decision support tools and DSSs [46–49]. Design decision-making techniques and tools are also used for concept selection design decisions, which criticality is discussed below. More information on techniques and tools is provided in the specific literature review subsection of Chapter 1.

1.1.6. Concept selection as a critical design decision

Concept selection is the type of design decision, in which alternatives consist of possible concepts of a designed product or system. As the notion of architecture is very close to that of concept, concept selection is similar to architecture selection, which is a design decision that uses possible architectures of designed systems as alternatives. Understanding the criticality of both these related types of decisions is crucial for the dissertation's research. As mentioned in the Introduction, NASA, Urlich, and Eppinger emphasized that concept selection is one of the most critical design decisions due to its position in the early beginning of the life cycle of new products and systems [7,8]. It is also valid for architecture selection as it directly follows concept selection or is used instead. Crawley et al. demonstrated the criticality of concept and architecture for complex systems by putting them in a funnel while illustrating the themes in architecting complex systems (Figure 7) [4].

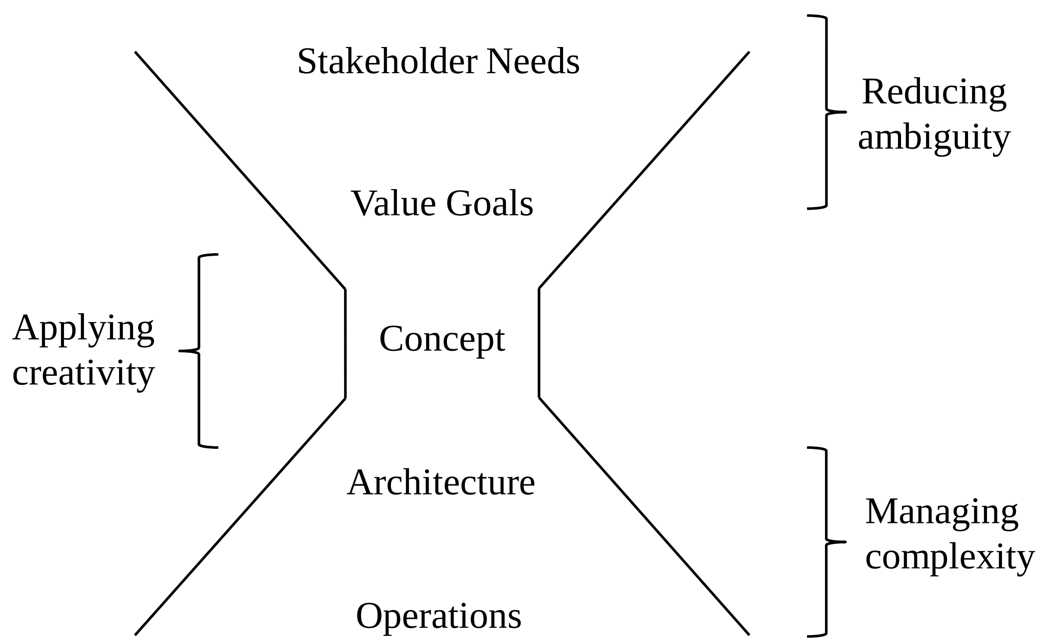


Figure 7 – Themes in architecting complex systems [4].

According to Figure 7, architecting complex systems represents a funnel and contains the following three themes: reducing ambiguity, applying creativity, managing complexity.

Applying creativity is associated with the concept placed in the bottleneck of the funnel. Architecture appears to be the first step after the concept toward the expansion of the funnel aiming to manage the complexity of complex systems. Therefore, any decision made for concept or architecture selection seriously influences the results of the whole systems architecting process and subsequent operational activities, proving the high degree of their criticality. In terms of economics, good concept selection potentially allows preserving more energy, financial and other resources than any other good design decision, which is especially critical in the case of complex systems based on technological innovations.

1.1.7. Technological innovations

The role of innovations in the technological advances starting from the 1st Industrial Revolution (industrialization) until the current-day 4th Industrial Revolution (digital transformation) is significant [1]. Its general notion relates more to economic and social than to engineering sciences [50]. Yezersky noted that the term “innovation” possesses various definitions [51]. The one given by Smits is adopted in the thesis due to its clarity and synthesizing nature. According to him, innovation is a transformed invention or a new knowledge occurring in case of its successful application [52]. The core of innovation includes an invention, which differs from innovation by the presence of an economic value [29,53]. Guseynova generalized all existing definitions and identified novelty as the foundation of any innovation [2]. Knyazeva generalized that innovation builds upon a novelty, which found its successful application [54]. Thus, the new knowledge brought by the invention is synonymic to novelty. In its turn, scholars argue about the precise definition of novelty, but the majority of them link it with the appearance of new characteristics (of any object) [55]. The existence of several closely related terms in the definition of innovation (new characteristics, novelty, and new knowledge) can be confusing. Therefore, in the thesis, these terms are substituted by the general combining neutral term “innovativeness” [53].

Many different types of innovation exist [51]. The primary division is the differentiation of innovations occurring in the engineering domain (technological) with those in society (social). Technological innovations, an object of this dissertation's research, represent inventions from the industrial arts, engineering, pure and applied sciences. Garcia and Calantone reviewed the existing literature on technological innovations, identified their various classifications consisting of the number of categories ranging from 2 to 8, and noted the degree of innovativeness as the main parameter of their categorization [53]. Radical technological innovations, also called basic technological innovations, introduce principally new practical means or technologies that satisfy the needs of new customers. This type of innovation results in a paradigm shift like in the case of the invention of a transistor or that of a microprocessor. Incremental technological innovations, also called modifying technological innovations, transform existing practical means that satisfy the present-day relevant needs of customers. This type of innovation lies in modification of existing functionalities by increasing efficiency or reducing cost [2,56].

Nowadays, many scholars consider that innovations are to be disruptive. Disruptive innovations are among the most frequently mentioned types of innovation in the literature sources during the last three decades. Marquardt et al. found that the number of papers on disruptive innovations increased three times from 2008 to 2017, and the number of citations increased twice in from 2014 until 2016 [1]. The engineering side of disruptive innovations consists of radical functionality and similar technical standards of compatible technologies, equating them in innovativeness with radical technological innovations [57]. For the dissertation's research, the division of innovations in radical and incremental, revealing radical-level and incremental-level innovativeness, respectively, is adopted due to its essence, clarity, and fundamentalism. Disruptive technological innovations are combined with radical innovations based on their common feature of radical functionality. Market diffusion questions are neglected in the thesis due to the focus on the engineering side of the research.

1.1.8. Innovative complex systems

As mentioned in the Introduction, the term “innovative complex systems” is a synonym to technological innovations of new complex systems. Systems of this type combine characteristics of technological innovations and complex systems. Constituents of technological innovations and complex systems bring innovativeness and complexity to innovative complex systems, respectively. The innovativeness of such systems could be of a radical or incremental level. Radical-level innovativeness pays off in exploration research activities when new functionalities and technological possibilities of future complex systems are searched. Incremental-level innovativeness appears in the research associated with exploiting complex systems when modifications and adaptations to the current customer needs are required. Projects devoted to innovative complex systems are challenging. Due to the complexity of such systems, associated decision problems are also complex. Their final output depends on the quality of design decisions to which concept selection belongs [11,29].

1.2. Specific literature review: Design decision making in technological innovations

The prepared literature analysis formed the knowledge basis for the specific literature review described in the current subsection. The specific literature review reflects the descriptive study I stage of the dissertation’s research and highlights the state of the art of the research topic. It presents empirical data analysis of the information from the literature sources on design decision-making in technological innovations of new products and systems. The specific literature review does not separate concept selection of innovative complex systems from the general case of design decision making in technological innovations as it is not typically done by the researchers in the field. The subsection starts by describing the literature search, continues by explaining design decision-making specifics of technological innovations, and finishes by outlining applied design decision-making techniques and tools.

1.2.1. Literature search

The scope of the literature search included Scopus, Web of Science, and eLIBRARY abstract/citation databases, IEEE, Design Society, ASME, and OnePetro articles and conference papers. An additional search was conducted via Google Scholar and disserCat databases to find appropriate books and theses, respectively. Based on the clarification of terms from the previous subsection, the following keywords and their different combinations were selected: “technological innovation,” “incremental/disruptive/radical innovation,” “complex system,” “decision making/support,” and “concept/architecture.” Additionally, an option of simply combining “decision” and “innovation” as keywords was attempted, which did not result in any success, due to an overwhelming majority of all publications on the combination of these keywords relating to the innovation theory and market decisions. Identified keywords were used to narrow the literature search area. However, about 1900 papers and books were considered. More than 50 publications were selected for the subsequent examination. The dynamics of their publishing by years is illustrated in Figure 8.

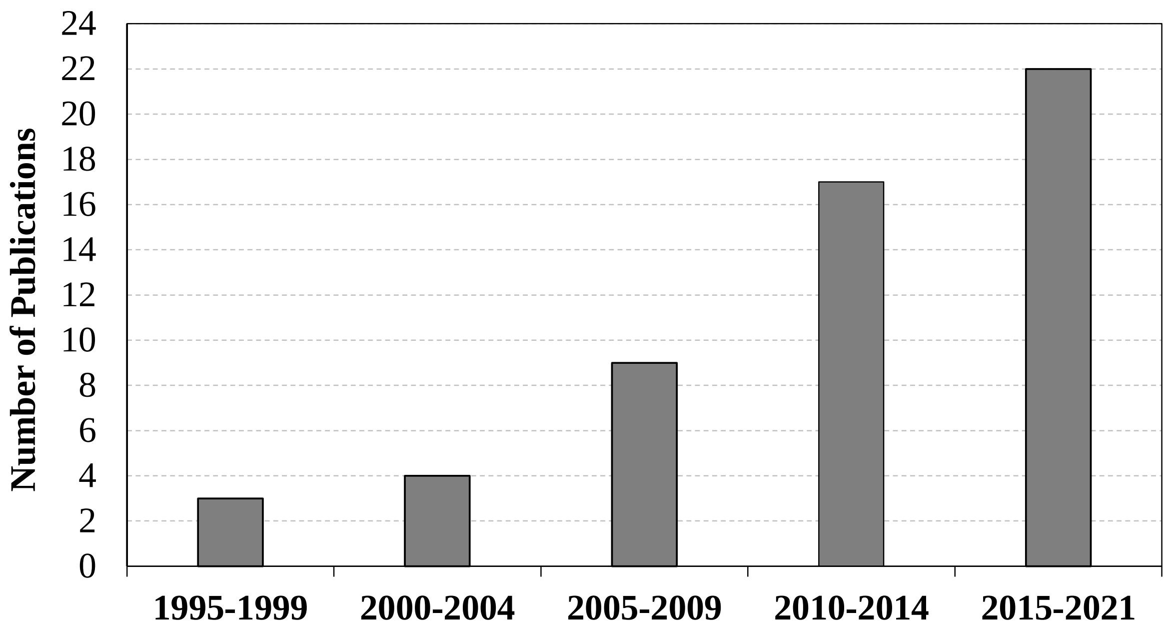


Figure 8 – Dynamics of publishing on decision making in technological innovations.

According to Figure 8, publications starting from 1995 were considered for the search. Although some papers touching on design aspects in technological innovations existed earlier, the interest of researchers was relatively rare until the first paper on disruptive technologies was published in 1995 [58]. It caused encouragement among scientists and engineers to conduct research in technological innovations and associated design aspects. Therefore, the interest of researchers about the subject has been continuously growing since 1995. As demonstrated in Figure 8, until 2005, the number of publications on the topic was relatively low (3-4 per every 5 years). In 2005-2009 it increased almost three times up to 9 publications per year and continued its growth, reaching 17 and 22 papers for 2010-2014 and 2015-2021, respectively. Years 2020 and 2021 were united with 2014-2019 for comfortability. Almost all selected publications refer to foreign literature sources, as those published in the Russian Federation had proved to nearly always consider decision making and innovations in the domain of economics and not engineering. No specific review paper was found on the subject. Selected publications discover design decision making specifics of technological innovations, decision-making approaches, processes, models, and decision support instruments.

1.2.2. Design decision making specifics of technological innovations

Knyazeva noted that failures in adopting technological innovations are the inevitable component of any innovative process [54]. No innovative process guarantees the successful application of an invention and its success in the market. Developing technological innovations of new products and systems is associated with the uncertainty induced by their innovativeness. Petetin et al. considered it in design decision making by emphasizing that decision situations in technological innovations are characterized by a high degree of uncertainty originating from the limited knowledge of decision-makers and resulting in the partial rationality of decisions [28,29]. As the development of technological innovations aims to create their values and innovation differs from an invention by its successful application and economic value, this type of uncertainty constitutes a threat [52,53,59]. It serves as the source of possible risks for the values of technological innovations [11,29].

The main groups of risks threatening the values of technological innovations are divided into market and technological. Market risks for technological innovations represent an ambiguity about the customer needs that anticipates satisfaction by the technology. Technological risks relate to uncertainties of the technologies underlying the innovation and consist of the risks resulting from the lack of their predictability and capability. The risk mitigation strategy for market risks includes increasing the knowledge of the customer, for technological risks it assumes decreasing the uncertainty of technologies underlying the innovation [28,29]. Thus, the necessity to consider the high degree of uncertainty induced by the innovativeness of new products and systems and associated market and technological risks constitute design decision making specifics of technological innovations. Innovative complex systems, representing a particular case of technological innovations, follow these specifics. Researchers on the subject do not typically separate innovative complex systems in their specifics from the general case of technological innovations. As reviewed below, the identified specifics challenged adapting design decision-making techniques and tools to use with technological innovations.

1.2.3. Decision-making approaches

Design decision-making techniques and tools consist of decision-making processes, models, and decision support instruments: decision support tools and DSSs. Their adaptation challenges adopting existing decision-making approaches that reveal themselves explicitly or are integrated into design decision-making techniques and tools. Various decision-making approaches that, to some extent, are applicable to decision making in technological innovations were found in the literature sources [11]. Gutierrez et al. proposed a generalized set of approaches for making decisions and understanding innovations (Table 3) [60].

Table 3 – Approaches for making decisions and understanding innovations [60].

№	Dimension	Division	Feature
1	Occurrence	Static	Innovation can be predicted
2		Dynamic	Innovation cannot be predicted
3	Rationality	Rational	Analytical procedures can be applied
4		Non-rational	Analytical procedures cannot be applied
5	Formalization	Formal	Written procedures are applied
6		Informal	Written procedures are not applied
7	Classification	Hierarchical	Decisions are made at the highest organizational level
8		Non-hierarchical	Decisions are made at lower (than highest) organizational level

As listed in Table 3, firstly, approaches for making decisions and understanding innovations are divided depending on whether the innovation can be predicted or not: changes occurring due to innovation can be forecasted and planned or occur inevitably. Secondly, the approaches are divided according to their rationality. The approach is rational, if analytical procedures are applicable. A non-rational approach assumes only the applicability of subjective evaluations. In some complex cases, authors mention the use of gut feeling decision making [11,24]. It refers to the non-rational type of approach as a subdivision. Thirdly, the level of formalization plays a considerable role in classifying approaches for making decisions and understanding innovations based on the application of written procedures. Finally, the approaches are divided on those made at the highest or lower organizational level. Overall, the classification given by Gutierrez et al. in Table 3 provides the knowledge of dividing approaches for making decisions and understanding innovations based on their structural (rational, classification) and appearance characteristics (occurrence, formalization).

The second set of decision-making approaches applied to technological innovations originated from the decision theory: descriptive and prescriptive approaches from descriptive and prescriptive decision theory, respectively. Descriptive decision theory focuses on explaining how and why decisions are made in reality. Prescriptive decision theory, also called normative, is oriented on how decision-makers should make decisions, explores decision-making logic and aims to achieve rational decisions. Design decision making typically uses the prescriptive approach as it primarily deals with rationalized decisions. However, due to possible deviations from the rational input (e.g., individual beliefs, political aspects), it can touch on the descriptive approach [61,62]. This classification of decision-making approaches is valuable to separate rational from non-rational design decisions.

The development in cognitive science formed the basis for one more set of decision-making approaches applicable to technological innovations. According to it, the first approach, called prescriptive, is based on current operational research and aims to search for an optimal solution. The second approach, called cognitive, is based on current cognitive science and aims to search for an acceptable solution. The third approach, called naturalistic, focuses on decision situations and aims to restrict the influence of emergency situations. These approaches lead to powerful design decision support in technological innovations in cases, when the proper physical/mathematical problem definition is available [11,28].

The aforementioned approaches relate to various fields of knowledge, bringing value to their disciplines. Approaches for making decisions and understanding innovations relate to the innovation theory. Descriptive and prescriptive approaches originate from the decision theory. Prescriptive, cognitive, and naturalistic approaches belong to the cognitive science. Systems analysis and systems engineering also possess approaches applicable to design decision-making in technological innovations and bring value to the design of new systems.

Nunes noted an important role of systems thinking for design decision making [63]. As mentioned in the Introduction, Kossiakoff et al. for systems engineering and Sannikov, Kutsubina for systems analysis put the systems thinking approach as the basis for decision making in complex systems [22,25]. Semenov et al. also mentioned systems thinking as a basic approach for decision making in complex systems and claimed that it requires well-defined goals and criteria as essential elements for selecting alternatives [27]. Many other authors mention systems thinking as an approach for decision making in complex systems without specifying what needs to be identified first: the alternatives or the criteria for their evaluation. In 1992, Keeney formulated two underlying philosophies for decision making, also known as decision-making approaches: AFT and VFT, both encompassing systems thinking. AFT, an older approach, puts alternatives in the first place and later evaluates them using the criteria (values). VFT, also called the "value approach," does vice versa [3,17]. Nowadays, the value approach is widely used for decision making in systems engineering. Its success was proven by its application for design decision making at NASA [7].

Petetin et al. applied the value approach to design decision making in disruptive technological innovations and proved its validity in case studies from the aerospace industry [29]. The value approach in application to technological innovations considers the value creation and risk of innovation. It serves as a basis for the subsequent adapted decision-making process and model, as shown below.

1.2.4. Decision-making processes

Decision-making approaches are not directly applied to design decision making: they underpin the development of processes used to make decisions by decision-makers, called decision-making processes. These processes form the basis for the subsequently developed decision-making models that abstractly reflect decision making as it occurs in reality. Thus, decision-making processes occupy an intermediate position between approaches and models. They play a significant role in design decision-making by assisting practical applications of "theoretical" decision-making approaches.

Petetin et al., in their work on decision-making in technological innovations, analyzed existing decision-making approaches and concluded that they all fit the generalized decision-making process depicted in Figure 9 [29,46]. This process was mentioned in the publications primarily devoted to systems engineering. Researchers typically use it as a foundation for subsequently developed decision-making models.

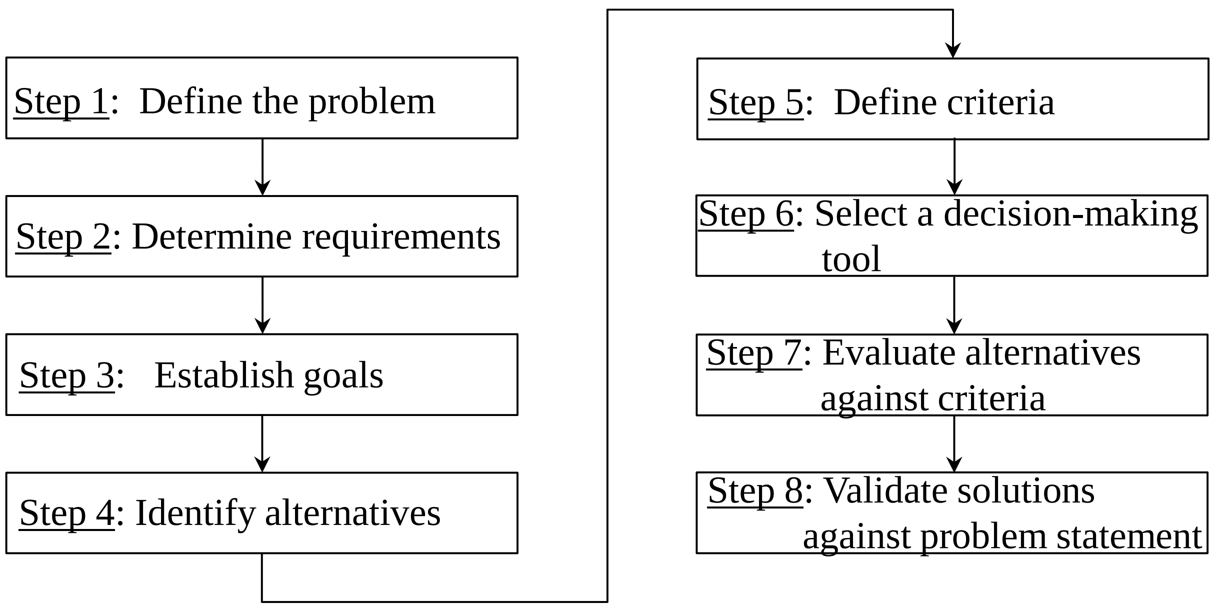


Figure 9 – Generalized decision-making process scheme [29,46].

The generalized decision-making process (Figure 9) starts by defining the decision problem, requirements, and goals (steps 1-3). It continues by identifying alternatives and the criteria for their evaluation (steps 4-5) and selecting a decision-making tool, which is another term for a decision support tool (step 6). The process finishes by evaluating alternatives against identified criteria using the selected tool and validating solutions against the problem statement, also called the decision validation (steps 7-8). The generalized decision-making process refers to AFT or VFT depending on the selected understanding of the notion of value. Keeney defined values as principles used for evaluation [17]. However, Crawley et al., in their funnel for illustrating the themes in architecting complex systems, put them in one line with goals (see Figure 7) [4]. Therefore, if criteria from step 5 are assumed to be values, then the generalized decision-making process refers to AFT (alternatives identified before values). If goals from step 3 are assumed to be values, then the process refers to VFT. Petetin et al. used the generalized decision-making process as the basis to propose their knowledge creation process for decision-maker information (Figure 10) [29].

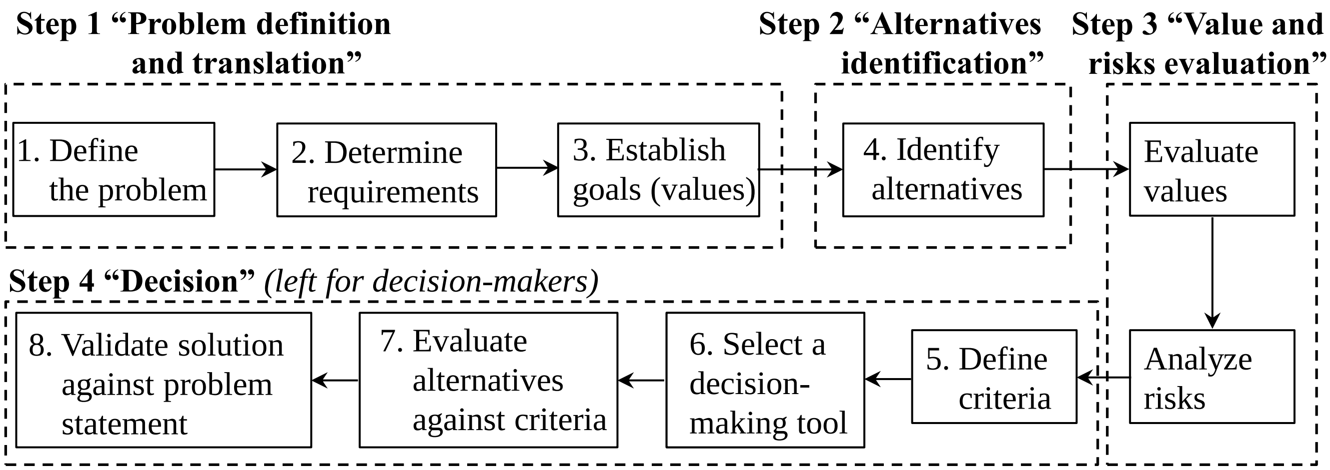


Figure 10 – Knowledge creation process for decision-maker information ([29], adapted).

The knowledge creation process, shown in Figure 10, actually represents one of the possible decision-making processes based on the value approach. It uses the generalized decision-making process as its foundation. The knowledge creation process assumes goals as values, unites the first three steps of the generalized decision-making process into its Step 1 "Problem definition and translation," uses the fourth step as its Step 2 "Identification of alternatives," adds its own Step 3 "Value and risks evaluation," consisting of evaluating values and performing risks analysis. It finishes with Step 4 "Decision", which unites steps 5-8 of the generalized decision-making process and is left for decision-makers. This knowledge creation process demonstrates, how Petetin et al. successfully adapted the generalized decision-making process for disruptive technological innovations, using the value approach. Its validity was proven by the successful application to making a design decision for technological innovation in one of the projects from the aerospace industry. The idea behind the adaptation lies in the statement that the generalized decision-making process requires decisions to be entirely rationalized, which is impossible in technological innovations due to the uncertainty induced by their innovativeness. Petetin et al. claimed that their knowledge creation process allowed avoiding full rationalizing [28,29]. It represents a successful example of a process that considers design decision-making specifics of technological innovations.

A big group of decision-making methods considering many evaluation parameters, called multi-criteria decision-making (MCDM) methods, are mentioned in the publications devoted to design decision making in technological innovations. They include a wide variety of methods like analytic hierarchy process (AHP), multi-attribute utility theory analysis (MAUT), TODIM (an acronym from Portuguese for interactive and multi-criteria decision making), etc. [27,29,64]. MCDM methods present procedures, which can be referred to both as decision-making processes and decision support instruments. As design decision making in technological innovations requires considering several criteria for evaluation [29], these methods are also applicable to the subject. However, MCDM methods mostly require decisions to be fully rationalized, which is not the case of technological innovations, and are, therefore, rarely specifically used for design decision making in such cases.

According to the general overview of publications in systems analysis, researchers in this domain do not typically separate design decisions made in technological innovations from the general case of design decision making. Semenov et al. provided the systems analysis process and selection of alternatives scheme, which actually represents one more generalized decision-making process (Figure 11) [27]. The scheme represents a comprehensive decision-making process in complex systems considering the critical role of the final decision-maker in the organization, the chief executive, who takes official responsibility for made decisions. The process starts with the decision problem statement and understanding the initial conditions. It then goes to problem and goals clarification, which assumes iterations by returning to the problem definition. Further steps lead to evaluating alternatives linked by the inverse relationship with the problem definition and the chief executive.

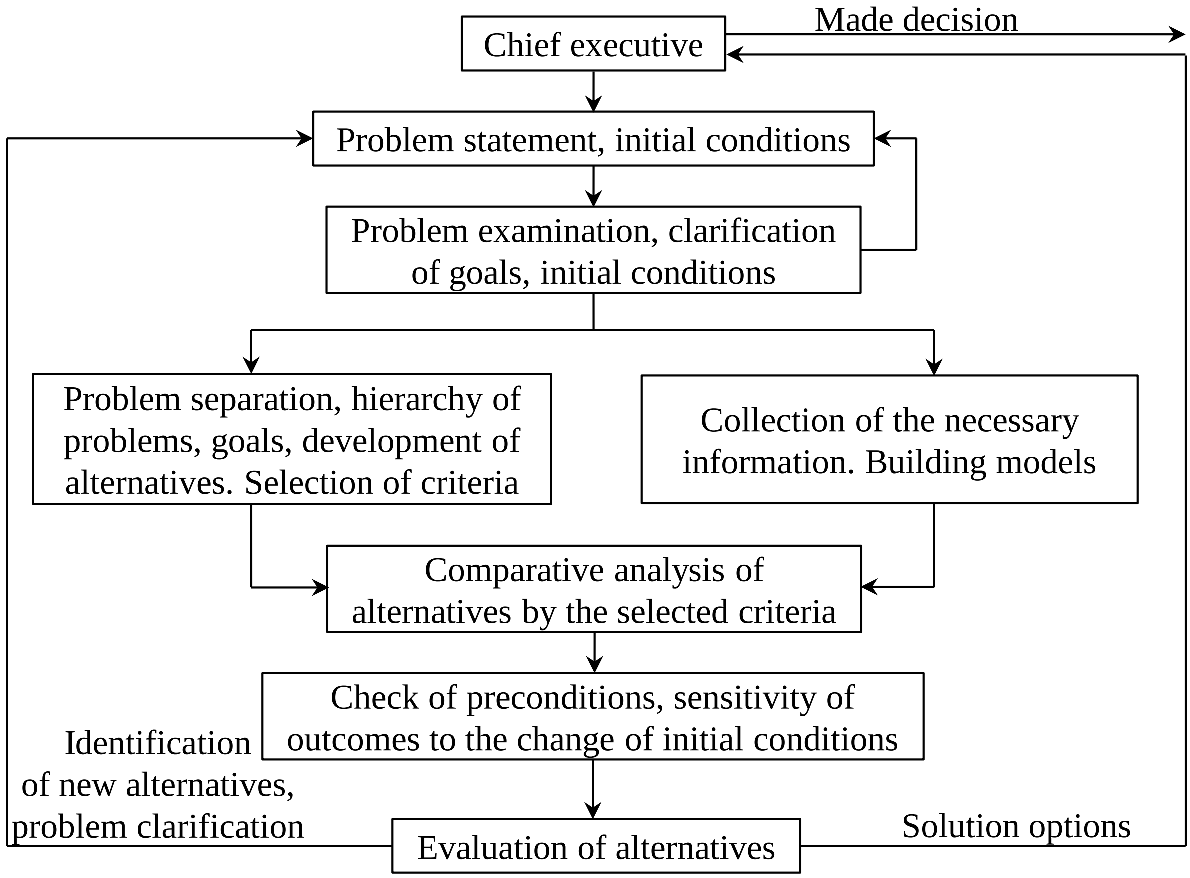


Figure 11 – Systems analysis process and selection of alternatives scheme [27].

The scheme in Figure 11 demonstrates the iterative character of the decision-making process, the necessity to clarify the decision problem and initial conditions, and the requirement for the decision to be approved by the established authorities before it is implemented. The systems analysis process and selection of alternatives scheme is similar by the sequence of actions to the identified generalized decision-making process but differs from it by including organizational aspects and inverse relationships. Both these generalized decision-making processes can be roughly equated and adapted for design decision-making in technological innovations similar to what was done by Petetin et al. for the value approach.

Crawley et al. in the book on complex systems architecting and Kossiakoff et al. in the book on systems engineering mentioned Simon's structured decision-making process [4,22]. Simon's process became a reference in decision making and decision support within systems engineering and is also applicable to design decision making in technological innovations. It is described below as the foundation of the related three-phases and consequent seven-phases decision-making models, which are followed by the six-phases model for the value approach.

1.2.5. Decision-making models

According to Kossiakoff et al., decision-making models represent a simplified representation of reality. In the general case, they include schematic, mathematical, human factor, and other models [23]. Based on the information from the reviewed publications, design decision-making in technological innovations mainly operates with process-based models that are schematic models reflecting decision-making processes. Developing decision-making models assumes representing the decision context and environment [22]. Therefore, the role of underlying decision-making approaches and processes in models is significant.

Petetin emphasized the great role of the cognitive approach to design decision making in technological innovations [28]. In 1960, Simon developed a decision-making process-based model that became the basis for most contemporary decision-making processes and models [30]. It consists of three phases and follows the cognitive decision-making approach. Later, Mintzberg et al., following the cognitive approach and Simon's work, developed a decision-making model, consisting of seven phases. It expanded the principles of the earlier established Simon's three-phases model.

The three-phases model consists of the following phases: "Investigation," "Design," and "Choice." The "Intelligence" phase assumes the information-gathering activities on the decision problem. The "Design" phase represents decision problem structuring: identifying alternatives, criteria, and others. The "Choice" phase consists of the selection between alternatives. The seven-phases model further splits the constituents of the three-phases model, making it more detailed. The comparison of these two models is listed in Table 4 [28].

Table 4 – Three and seven-phases decision-making models in comparison [28].

№	Three-phases model [30]	Seven-phases model [32]	Procedure contents
1	Investigation	Decision recognition	Identification of decision to be made
2		Decision diagnosis	Clarification of decision information
3	Design	Solution search	Search for solutions
4		Solution design	Development of existing/new solutions
5	Choice	Screen	Elimination of inappropriate solutions
6		Evaluation-choice	Evaluation and selection of alternatives
7		Authorization	Solution activation as per the hierarchy

According to Table 4, firstly, the "Investigation" phase is divided into the "Decision recognition" and "Decision diagnosis" phases to identify the decision problem and clarify available information on the decision. Secondly, the "Design" phase is split into the "Solution search" and "Solution design" phases to search and develop decision solutions. Both developing existing and establishing new solutions are included in the latter phase. Finally, the "Choice" phase is divided into the "Screen," "Evaluation-choice," and "Authorization" phases, leading to selecting and ranking the alternatives. "Investigation," "Design," and "Choice" phases of the three-phases model and corresponding phases of the seven-phases model allow performing design decision making within the cognitive approach and limited decision rationality as it occurs in technological innovations of new products and systems according to Petetin's findings [11,28–30,32].

Crawley et al. and Kossiakoff described variations of Simon's decision-making processes and process-based models consisting of four phases: with the "Review activity" and "Implementation" fourth phases, respectively [4,22]. These models could also be compared with the seven-phases model. They were skipped as the comparison in Table 4 already demonstrates the relationship between the models by Simon and Mintzberg et al. Both the three-phases and seven-phases models are mentioned in the publications on design decision-making in technological innovations of new products and systems and are, to some extent, applicable to the subject due to the cognitive approach that underpins them.

The value approach also leads to the development of models applied to decision making in technological innovations that could be built on the generalized decision-making process (Figure 9) or its modifications. An example is the six-phases model (Figure 12) [28].

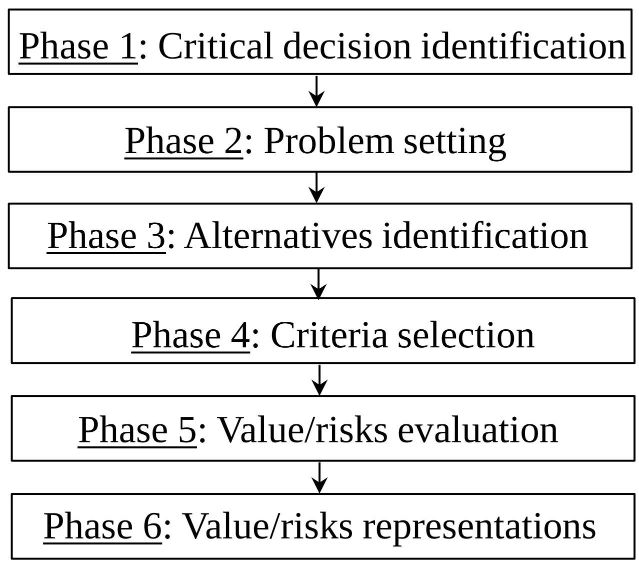


Figure 12 – Six-phases decision-making model for the value approach [28].

The six-phases decision-making model is a schematic process-based model built upon the knowledge creation process for decision-maker information (Figure 10) and represents its further development. As shown in Figure 12, the model starts with a critical decision identification and problem setting. These two initial phases are performed by conducting the preliminary literature review and interviewing stakeholders to obtain all necessary information about the decision context and environment related to innovation. At these phases, values in the form of goals are also established. The next phase, devoted to identifying alternatives, aims to find alternatives based on the values. It assumes separate or combined (in different combinations) use of the following tactics: idea tactics, design tactics, benchmarking, integrated benchmarking tactics, search and cyclical search tactics. Criteria selection, which comes next, consists of selecting requirements, including value creations as decision criteria. Value/risks evaluation and representation constitute the final phases of the model and assume a measurable assessment of the values created by each alternative. The information obtained with the help of the model is provided to a decision-maker to support in making a design decision for the particular technological innovation under consideration. This way, the six-phases model supports the practical application of the value approach for decision making in technological innovations of new products and systems in general and disruptive technological innovations in particular.

Different schematic models regularly appear in the publications devoted to the subject, and they all are closely related to the generalized decision-making process. No decision-making models directly associated with the systems analysis process and selection of alternatives were found in the literature sources. However, due to its similarity, all linked with the generalized decision-making process schematic models, including the six-phases model for the value approach, can to a certain extent also relate to it. All models are united by considering technologies driving product innovations and associated uncertainty [11,48].

As for other types of models, their usability to the subject is limited by design decision making specifics of technological innovations. However, elements of mathematical and human factor modeling are often considered within decision support instruments. Mathematical models, for example, provide valuable information on the relationship between the innovation process and mathematical laws: chaos theory for technology forecasting, the law of functional expansion for design theory, etc. [65,66].

1.2.6. Decision support instruments

As mentioned earlier, decision support instruments include decision support tools and DSSs. Decision support tools typically refer to mathematical or software applications used for the sixth step of the generalized decision-making process (Figure 9) or for comparative analysis of alternatives in the systems analysis process (Figure 11) [47,67]. They provide decision-makers with the essential instrumentation but lack giving advanced features in decision support compared to DSSs. DSSs represent various systems developed to support management and strategic planning decision-making activities, including model-, data-, group communications-, document-, knowledge, and web-based-driven systems [68]. Kossiakoff et al. noted the importance of using DSSs for semi-structured decisions: decisions with limited rationality similar to those in technological innovations [23]. DSSs are often applied to support design decision making in innovative projects in general and technological innovations in particular. Examples of DSSs touching to some extent on design decision support in technological innovations are as follows: DSS for strategic innovation partner selection based on a MS Excel spreadsheet with macro programming, a DSS framework for innovation management representing a web-based tool, methods-time-measurement DSS aiming to facilitate assembling line planners, etc. [49,69,70]. All these systems support management and strategic planning decision-making activities for technological innovations and are united by considering technological and market risks associated with them.

Decision support tools include many different techniques to facilitate organizing, representing, and analyzing information to support design decisions. The University of Cambridge provides a comprehensive list of such tools, distributing them in five groups: information control tools (gathering, storage, organization of data and knowledge), paradigm and simulation models (paradigms and frameworks to "handle" the situation), ways of choosing (tools that assist in narrowing the field of selection), representations aids (tools allowing visualization of decision problems), and processes (management techniques or philosophies) [71]. All these tools can potentially be used to support design decision making in technological innovations, and their choice is a matter of preference for decision-makers. Petetin et al., for example, used a cross-plot, an especially adapted chart, to represent values and risks for his six-phases model for the value approach [28,29].

There has been a rising interest of scientists and engineers in the last years in applying artificial intelligence technologies, such as machine learning and deep learning to improve the decision support instrumentation. Havins, a member of IEEE, recently noted that well-rounded and reliable DSSs are developed based on the combination of adequate data storage and artificial intelligence. It was concluded that artificial intelligence technologies facilitate the "learning" of such systems from the previous results, improving their capability to provide better future recommendations [72]. No currently published papers were found on the topic in application to technological innovations, possibly due to their design decision making specifics. However, this type of research seems to constitute the primary future trend.

1.2.7. Proof of validity

Design decision-making techniques and tools are applied to technological innovations from various industries: aerospace, automotive, telecommunications, and others [48,63,73]. The publications representing case studies provide validity proofs predominantly for the techniques based on the value approach. Literature sources on systems analysis demonstrate proofs for the systems thinking approach in general design decision-making cases, not emphasizing their applicability and validity for technological innovations. Meanwhile, the value approach possesses solid proofs of its validity for the subject as well as for the related processes and models. It is successfully applied for design decision making of space missions and systems by NASA [7]. For instance, in 2008 the value approach demonstrated success in analyzing the technical feasibility and relative productivity of alternate robotic missions to search for frozen water at the lunar South Pole, which was based on the computed values for each mission concept [74]. Petetin et al. proved the validity of the knowledge process and six-phases model by successfully selecting a ceramic manufacturing process for a disruptive innovation project in an aeronautical company [28,29]. Other successful examples exist on the subject, including those from the oil and gas industry [12,75].

1.2.8. Observed tendencies

The specific literature review raised the question of design decision-making techniques and tools applied and applicable to technological innovations of new products and systems. It started by describing the associated literature search and proceeded by analyzing the information from the literature sources on design decision making in technological innovations. The initial purpose of the review was to identify design decision making techniques and tools applied for concept selection of innovative complex systems. During the literature search, the following two tendencies were observed: firstly, the subject of concept selection of innovative complex systems is not typically separated from the general case of design decision making in technological innovations; secondly, many of the found techniques and tools are potentially applicable to the subject, although their applicability is not explicitly described in the publications. These tendencies led to considering a broader subject of design decision-making techniques and tools applicable to technological innovations.

An overwhelming majority of the selected and analyzed publications to different degrees are devoted to the value approach and associated decision-making techniques and tools, constituting another observed tendency. Even the systems thinking approach described for design decision making in systems analysis can be aligned with it due to the similarity of decision-making processes. Proofs of validity and the majority of publications allow one to conclude that the value approach is nowadays the most successful decision-making approach. Various design decision-making techniques and tools can be developed based on it, including those considering design decision making specifics of technological innovations.

The general overview of publications related to the topic or close to it, made during the literature search, revealed one more observed tendency of the researchers coping with design decision-making in technological innovations: many of them tend to apply mathematical operations to reduce the uncertainty brought by innovations. Vivid examples of using mathematics for this purpose are provided by Polverini et al. and Le Glatin et al. [76,77].

1.3. Conclusion on Chapter 1

Chapter 1 partially covered the research clarification and entirely the descriptive study I stages of the dissertation's research via the literature analysis and specific literature review, respectively. It is based on the related review paper by Nikolaev and Fortin, which information was updated, enhanced, and complemented by clarifying essential terms to fit the goals of the thesis [11]. The main findings of the chapter are as follows:

1. The core research-related terms were clarified through performing the literature analysis of the information from the publications on systems engineering and systems analysis. The clarification included basic terms ("system," "complex systems," etc.), more specific terms ("decision," "decision making," etc.), and "technological innovations." The clarification of all these terms facilitated the understanding of the theoretical fundamentals of the dissertation's research and the identification of the proper keywords for the subsequent literature search.
2. As a result of the literature search, more than 50 publications on design decision making in technological innovations were selected from about 1900 considered papers and books. It turned out that the subject of concept selection of innovative complex systems is not typically separated from the general case. Therefore, a broader subject was considered, which allowed identifying applied and applicable techniques and tools.
3. Selected publications were analyzed, and design decision-making specifics of technological innovations, applied and applicable decision-making approaches, processes, models, and decision support instruments were identified. They included the value approach that was concluded to be the most successful decision-making approach nowadays. This approach also aligns with the systems analysis perspective on decision making as it absorbs systems thinking.

No prior works were found to consider emergent properties for design decision making in technological innovations, which leaves opportunities for further research in this field.

CHAPTER 2. ONTOLOGY, APPROACH, AND MODELS

This chapter represents the prescriptive study of the dissertation's research. It describes the development of the systems thinking ontology of emergent properties for complex systems (STOEP), the emergence approach to design decision making in innovative complex systems (for short, the emergence approach), and combined decision-making models of two levels. Level-one model (CDMM-1) represents an essential process-based decision-making model. Level-two model (CDMM-2) demonstrates the modernization of CDMM-1. All these components, indicated in the title as ontology, approach, and models, constitute scientific contributions of the thesis and closely relate to each other (Figure 13).

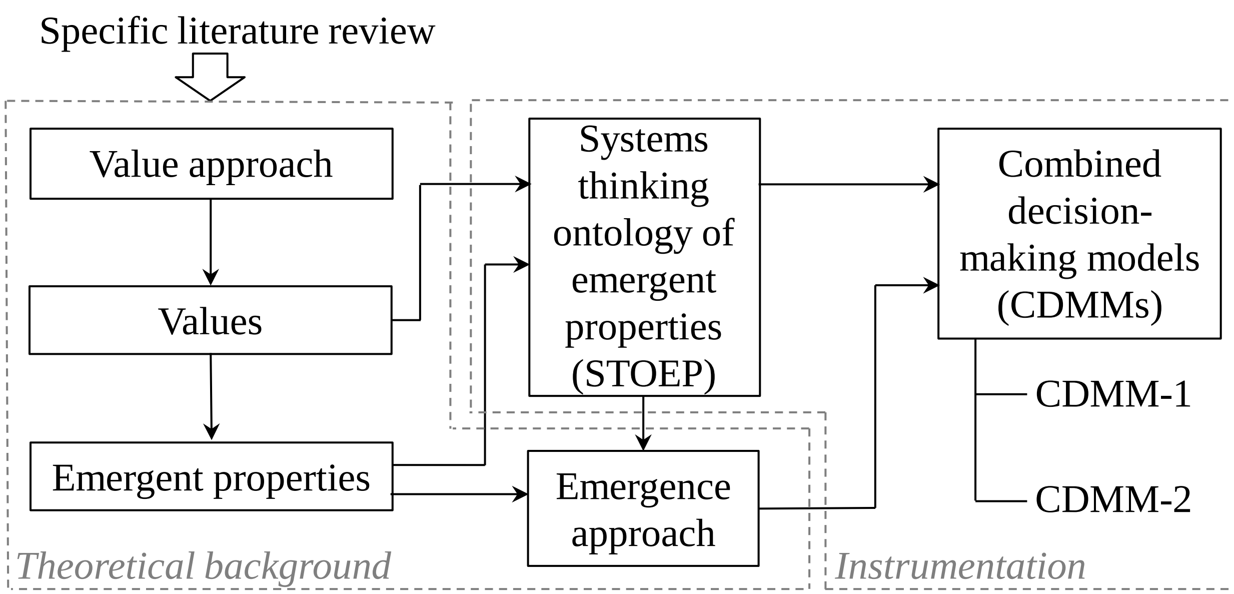


Figure 13 – Relationship between ontology, approach, and models in the research.

According to Figure 13, STOEP and the emergence approach share the central position in the dissertation's research. Their foundation, the value approach, was identified via the specific literature review described in Chapter 1. The value approach relates to them through values and emergent properties. The emergence approach serves as a theoretical background for using emergent properties in design decision making. It is a modification of the value approach and includes the principle of complementarity for design decision making in innovative complex systems that reflects the possibility to consider the combination of innovativeness and complexity of such systems using their emergent properties. STOEP is an ontological model drawn up on the basis of analyzing the semantics and relationships of emergent properties and plays the role of an instrumentation. CDMM-1 and CDMM-2 serve as the means for applying the emergence approach in practice for design decision making.

Chapter 2 starts with STOEP as the initial step for understanding the notion of emergent properties and identifying the possibility to modify the value decision-making approach. It continues by formulating the emergence approach and finishes by describing CDMM-1 and CDMM-2. Overall, the chapter proposes a solution for the adaptation of design decision-making for concept or architecture selection of innovative complex systems.

2.1. Systems thinking ontology of emergent properties for complex systems

The role of emergent properties in analyzing complex systems is significant. As mentioned in the Introduction, Crawley et al. noted that emergent properties indicate systems success and failure. Systems success occurs if anticipated emergent properties appear. Systems failure takes place if anticipated emergent properties fail to appear or the appearance of unanticipated properties occurs [4]. From both systems engineering and systems analysis perspectives, emergent properties are primarily used to characterize systems emergence, which is a more general term [4,26]. They are also linked with the occurrence of systems emergent behavior and allow reaching values [4,16]. The described below STOEP considers all these pieces of information. Firstly, the adaptation of the term “ontology” for systems thinking is provided. Secondly, the description of a conducted supplementary literature search on emergent properties and emergence is described. Thirdly, the developed ontological model, consisting of semantics and relationships of emergent properties is given. Finally, possible applications of STOEP are listed. The current subsection describes the material published in the related paper by Nikolaev and Fortin [6]. The information from this paper was slightly updated before the integration into the text of the thesis.

2.1.1. Adaptation of the term "ontology" for systems thinking

The term "ontology" originated from the philosophical works on metaphysics, or the science of being, in the 17th century. Its initial use was associated with the description of various metaphysical models but later was narrowed to the description of a single model [78]. In the 20th century, the term was adopted by scholars from the natural and engineering sciences. From the systems engineering perspective, an ontology represents a combination of concepts, relationships, and rules governing how these concepts are linked to each other [79]. From the design theory perspective, where a specific type of "a design ontology" was introduced, it represents a set of hierarchically structured terms and serves as the foundation for a knowledge base [80]. Both these points of view are similar and identify semantics and relationships. Semantics include identification of objects and entities in the domain. Relationships consider objects and entities inside and outside the boundary of the domain, and rules governing the existence of entities and behavior [6]. No specific explanation of ontology was found in the systems analysis literature sources.

As systems thinking is an approach primarily implemented in systems architecture, conceptual design of complex systems, and systems analysis, the term "systems thinking" unifies simultaneous affiliation of the systems thinking ontology to systems engineering, design theory, and systems analysis. The combining term "systems thinking" is added to its title to emphasize the concrete underlying approach. Generally, an ontology in the design represents a documentation of the terminology used to describe objects, properties, and associations in a particular domain. Thus, STOEP as a systems thinking ontology consists of semantics and relationships. It can also be called "an ontological model" as ontology represents a model of reality [6,80].

2.1.2. Supplementary literature search

The object of a conducted supplementary search consisted of searching for publications on emergent properties and emergence. Its scope included Scopus and Web of Science abstract/citation databases, Design Society, IEEE, and OnePetro articles and conference papers. ASME, e-LIBRARY, and disserCat were skipped as preliminary searching attempts demonstrated the absence of publications on the topic in them. Additionally, Google Scholar was used for searching appropriate books. After several attempts, combinations of "system" and "emergent properties" or "emergence" were chosen to narrow the area of the search. Over 45 publications out of more than 1200 books and papers were selected for further analysis. The dynamics of their publishing by the years is shown in Figure 14 [6].

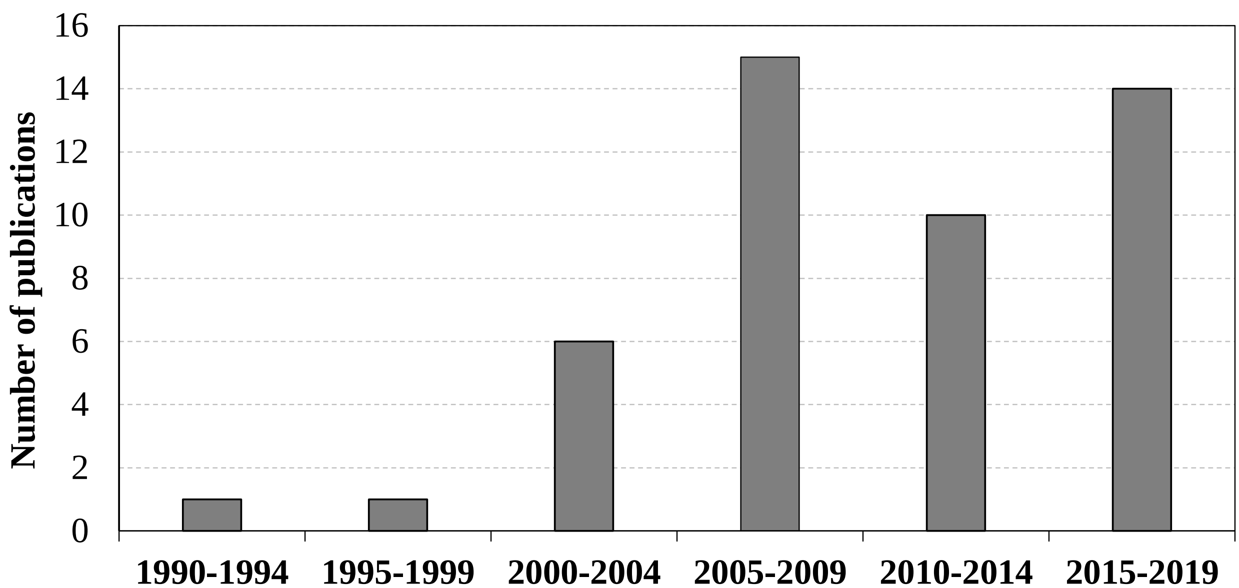


Figure 14 – Dynamics of publishing on systems emergent properties/emergence [6].

No data for years 2020 and 2021 were included in Figure 14. An attempt to update the performed supplementary literature search, initially conducted in 2020, demonstrated the absence of appropriate publications from these years, except the one by Nikolaev and Fortin, reflected in the current subsection [6]. According to Figure 14, the interest of researchers on the topic grew, starting with one publication every five years in the 1990s, increased in the

2000s, reaching its peak in 2005-2009. It maintained a high level of interest in the 2010s. The search started in 1990 as it was a meaningful year for contemporary systems engineering: the foundation of INCOSE [81]. Currently, scientific topics with emergent properties and emergence continue to be popular in various disciplines. STOEP is based on analyzing publications selected as a result of the described supplementary literature search.

2.1.3. The semantics of emergent properties, associated terms

Emergent properties constitute the object of STOEP. Its development started by identifying the semantics of emergent properties and associated terms and followed by describing the semantics of entities and relationships. For the latter, the object of the ontological model was decomposed using the classifications of emergent properties. The identified information was presented schematically, constituting the form of STOEP representation ready to apply for systems engineering and systems analysis purposes.

Emergent properties were defined as discovered behaviors of systems that emerge spontaneously by de Weck et al. [82]. Crawley et al. noted that these properties characterize emergence and exhibit themselves when the entities of a system are put together [4]. Damper emphasized that emergent properties are systemic as only a system reveals them but not its individual entities [83]. Georgiou noted that such properties could also be considered as “unforeseen consequences” of a system [84]. Knyazeva outlined that emergent properties are a distinctive characteristic of complex systems, in the analysis of which they play an important role [6,54]. Hitchins supported this statement by putting their identification, realization, and maintenance as the primary task of systems engineering [85]. The term “emergent properties” is close in its meaning to the following related terms: “emergence,” “emergent behavior,” and “synergy.” However, no single definition exists for any of them. For instance, Pomorova and Hovorushchenko prepared a list of 14 sources providing different definitions of emergent behavior and emergent properties [86].

"Emergence" is the closest term to "emergent properties." It means "the whole is more than the sum of its parts" and is the goal of systems thinking [4,87]. Emergence constitutes the central feature of complex systems and represents the transition of their quantitative characteristics (many elements and relationships in complex systems) to qualitative (appearance of emergent properties) [12,88]. Damper noted that one of the earliest mentions of the term is met in Hume's "Dialogues concerning natural religion," a philosophical work published in 1779 [83]. In the 20th century, the notion of emergence appeared in scientific publications related to the engineering disciplines. Nowadays, this term is widely described in the literature sources on systems engineering. Volkova and Denisov prepared an overview of emergence in the book on systems analysis [26]. As emergence and emergent properties found their application in the analysis of complex systems, scholars frequently equate them. Kopetz et al. directly built the definition of emergence upon the definition of an emergent property [89]. Thus, singular "emergence" and plural "emergent properties" represent fungible terms and can be equated [6].

Other close terms to "emergent properties" are "emergent behavior" and "synergy." INCOSE provided an essential definition of emergent behavior as a behavior of a system that cannot be understood only by considering the behavior of its separate entities [16]. Analyzing the list of other definitions prepared by Pomorova and Hovorushchenko, it can be concluded that emergent properties represent the attributes of a complex system resulting from its emergent behavior and characterizing it. Synergy is defined as properties or behaviors that exist because distinct elements can interact [82]. It is the kind of emergence that represents enhancing existing functions of systems elements instead of reflecting the appearance of new functions [90]. However, synergy still constitutes a part of emergence. Therefore, the term "synergy" can be equated with the term "emergent properties," at least in cases of enhancing existing systems functions. Identified semantics of emergent properties and associated terms allow proceeding to the semantics of entities of the object and relationships.

2.1.4. The semantics of entities, relationships

The semantics of the entities of the developed ontology's object and relationships were defined by analyzing the classifications of emergent properties and emergence as its most closely related term. Considering the made above conclusion on the possibility to equate the terms "emergent properties" and "emergence," a summary table of their existing classifications was prepared (Table 5) [6]. Classifications combined in this table represent the decomposition of the object of STOEP on entities (types of emergent properties, emergence).

Table 5 – Summary table of classifications of emergent properties and emergence [6].

№	Classification	Types of emergent properties/emergence	Citations
1	Strength-based	Weak, strong	[89,91]
		Weak, strong, dynamic	[92]
		Weak, synchronic, diachronic	[83]
		Simple, weak, strong, spooky	[93]
2	Complexity-based	Simple, complex	[94]
3	Impact-based	Positive, negative	[95,96]
4	Anticipation-based	Expected (desirable/undesirable), unexpected (desirable/undesirable)	[4,97]
5	Systems-thinking based	Function, performance	[4]
		Ilities (operability, usability, safety, etc.)	[4,82,98–100]
		Emergency	[4]
6	Strategy-based	Knowledge	[101]
		Elegance	[4,102]
7	Various	Fault and adversary tolerance, program accountability, road congestion, etc.	[103–105]

The list of emergent properties and emergence types, presented in Table 5, is essential and considers the possibility of its expansion by including new types of emergent properties, continuously established by the researchers in the field. The strength-based classification in the summary table principally differentiates between weak and strong emergence. Weak emergence represents the type of emergence defined from the relationship between a system and its parts. Strong emergence occurs from the relationship between the system and aspects of the environment. The strength-based classification is governed by the level of emergence occurrence: inside the system (weak), states of the system, or the relationships between the system and environmental aspects (strong) [92]. Other types of emergence within this classification represent transitional points between the strong and weak emergence. The strength-based classification is extensively applied to describe physical systems. However, it is very consolidated and does not support the sufficiently detailed separation of emergence and emergence properties on their types. The complexity-based classification, also governed by the levels of emergence occurrence, is very close to it and is also consolidated [6,94].

Impact-based and anticipation-based classifications are both governed by the usefulness of emergent properties and emergence. Although the division of emergence on positive (exhibiting designed behaviors) and negative (exhibiting misbehaviors) is very consolidated, the division on expected/unexpected and desirable/undesirable emergent properties seems to be sufficiently detailed and can be considered in the development of STOEP [6,96,97].

Systems thinking-based and strategy-based classifications are governed by the consideration of values and are sufficiently detailed for characterizing emergent properties. They include the following types of emergent properties with brought values [4,28,101]:

1. Immediate value: function and performance.
2. Life-cycle value: ilities (operability, maintainability, usability, durability, safety, etc.).
3. Undesirable value: emergency (unexpected and undesirable emergence).
4. Strategic-level values (educational and overall): knowledge, elegance.

The function represents what a system does. Performance reflects how well the system executes its function. Ilities are the life-cycle attributes of complex systems [4]. The emergency is differentiated on low (unexpected, undesirable emergence) and high (severe emergence). Elegance is a sense of quality and low apparent complexity [4,12]. The anticipation-based classification can be incorporated in the combination of systems thinking-based and strategy-based classifications by distributing expected and desirable emergent properties among function, performance, and ilities, and undesirable and unexpected emergent properties in the emergency. The combination of these three classifications results in STOEP. The "various" classification is not considered as it unites unique types of emergent properties.

Crawley et al. pay much attention to the roles of benefit and cost in the notion of value. Therefore, it was decided to include them in STOEP as emergent properties. As benefit represents the worth created by a system, it was put in it as a strategic-level emergent property bringing economic value. Cost was put as an engineering-level emergent property bringing life-cycle value as it reflects contribution to be made in exchange for the benefit [4].

2.1.5. Schematic representation of STOEP

The schematic representation of STOEP is given in Figure 15 [6].

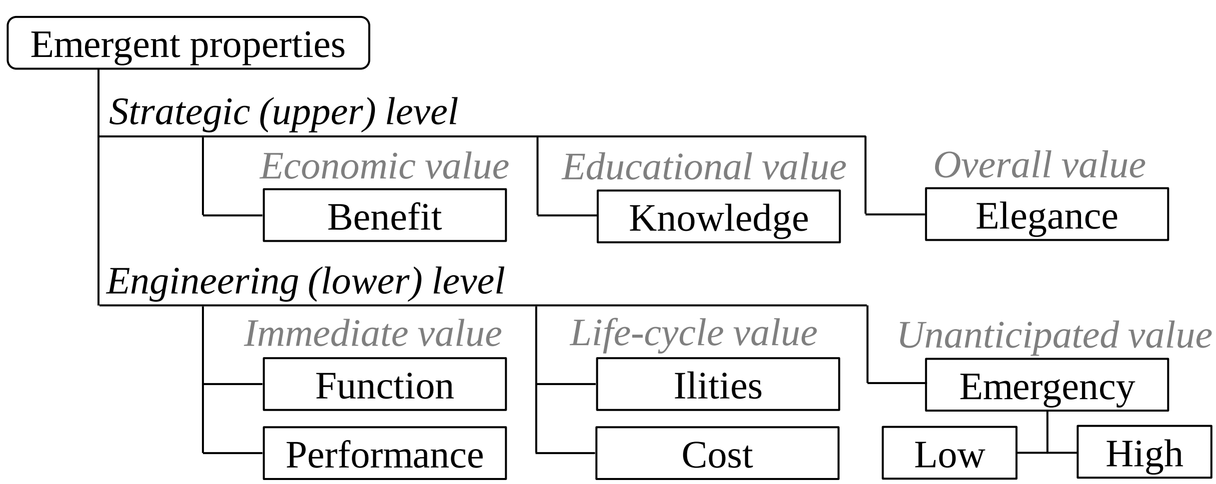


Figure 15 – Schematic representation of STOEP (schematic ontological model) [6].

According to Figure 15, the schematic representation of STOEP represents the division of all emergent properties into two levels. The upper, strategic level, unites benefit, knowledge, and elegance. The lower, engineering level, contains function, performance, ilities, cost, and emergency. The strategic-level emergent properties bring economic (benefit), educational (knowledge), and overall (elegance) values. The engineering-level emergent properties correlate with immediate (function, performance), life-cycle (ilities, cost), and unanticipated (emergency) values. The division of emergency on low and high is also considered. The ontological model is flexible, and over time can be extended or modified. Overall, STOEP allows characterizing emergent properties, demonstrating their semantics and relationships, and applying it to practical applications (Table 6) [6].

Table 6 – Possible systems engineering and systems analysis applications of STOEP [6].

№	Application	Application domain	Sources close to it
1	Systems architecting	Support in converting function to form	[4]
2	Managing complexity	Support in performing decomposition	[4]
3	Risk assessment	Support in predicting undesirable emergence	[97]
4	Verification	Support in doing verification of systems	[106]
5	Decision making	Support in making design decisions	[12]

According to Table 6, the developed ontology possesses various possible applications, which can be extended over time. Firstly, STOEP can be applied to support converting function to form via enhancing the possibilities of functional and formal relationships analysis. Secondly, it can be used as a decomposition tool for managing systems complexity. Thirdly, STOEP can be applied to support predicting undesirable or unanticipated emergence and performing verification of systems. Finally, it can be used to support design decision making as highlighted by this thesis. Innovativeness and complexity are distributed between the strategic and engineering-level emergent properties, as explained in the subsection below.

2.2. Emergence approach to design decision making in innovative complex systems

As noted earlier, the emergence approach serves as a theoretical background for using emergent properties in design decision making. It is based on modifying the value approach, which was identified as the most successful contemporary decision-making approach in Chapter 1, and includes a theoretical background and instrumentation of its own. The components of the emergence approach development are illustrated in Figure 16 [107].

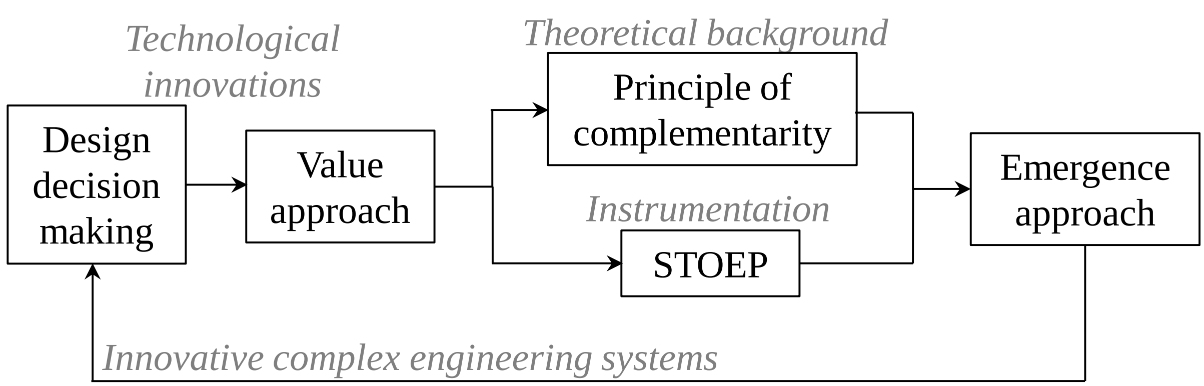


Figure 16 – Development of the emergence approach to design decision making [107].

According to Figure 16, the starting point in the development of the emergence approach is the identification of the value approach in its application for design decision making in technological innovations. Then it goes through using the principle of complementarity for design decision making in innovative complex systems as a theoretical background, STOEP as instrumentation, and applying them for design decision making in systems. The mentioned principle is explained below. It plays a key role in the development of the emergence approach. The current subsection starts with its formulation, proceeds to the formulation of the emergence approach, and finishes by discussing the applicability of the approach. The application of the emergence approach for design decision making in innovative complex systems is demonstrated in Chapter 3. Most of the information described in the subsection was published as a separate research paper by Nikolaev and Fortin [107]. The information from this publication was updated before the integration into the text of the thesis.

2.2.1. Principle of complementarity for design decision making in innovative complex systems

To a considerable extent, this subsection is based on using previous research results obtained by the supervisor of the dissertation's author doctoral research, Prof. Dr. Clement Fortin, in collaboration with his colleagues in Polytechnique Montréal (Canada) and the Skolkovo Institute of Science and Technology (Skoltech). The author also extensively used research results obtained by his other colleagues from the Systems Thinking Group (STG) of Skoltech. Prof. Fortin organized STG in the Skoltech Space Center to unite Skoltech researchers, including the author of this thesis, working in research domains of systems engineering and design of complex systems. In 2022 the Skoltech Space Center became part of the Center for Digital Engineering of Skoltech. The basic information for this subsection was taken from the relatively recent publication by Brovar, Menshenin, and Fortin, "Study of system interfaces through the notion of complementarity," which was prepared as a part of research conducted by STG [108]. The author of the thesis considers their paper to be the quintessence on the research topic of the link between complementarity in complex systems and emergence, related to his dissertation's research. To bring his own scientific novelty, the author additionally developed the idea of complementarity in innovative complex systems and formulated the associated principle of complementarity the way it could be applied for design decision making in innovative complex systems using emergent properties.

The principle of complementarity for design decision making in innovative complex systems, described in the current subsection, reflects the possibility to consider the combination of innovativeness and complexity in innovative complex systems through emergence using emergent properties for design decision-making tasks. For conciseness, it is mentioned as "the principle of complementarity" in the text of the subsection. Although the word combination "for design decision making" in the principle's full formulation demonstrates its intended application to design decision-making tasks in innovative complex systems, the principle of complementarity can potentially be used for other design tasks, for which additional research is required. It is foreseen that this principle can serve as the bridge between innovativeness and complexity of innovative complex systems and emergent properties. It fixes the reason why one needs emergence and emergent properties to reach innovativeness and complexity in such systems for design decision making. The principle of complementarity was left as a hypothesis in the conducted dissertation's research and requires a further search for proof. However, two examples of its workability were found.

The use of the notion of complementarity in the application to innovative complex systems was inspired by two presentations given by Prof. Fortin. The first one, entitled "Developing international collaborations based on complementarity," was a keynote speech at QS (Quacquarelli Symonds) in Conversation conference held in 2019 at the Vytautas Magnus University [109]. From this presentation, the following idea appeared: if the notion of complementarity could be applied to Skoltech, it could also be applied to innovative complex systems in general. The reason behind that is that Skoltech, being an innovative institution, actually represents an example of an innovative complex system. The second presentation, entitled "On the complementarity of systems," was given by Prof. Fortin in 2020 for STG to share his scientific thoughts on complementarity in complex systems based on his previous scientific investigations [110]. It inspired the author of the thesis to apply three proposed principles of complementarity (similarity, irreducibility, and extended relationships) to innovative complex systems to demonstrate that the complementarity of innovativeness and complexity in such systems could be reached through emergence for design decision making.

Among all publications produced by Prof. Fortin and his colleagues in Polytechnique Montréal, the following two were predominantly used by STG for the preparation of the aforementioned paper by Brovar et al.: "Application of the CMII model to an integrated engineering and manufacturing development environment" by Gagné and Fortin and "Information structures and processes to support data exchange between product development and production planning and execution systems” by Huet et al. [111,112]. It should be noted that many researchers throughout the world, including those from the Russian Federation, investigate the topic of complementarity in engineering, economic, and other systems. Therefore, other high-quality publications exist on the topic. The information from appropriate papers on the topic was considered for this thesis via the paper by Brovar et al. [108].

Tsvetkov, a researcher in systems analysis from the Russian Federation, listed various definitions of the term “complementarity” from trusted dictionaries (Table 7) [113].

Table 7 – Definitions of the term “complementarity” from different dictionaries [113].

№	Definition	Dictionary
1	A relationship or situation in which two or more different things improve or emphasize each other's qualities	Oxford Languages
2	The quality or state of being complementary	Merriam-Webster
3	The principle of additionality	Business English

Brovar, Menshenin, and Fortin used the definition from Oxford Languages. They noted that complementarity in complex systems is associated with relationships and emergence and quantified it using the principles of similarity and irreducibility and the definition of extended, also called sophisticated, relationships. Similarity of systems was represented as similar objectives in the use of compared systems. Irreducibility of systems was defined as the impossibility to reduce one system into the other without losing its essence [108]. Brovar et al. demonstrated that complementarity in complex systems could be achieved through the emergence of such systems, which was used simultaneously as the foundation and an example of workability of the proposed below principle of complementarity.

There is the need to analyze complementarity in innovative complex systems to apply the described above scientific findings by Brovar et al. to such systems. Innovative complex systems reveal the complementarity of innovativeness and complexity (Figure 17).

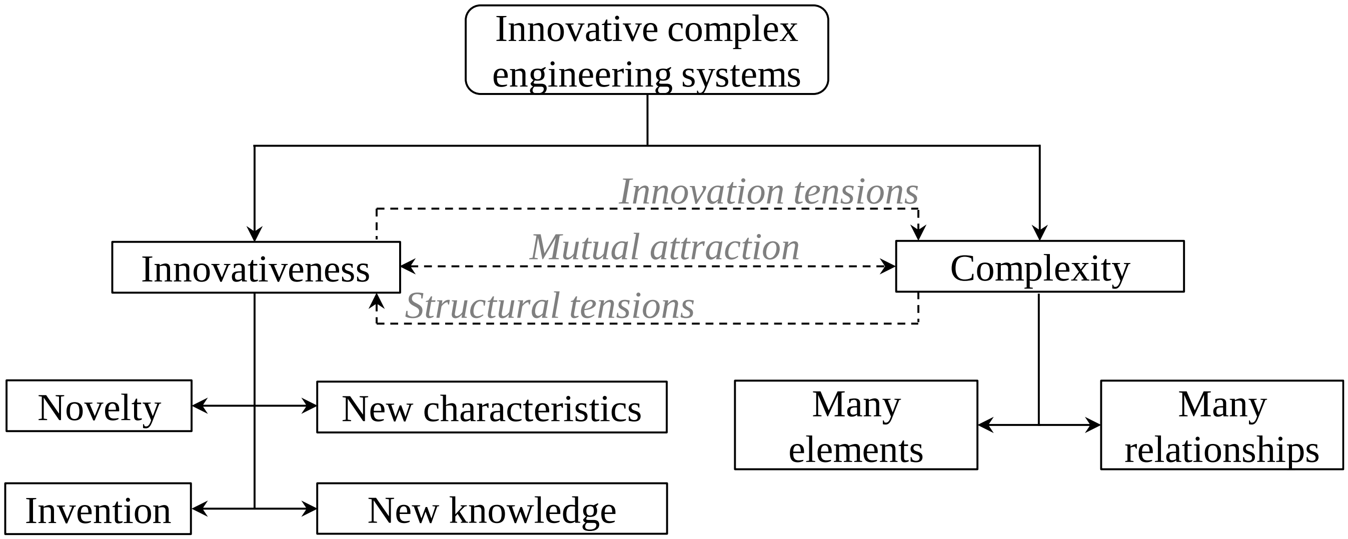


Figure 17 – Complementarity in innovative complex systems.

As depicted in Figure 17, on the one hand, innovative complex systems are characterized by innovativeness, which combines their brought novelty, inventions behind their technological innovations, introduced new characteristics, or new knowledge [53–55]. On the other hand, such systems are characterized by complexity, which combines many elements and relationships between systems elements [4]. Both innovativeness and complexity are attracted to each other through emphasizing each other's quality. Thus, complementarity serves as the reason for their mutual attraction. At the same time, innovativeness and complexity influence each other by certain tensions. Innovativeness influences complexity by exploitation-exploration tensions, also called innovation tensions. Exploitation activities in technological innovations assume seeking greater efficiency for more incremental-level innovativeness, though exploitation activities imply developing new knowledge for more radical-level innovativeness [114]. For innovative complex systems, the more novelty is to be brought by a system, the higher complexity it reveals. It is almost impossible to build simple innovative systems that nowadays bring significant novelty. The complexity of innovative complex systems influences innovativeness by system structural tensions. They represent tensions occurring in systems control (from autonomy to integration), change (from stability to adaptation), and design (from self-organization to purposeful design) dimensions [115]. The more autonomy, adaptation, and self-organization an innovative complex system requires, the more innovativeness it reveals. Thus, change in the degree of innovativeness in innovative complex systems influences their level of complexity and vice versa.

The mutual influence between tensions of innovativeness and complexity can also be explained through the distribution of innovativeness between the strategic-level emergent properties and complexity between the engineering-level emergent properties. Benefit, knowledge, and elegance from the upper level of STOEP experience innovation tensions between them: e.g., more profound knowledge brings less elegance and vice versa. Function, performance, cost, ilities, and emergency from the lower level of STOEP experience structural tensions: e.g., the higher number of performed functions result in worse maintainability and vice versa. Other examples of tensions between emergent properties exist. The presence of innovation tensions between the strategic-level emergent properties and structural tensions between the engineering-level emergent properties demonstrate the distribution of innovativeness and complexity between two levels of emergent properties in STOEP. Innovativeness is oriented toward accomplishing strategic goals by innovative complex systems and is followed by innovation tensions. Therefore, it is distributed between the strategic-level emergent properties. Complexity is linked with engineering tasks, system structural tensions and is, therefore, distributed between the engineering-level emergent properties.

Although innovativeness and complexity mutually enhance each other in innovative complex systems, both these features can exist separately in engineering systems. However, it is their combination that brings novelty to complex systems, resulting in the occurrence of innovative complex systems. By their definition (mentioned in the Introduction and explained in the literature analysis subsection of Chapter 1), innovative complex systems do not exist without innovativeness or complexity. The lack of the constituent of innovativeness in new engineering systems results in the occurrence of complex systems that do not bring novelty. The lack of the constituent of complexity in them leads to the occurrence of simple systems constituting technological innovations. Thus, innovativeness and complexity complement each other and constitute complementary features of innovative complex systems.

Real-life innovative engineering systems demonstrate the complementarity of innovativeness and complexity. For example, in the rock core description systems from the oil and gas industry, an increasing number of included techniques, representing complexity, separately brings low value. This way, it does not solve existing problems in the industry, consisting of low speed and low quality of the rock core description. At the same time, automation, representing innovativeness, also separately brings low value, as it does not hit the problem of describing a wide variety of existing rock types. However, these two features complement each other in the successful automated rock core description system (ARCDS) [12]. Another example is demonstrated by the Arctic LNG transportation system (ALTS). This system requires all-the-year-round transportation of LNG through the Northern Sea Route. Application of conventional ice-breakers to assist transportation during the wintertime, representing complexity, separately brings low value as it does not allow accomplishing all the strategic goals of the operating company. The introduction of innovative ice-breaking LNG carriers, representing innovativeness, also separately brings low value, as it requires relatively higher transportation costs. System success consists in combining complexity and innovativeness, in other words, in their complementarity [116–118].

The separate principle of complementarity for design decision making in innovative complex systems can be formulated. The idea of the principle of complementarity is not new for contemporary science. Such principles exist in physics and biology, although the notion of complementarity is also used in economics and design theory. For instance, there is the principle of complementarity in quantum physics by Niels Bohr, who concluded that two mutually exclusive theories were required to explain a single phenomenon. Brovar et al. applied the notion of complementarity to study product and system interfaces in systems engineering and the design of complex systems [108,119,120]. Based on the findings by Brovar, Menshenin, and Fortin for the link between complementarity and emergence in complex systems, findings on complementarity in innovative complex systems by the author of the thesis, and that emergence is characterized by emergent properties, the following principle of complementarity for design decision making in innovative complex systems was formulated: “The combination of innovativeness and complexity as complementary features of innovative complex systems (for design decision-making purposes) can be considered through systems emergence, characterized by systems emergent properties” [107].

The first example of the workability of the proposed principle of complementarity is based on the paper by Brovar et al.: if similarity, irreducibility, and extended relationships could be applied to innovative complex systems, then the combination of innovativeness and complexity could also be reflected through the emergence of such systems using their emergent properties. In innovative complex systems, innovativeness and complexity demonstrate similarity by their objective of bringing novelty to systems: innovativeness relates to it by definition and complexity by the global trend of the increasing complexity of new systems [3,53,107]. The impossibility to bring novelty without combining innovativeness and complexity constitutes their irreducibility. Mutual influence of innovativeness and complexity by tensions, which was specified earlier, forms extended relationships. The applicability of all these three components (similarity, irreducibility, extended relationships) to innovative complex systems demonstrates the possibility to consider innovativeness and complexity in innovative complex systems as their complementary features through emergence [107]. This example reflects the possibility to consider complementarity through emergence from the perspectives of systems engineering and the design of complex systems.

The second example is based on the book section on complementarity in organizations by Brynjolfsson and Milgrom. They provided an example of the possibility to consider complementarity through emergence, and hence, the workability of the principle. According to their publication, complementarity in organizations, which is defined mathematically and applied for decision making, represents almost a synonym to synergy [120]. Firstly, enterprises are almost equal to organizations, as they represent cooperated combinations of resources aimed to achieve business and operational objectives [16]. Secondly, Nikolaev and Fortin, analyzing the semantics of emergent properties and associated terms, determined that synergy constitutes a specific type of emergence [6]. Hence, it can be concluded that the complementarity of features in enterprises constitutes their synergy, or, in other words, a part of emergence. Kossiakoff et al., in the pyramid of system hierarchy, put enterprises to the highest level (Figure 18).

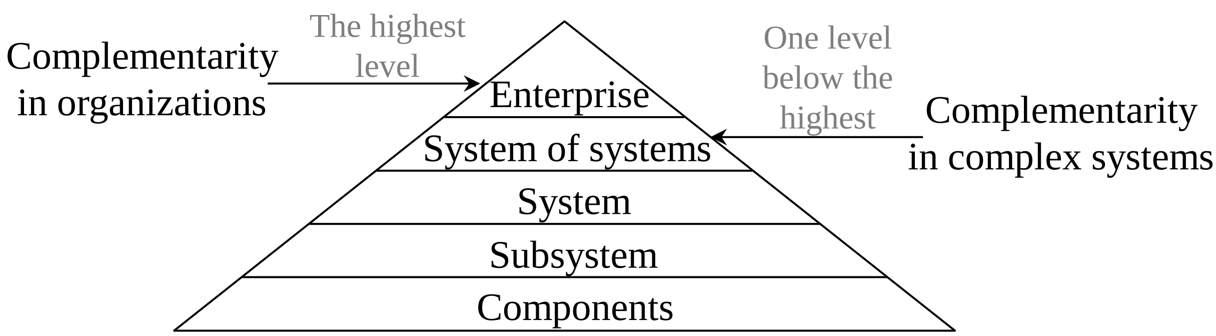


Figure 18 – Complementarity in the top levels of systems hierarchy (adapted from [23]).

According to Figure 18, the position of a system of systems in the pyramid of system hierarchy is only one level below that for an enterprise [23]. As systems of systems are often complex systems, the understanding of complementarity in enterprises or organizations cannot differ much from that for a lower level of systems of systems or, in a broader sense, complex systems [107,121]. Complementarity most probably transfers its synonymic character for synergy from the level of enterprises (organizations) to the lower level of systems of systems (complex systems) and represents a part of emergence in them. Thus, complementarity in complex systems turns out to be linked with their emergence. It demonstrates the possibility to consider the combination of innovativeness and complexity in innovative complex systems through emergence from the perspective of organizational economics.

The principle of complementarity given in this subsection uses research results by Prof. Dr. Clement Fortin and the STG members. The scientific novelty, brought by the author of the thesis, consists of that he analyzed the notion of complementarity in application to innovative complex systems and formulated the associated principle the way it can be used for design decision-making tasks in such systems. The formulated principle represents a hypothesis, although two examples confirming its workability were given in the subsection. In this thesis, searching for proof was left for future research. The principle of complementarity for design decision making in innovative complex systems serves as the theoretical foundation for the formulated below emergence approach to design decision making.

2.2.2. Formulation of the emergence approach to design decision making

The formulated above principle of complementarity for design decision making in innovative complex systems reflected the possibility of using emergent properties to consider innovativeness and complexity in innovative complex systems as their complementary features. However, this principle requires instrumentation, for which the developed STOEP was selected. STOEP considers the diversity of emergent properties existing in complex systems. It also provides the link between emergent properties and values, making it possible to reach values through emergent properties, and this way allows modifying the value approach. Hence, the emergence approach to design decision making in complex systems finds the following formulation: "The emergence approach to design decision making is a modification of the value decision-making approach. It uses the principle of complementarity for design decision making in innovative complex systems as a theoretical background for using emergent properties to make decisions and reaches systems values through systems emergent properties using STOEP as instrumentation" [107]. Its value for systems engineering and systems analysis consists of the possibility to consider the combination of innovativeness and complexity in innovative complex systems to improve design decision making for them.

2.2.3. Applicability of the emergence approach

The emergence approach turned out to be a successful solution for design decision making in innovative complex systems, which was proven by applying it in case studies from the oil and gas industry (see Chapter 3). However, it is only an approach, and its direct applicability without the incorporation into design decision-making techniques and tools possesses certain difficulties. Firstly, it raises the question of instrumentation, or simply, how to separately use it for design decision-making. Secondly, the question of comfortability of the separate use of the emergence approach for decision making appears. Decision-makers most probably would experience difficulties in using the approach without applying adequate instrumentation to it. Finally, as indicated in Chapter 1, decision-making approaches are not directly applied to design decision making and underpin the development of decision-making processes, through which they are further incorporated into design decision-making techniques and tools. Although the emergence approach possesses a separate name, it does not represent a purely new decision-making approach and constitutes an emergence-oriented modification of the value approach. Therefore, it also requires using associated decision-making processes and other decision-making techniques and tools through them. However, the emergence approach contains STOEP, which, depending on the wish of decision-makers, can be used separately for gut feeling or preliminary decision making as a decision support tool. For the cases of general use, CDMM-1 and CDMM-2 were developed.

One more limitation of the emergence approach applicability touches on the mention of emergent properties only for the conceptual design of complex systems [4,12]. However, these properties are also applicable to complex systems at other design stages, which was left for future research in the current thesis. In this dissertation's research, emergent properties are applied only for making concept and architecture selection design decisions. CDMM-1 and CDMM-2 that are described below assist in applying the emergence approach in practice. These models can be considered for other design stages if properly adapted.

2.3. Level-one combined decision-making model

The level-one combined decision-making model (CDMM-1) is the means for implementing the emergence approach in practice. The model allows making concept or architecture selection decisions using emergent properties and incorporates the developed STOEP. It represents an essential process-based decision-making model and is built upon modifying the generalized decision-making process. CDMM-1 consists of six phases (Figure 19).

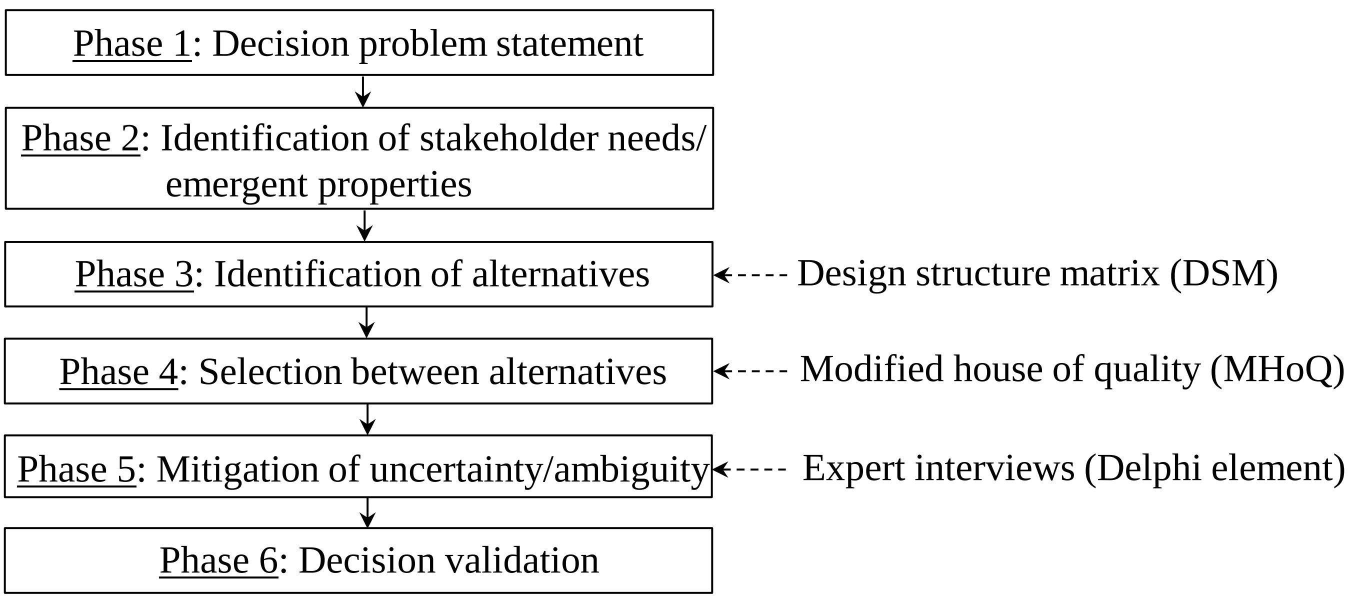


Figure 19 – Level-one combined decision-making model (CDMM-1).

According to Figure 19, CDMM-1 starts by stating the decision problem, continues with the identification of stakeholder needs and emergent properties, identifies alternatives and performs the selection between them, mitigates uncertainty and ambiguity, and finishes with decision validation. The model uses various support tools for its phases: the design structure matrix (DSM) to support identifying alternative architectures, the modified house of quality (MHoQ), which originated from quality function deployment (QFD), to support selecting between alternatives, and expert interviews from the Delphi method to mitigate uncertainty and ambiguity. All its phases are described in this subsection. CDMM-1 can be applied for group decision making in a collaborative or co-located mode or individually.

The Delphi method was well explained by Semenov et al., Volkova, and many others. Its title originated from the "Oracle of Delphi," the Panel of the Wise of the ancient Greek town Delphi that helped solve problems of townspeople based on the group opinions of its members. The method assumes total rejection from the group discussions. It consists of conducting several rounds of individual expert interviews using questionnaires and formulating a generalized answer. For this, each expert's answer is given in the form of a number, each expert is given his weight, and questionnaires are clarified for each round. However, the realization of the Delphi method can be different. The method was proposed by Helmer et al. and was first applied in practice in the 1940s by the RAND Corporation. It allows diminishing uncertainty and ambiguity but requires significant time resources [26,27,122].

The term "DSM" was coined by Steward in the 1960s for mathematics. Its comprehensive explanation for the design of complex systems was given by Eppinger and Browning in the book "Design structure matrix methods and applications" in 2012. Generally, DSM represents a square matrix with systems elements listed both vertically and horizontally, which correlations allow concluding the information on the functional relationships (interactions) between systems elements. It can be binary (the presence of interactions is marked) or numerical (types of interactions are numbered). Eppinger and Browning differentiated all DSM models on the following types: product architecture DSM, organization architecture DSM, process architecture DSM, and multi-domain matrix (MDM, combines the previous three types). They all represent powerful tools for designing complex systems [123,124].

QFD is a method developed initially by Akao in Japan in the 1960s to help transform the voice of the customer into engineering characteristics for a new product. Nowadays, it also represents a powerful decision support instrument that uses various QFD-models: four-phases, comprehensive, etc. One of the most valuable tools of QFD is the house of quality (HoQ). It was introduced in 1972 in the design of an oil tanker by Mitsubishi Heavy Industries and, nowadays, is often separately used for decision support [23,125,126].

2.3.1. Phase 1: Decision problem statement

Decision-making processes and models in systems engineering and systems analysis typically start by defining decision problems, identifying critical decisions, etc. [27,28,46]. All these formulations can be combined in a "decision problem statement." Similar to the formulation of the research question in the design research methodology, it plays a key role in decision making [33]. The significance of the decision problem statement consists of being the starting point in a related decision-making process or model. Therefore, it influences the entire design decision-making procedure and needs to be done accurately. Crawley et al. described the canonical framework "To-By-Using" for the problem statement and adopted it for systems architecting. This framework, due to the solid credibility of the source and demonstrated successful applications, was also adopted for the decision problem statement in CDMM-1. After "To," the framework puts the statement of intent. It uses statements of function and form after "By" and "Using" [4]. In CDMM-1, decision-makers write down their statements into a separate spreadsheet of the specially prepared MS Excel file. Additional general information about the title of an innovative engineering system of interest, its level of complexity (simple, medium-complexity, complex), decision title, and type of decision (concept or architecture selection) is also fixed in the same spreadsheet.

2.3.2. Phase 2: Identification of stakeholder needs and emergent properties

In CDMM-1, emergent properties serve as an alternative to decision-making goals or values, and their identification starts from identifying stakeholder needs for a new system. Firstly, the list of stakeholder needs is prepared. It results from the prior knowledge analysis or can be induced by the real-practice demands of the new system's users. The prior knowledge analysis includes reviewing the information from the literature sources, which can be performed in the form of fast screening for Phase 2, and interviewing the experts in the field. The list of stakeholder needs that results from the real-practice demands of users is prepared by discussing them between all or major decision-makers. In case of individual decision making, it can be prepared by a single decision-maker through analyzing available information. Secondly, each stakeholder need is referred to its close emergent property type: one stakeholder need is linked only with one type of emergent properties. This assumption allows translating the needs to emergent properties avoiding sophistication. However, stakeholder needs can be referred to several types of emergent properties, which constitutes an option considered in CDMM-2. Thirdly, brief formulations of stakeholder needs are listed to clarify emergent properties. These clarifications add comfortability to the selection between alternatives at Phase 4 as they provide an overview of all considered information on one page. Finally, the list of the main sources used in the prior knowledge analysis is created. All the obtained information is put into a separate spreadsheet of the MS Excel file.

2.3.3. Phase 3: Identification of alternatives

As mentioned in Chapter 1, identification of alternatives follows that for values in the value decision-making approach. As the emergence approach represents a modification of the value approach, and emergent properties serve as an alternative to values, identification of alternatives of Phase 3 follows identifying stakeholder needs and emergent properties of Phase 2 in CDMM-1. The current phase is mainly based on the prior knowledge analysis, which, similar to that in Phase 2, includes reviewing literature sources and interviewing experts, which can be used separately or in combination. Phase 3 typically results in the list of possible concepts put by decision-makers into a separate spreadsheet of the MS Excel file. The list of the sources for the prior knowledge analysis is not included in the spreadsheet as each particular concept may result from a combination of different information sources.

In the case of architecture selection decisions, DSM is also used to represent innovative complex systems architectures. It aligns with the note of Eppinger and Browning from their aforementioned book devoted to DSM that this type of matrix represents a flexible modeling method with broad applications in engineering management and various other domains, to which decision making can be included. The use of DSM allows obtaining additional information on the architecture for decision-makers in CDMM-1. This idea was taken from the book on complex systems architecting by Crawley et al., where binary DSMs are applied to architectural decisions. Such DSMs represent the existence of relationships between the subsystems but do not specify their type [4,123]. Considering that architecture selection represents a high-level architectural decision, the binary DSM was also chosen for CDMM-1. However, if decision-makers see the necessity, other types of DSM can also be considered for the model. Decision-makers identify existing subsystems of the new system, put them in the DSM using the prepared separate spreadsheet form of the MS Excel file, and analyze existing interactions between the subsystems. This way, they obtain more visual information on alternative architectures. Systems Modeling Language (SysML) and the Object-Process Methodology (OPM) can be also used to visualize architectures [108].

The prior knowledge analysis of Phase 3 requires a considerable amount of time, making it the most time-consuming phase of the model. For instance, for architecture selection of ALTS, Phase 3 took approximately 50 hours compared to 10-12 hours for other phases in total. The main reason behind this consists of the necessity to spend significant time resources searching for appropriate literature sources and analyzing them. Interviewing the experts in the field, as the practice has shown, requires less time.

2.3.4. Phase 4: Selection between alternatives

Phase 4 represents making the decision and is the core of CDMM-1. For this, MHoQ, which is based on modifying HoQ from QFD, is applied (Figure 20). MHoQ in CDMM-1 represents the adaption of HoQ for its use with emergent properties. This type of decision support tool was selected due to its apparent comfortability and the possibility to consider the parameters required for selecting between alternatives with emergent properties.

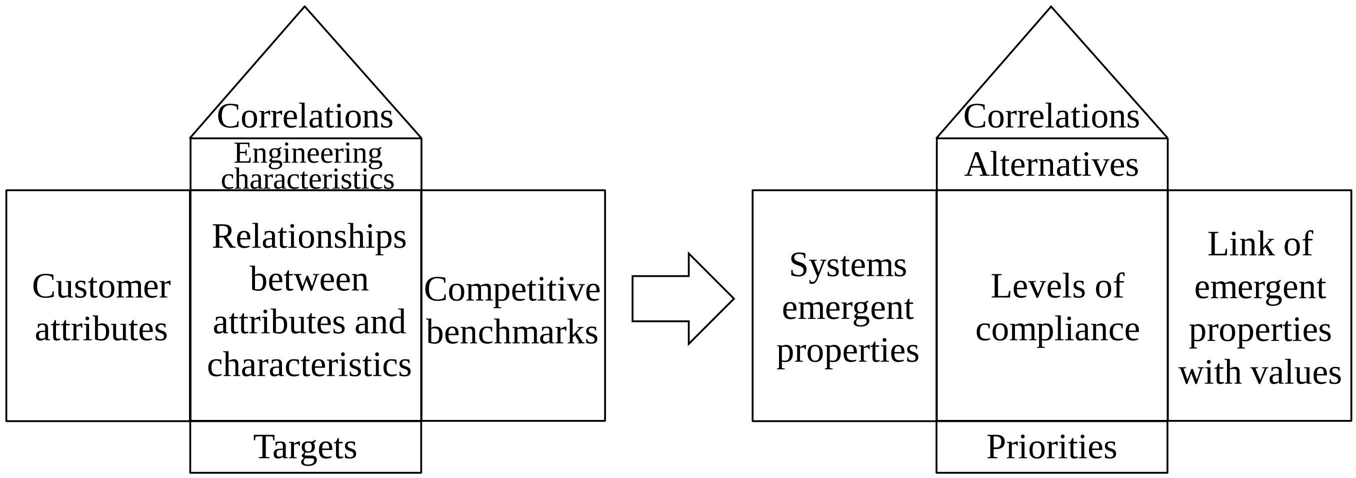


Figure 20 – MHoQ developed from HoQ in CDMM-1 (adapted from [107]).

HoQ possesses customer attributes in the left field, engineering characteristics at the top, their correlations in the roof, relationships between customer attributes and engineering characteristics in the central field, the importance of engineering characteristics (targets) at the bottom, and competitive benchmarks in the right field [125]. For MHoQ (Figure 20), the following modifications were made: customer attributes, engineering characteristics, relationships between attributes and characteristics, targets, and competitive benchmarks were substituted on emergent properties, alternatives, levels of compliance of emergent properties with alternatives, priorities for alternatives, and the link between emergent properties and values, respectively [107]. Levels of compliance of emergent properties with alternatives represent probabilities of successful fulfillment of emergent properties by alternatives.

Decision-makers start working with MHoQ by filling the list of emergent properties from Phase 2. Then they assign weights *W* to each emergent property according to the following grading scale: 0.9 – high importance, 0.5 – medium importance, and 0.1 – low importance. Decision-makers continue by listing the alternatives from Phase 3 and assessing levels of compliance *C*(*A*) of each emergent property with each alternative. The following grading scale is used: 1 – full compliance, 0.9 – high level of compliance, 0.5 – medium level of compliance, 0.1 – low level of compliance, and 0 – no compliance. For both scales, additional intermediate numerical values (0.75 and 0.25) can be applied. Thereafter, the decision value *DV* for each alternative is calculated using the formula below:

$$DV = \sum_{i=1}^{N} W_i \cdot C(A)_i \,, \tag{1}$$

Where: *DV* – decision value,

W_i – the weight of each emergent property,

$C(A)_i$ – the level of compliance of each emergent property with the alternative,

N – number of emergent properties.

Based on the calculated decision values *DV*, alternatives are prioritized. The alternative with the highest decision value *DV* is selected. Additionally, the link between emergent properties and values and correlations between alternatives are shown in the left field and the roof, respectively. They serve as the means for visualization in considering required information during the selection between alternatives. Data from the phase is filled in the prepared separate spreadsheet form of the MS Excel file, and calculations are performed in this spreadsheet. Phase 4 provides the made decision, which can be a matter of the influence of uncertainty and ambiguity. The following phase allows performing their mitigation.

2.3.5. Phase 5: Mitigation of uncertainty and ambiguity

As mentioned in Chapter 1, decisions are influenced by ambiguity, uncertainty, or both [24]. Concept or architecture selection of innovative complex systems is affected by the high degree of uncertainty and market and technological risks brought by innovations [11]. However, the role of ambiguity influence on such decisions is also significant. As indicated in Chapter 1, Bratvold and Begg claimed that decision objectives bring ambiguity to the decision due to the lack of clarity about the real goals [24]. Along with other mentioned conditions, Aliakbargolkar emphasized the necessity to consider the ambiguity of stakeholder needs in the cases of a high degree of innovation in system objectives and the early phases of the design process [127]. In innovative complex systems, decision-makers typically deal with similar situations. Finally, Knoll noted that the core difficulties in concept selection are constituted by ambiguity in stakeholder needs and uncertainty about implementation details [128]. Thus, concept or architecture selection design decisions in innovative complex systems require support to mitigate the influence of uncertainty and ambiguity.

One-round expert interviews from the Delphi method were selected as the means for mitigating uncertainty and ambiguity in CDMM-1. It allows keeping the balance between the complexity of decision making and the quality of uncertainty and ambiguity mitigation. Additionally, it allows avoiding the introduction of complicated mathematical calculations for uncertainty estimation. The conventional Delphi method assumes several rounds of expert interviews [26,27]. In this form, it requires relatively more time on decision making, leading to the increase of its complexity. One-round expert interviews allow avoiding such problems keeping an acceptable level of uncertainty and ambiguity mitigation.

For CDMM-1, decision-makers prepare a set of questions based on emergent properties and send it to 5-15 experts, asking which alternative best answers these questions. Most frequently mentioned alternatives constitute options expected to correlate with the high-priority alternative from Phase 4. If they do, then the level of uncertainty and ambiguity influence is acceptable, and the selected alternative can be proceeded to decision validation. Again, all the obtained data is fixed in a separate spreadsheet of the MS Excel file.

2.3.6. Phase 6: Decision validation

Generally, the product validation process aims to demonstrate that the final product satisfies its stakeholders' expectations [7]. Considering decision as a product of applying CDMM-1, its decision validation can be performed through analysis, demonstration (including operations), inspection, and test [18]. The final data is fixed in the MS Excel file.

2.3.7. Toy problem

The toy problem of selecting between the fountain and ballpoint pen writing systems facilitates understanding of how decisions are made using MHoQ, the core of CDMM-1. Fountain pens were extensively used for writing until the 1940s-1960s. Later they mainly were substituted by ballpoint pens. Many people still use fountain pens for writing nowadays. Thus, a decision problem of which system, fountain or ballpoint, is preferable to select for writing today appeared. The author applied MHoQ to select between them (Figure 21).

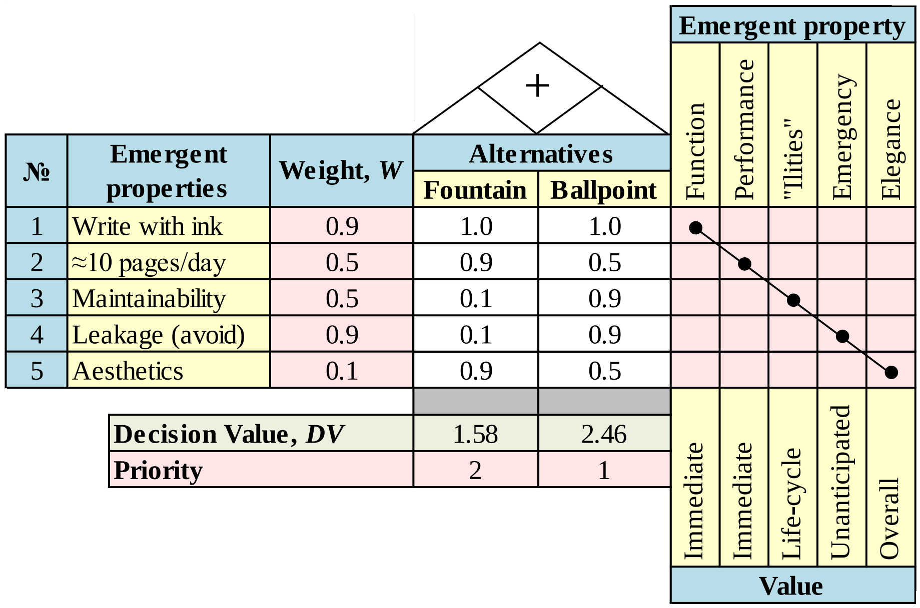


Figure 21 – MHoQ used to select between the fountain and ballpoint pen writing systems.

As shown in Figure 21, the author identified five main emergent properties based on his experience and listed them. Then he assigned weights W and levels of compliance $C(A)$ according to grading scales given in the current subsection. The roof of MHoQ allowed showing the existing correlation between both writing systems. The right field allowed specifying emergent properties by their types and showing the link between emergent properties and values. Decision values DV were calculated using formula (1). The higher calculated decision value DV for the ballpoint writing system demonstrated that it was the preferable option. This way, the toy problem provided a simplified example of how MHoQ "works."

2.4. Level-two combined decision-making model

CDMM-1 was limited by the assumed possibility of referring each stakeholder need only to one type of emergent properties. However, decision-makers can see the necessity of referring stakeholder needs to several types of emergent properties in various degrees, also called an expanded correlation of stakeholder needs with emergent properties. Therefore, CDMM-1 was modernized to provide this possibility if such a necessity occurs. The modernized CDMM-1 was named the level-two combined decision-making model (CDMM-2). Similar to CDMM-1, it serves as the means for implementing the emergence approach in practice and incorporates STOEP. CDMM-2 uses several QFD-based phases and cumulatively consists of four phases (Figure 22). This model was initially developed for concept selection design decisions but left an opportunity for including DSM to assist decision-makers in making architecture selection decisions. All the work with CDMM-2 is done in the specially prepared separate MS Excel file and fixed in it. The model can be applied for group decision making in a collaborative or co-located mode or individually.

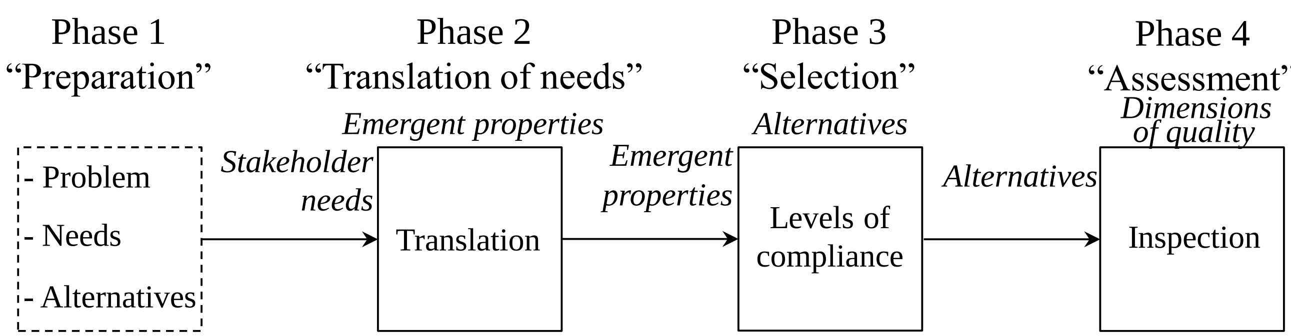


Figure 22 – Level-two combined decision-making model (CDMM-2).

According to Figure 22, CDMM-2 starts with Phase 1, "Preparation," which combines Phases 1-3 of CDMM-1, restricting its Phase 2 by the identification of stakeholder needs. It is devoted to the decision problem statement, identification of stakeholder needs and alternatives. The model continues by a set of three QFD-based phases, which idea was borrowed from QFD-models described by Maritan [125]. Phase 2 translates stakeholder needs to emergent properties and allows relating stakeholder needs to several types of emergent properties. Phase 3 is devoted to the selection between alternatives and is almost equal to Phase 4 of CDMM-1. The first difference between them consists of that weights of emergent properties in Phase 3 of CDMM-2 are not assigned by decision-makers but calculated in the previous phase. The possible lack of the roof in Phase 3 of CDMM-2 represents the second difference: the roof can be used or omitted. It is done to equate Phases 2-4 as they apply the structure of HoQ without the roof. Phase 4 is used for decision assessment. It is based on expert interviews and combines mitigation of ambiguity and uncertainty with decision validation.

Phase 2 of CDMM-2 uses the list of stakeholder needs in the left field, types of emergent properties at the top, evaluation of stakeholder needs in the right field, levels of compliance of stakeholder needs with types of emergent properties *C(EP)* in the central field, and calculated weights of emergent properties *W* at the bottom. By evaluating stakeholder needs, decision-makers assign weights of stakeholder needs *WSN* according to the grading scale for weights of emergent properties *W* from CDMM-1. Then they use the grading scale for levels of compliance *C(A)* from CDMM-1 and assess how much each stakeholder need complies with each emergent property. If no compliance is possible, no value is put to avoid excessive filling of matrices with zero numerical values. Weights of emergent properties *W* are applied for decision values *DV* in Phase 3. They are calculated using the formula below:

$$W = \frac{\sum_{i=1}^{N} WSN_i \cdot C(EP)_i}{N}, \tag{2}$$

Where: *W* – the weight of the emergent property,

WSN_i – the weight of each stakeholder need,

$C(EP)_i$ – the level of compliance (stakeholder need/type of emergent property),

N – number of stakeholder needs.

Phase 4, which is used for decision assessment, adopts the framework for evaluating the quality of decisions by Matheson and Matheson, described in detail by Bratvold and Begg. It considers six elements related to several questions (Figure 23) [24,129].

Figure 23 – Decision quality chain: six elements for decision evaluation [24].

All six elements of the decision quality chain, shown in Figure 23, are incorporated in the HoQ-based structure of Phase 4. Alternatives are listed in the left field, dimensions of decision quality are placed at the top. Experts separately fill the central field with assessment grades for alternatives, using the five-point scale with “5” as the highest grade. Grades are subsequently converted to a percentage, where “5” equals 100%, “4” equals 80%, etc., and demonstrated in the form of spider diagrams for better visualization. Answers from the experts, which actually represent results of one-round interviews, are used for ambiguity and uncertainty mitigation and for decision validation in the form of inspection.

Although CDMM-2 provides an opportunity for the expanded translation of needs, it is more complicated than CDMM-1. Both models were successfully tested on case studies from the oil and gas industry, as described in Chapter 3 of the current thesis.

2.5. Flexibility of combined decision-making models

Similar to STOEP, CDMM-1 and CDMM-2 are flexible, and over time can be extended or modified based on the needs of decision-makers. Many opportunities exist for this through selecting various types and elements of their decision support methods (Figure 24).

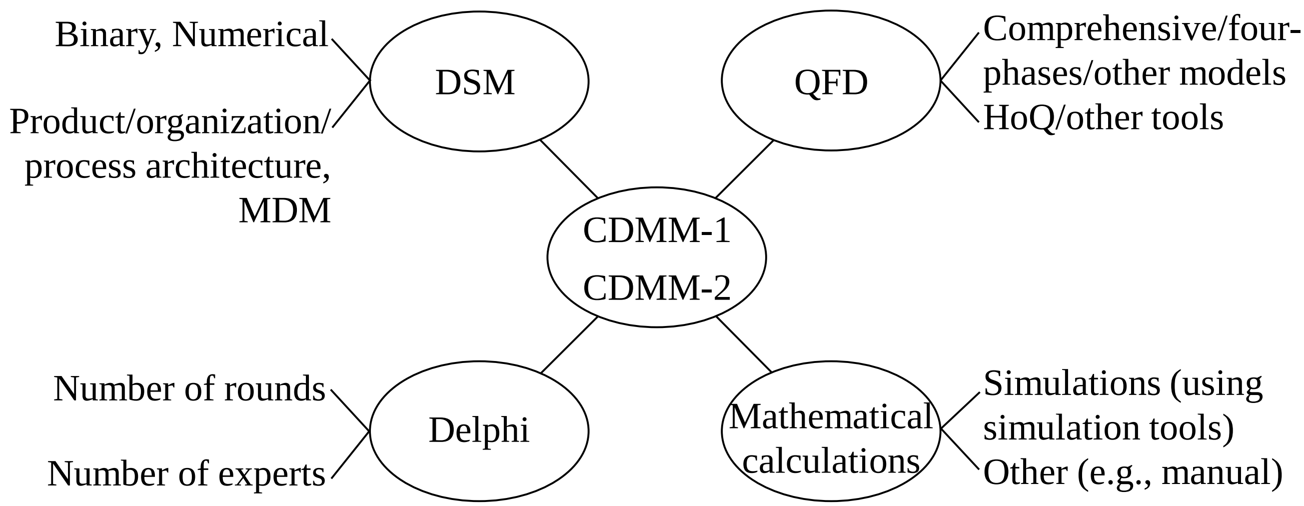


Figure 24 – Various options of decision support methods applied in CDMM-1, CDMM-2.

As depicted in Figure 24, various types of DSM, QFD, elements of the Delphi method, and mathematical calculations can be used in CDMM-1 and CDMM-2. Their choice depends on the preferences and needs of decision-makers. Firstly, decision-makers can select between binary and numerical types of DSM. The more advanced division between their types, including MDM, is also applicable. Secondly, various tools (not only HoQ) of comprehensive, four-phases, and other QFD-models can be considered for CDMM-1 and CDMM-2. Thirdly, as the conventional Delphi method assumes several rounds of expert interviews, decision-makers can select the number of rounds and experts that would satisfy them [27,123,125]. Finally, various mathematical calculations can be selected and applied. They mainly include simulations using appropriate simulation tools (simple or sophisticated) for analyzing characteristics of alternatives, probabilities in the analysis of uncertainties, etc. Their applicability is limited as explained by the Cynefin framework (see Figure 2).

2.6. Conclusion on Chapter 2

Chapter 2 covered the prescriptive study stage of the dissertation's research, which, to a different extent, includes the information from three research papers published by Nikolaev and Fortin [6,12,107]. The chapter was devoted to building an ontological model of emergent properties in complex systems, developing a modified decision-making approach, and two related decision-making models for the practical application described in case studies. The main findings of Chapter 2 are as follows:

1. An ontological model of emergent properties in complex systems, which was named STOEP, was developed. Its development required adapting the term "ontology" for systems thinking, conducting a supplementary literature search, analyzing the semantics and relationships of emergent properties, and building a schematic representation of ontology. STOEP allows structuring emergent properties, considering the link between emergent properties and values, and modifying the value approach.
2. The emergence approach to design decision making in innovative complex systems was developed and formulated. It represents a modification of the value approach, includes the principle of complementarity for design decision making in innovative complex systems as a theoretical background, STOEP as instrumentation, and allows reaching values via emergent properties. This approach, similar to other approaches, requires incorporation in design decision-making techniques and tools for application.
3. Two decision-making models for applying the emergence approach in practice were developed. CDMM-1 represents an essential model that includes DSM, MHoQ, which originated from QFD, and expert interviews from the Delphi method. CDMM-2 represents the modernization of CDMM-1 and includes several QFD-based phases. Both these models allow design decision making using emergent properties.

The presented in the subsection ontology, approach, and models were successfully tested on case studies from the oil and gas industry, which is described in Chapter 3.

CHAPTER 3. CASE STUDIES

This chapter represents the descriptive study II stage of the dissertation's research. It describes the combined practical application of the developed STOEP, the emergence approach, CDMM-1, and CDMM-2 in case studies from the oil and gas industry. The oil and gas industry was chosen as an example of the industry interested in technological innovations of national and global significance and actively developing and implementing them. However, the proposed techniques are applicable to innovative complex systems from any engineering industry. The summary table of information on cases studies is given in Table 8.

As listed in Table 8, the dissertation's research involved four case studies. The first case study tested the possibility of applying STOEP separately as a decision support tool for concept selection of the hull envelope subsystem for the innovative robotized tropospheric airship (IRTA), designed by "WARPA" (World Advanced Research Project Agency). IRTA represents a complex system, and preliminary decision making of its hull envelope was conducted in the individual decision-making mode. The second case study applied the abridged version of CDMM-1 for concept selection of the automated rock core description system (ARCDS). Compared to the conventional CDMM-1, it lacks DSM and expert interviews from the Delphi method. ARCDS is developed by "Digital Petroleum" and represents a system of medium complexity. Its concept selection was conducted in the group decision-making mode. The third case study covered the conventional version of CDMM-1 for architecture selection of the Arctic LNG transportation systems (ALTS). ALTS is a complex system implemented by the "Yamal LNG" company in the Arctic region of the Russian Federation. A retrospective study of its architecture selection reflected group decision making. The fourth case study tested CDMM-2 on concept selection of the medium-complexity innovative laboratory petrophysical system (ILPS) in the group decision-making mode. It started in the Skoltech Center for Hydrocarbon Recovery and was continued by STG in collaboration with a researcher from the Skoltech Center for Hydrocarbon Recovery.

Table 8 – Summary table of essential information on case studies conducted for the dissertation's research.

№	Item of information \ Case study			The 1st	The 2nd	The 3rd	The 4th
1	Decision-making technique			STOEP as a tool	Abridged CDMM-1	CDMM-1	CDMM-2
2	Innovative system	Title		IRTA	ARCDS	ALTS	ILPS
		Complexity		Complex	Medium-complexity	Complex	Medium-complexity
3	Type of selection decision			Concept	Concept	Architecture	Concept
4	Decision-making regime			Individual	Group	Group	Group
5	Study	Clarification		Review-based	Review-based	Review-based	Review-based
		Descriptive I		Comprehensive	Comprehensive	Review-based	Comprehensive
		Prescriptive		Comprehensive	Comprehensive	Comprehensive	Comprehensive
		Descriptive II		Initial	Comprehensive	Comprehensive	Initial
6	Time cumulatively spent on the prior knowledge analysis			25-30 hours	120-130 hours	50-60 hours	240-250 hours
7	Time spent on descriptive studies (excluding point 6)		I	3-4 hours	8-10 hours	not specified	10-12 hours
			II	3-4 hours	8-10 hours	10-12 hours	12-14 hours
8	Comment			Preliminary decision making	–	Retrospective study	–

Each case study contains internal research stages according to the design research methodology by Blessing and Chakrabarti [33]. Case studies 1 and 4 covered review-based research clarification, comprehensive descriptive I and prescriptive studies, and initial descriptive study II. Case study 2 presented review-based research clarification and comprehensive descriptive I, prescriptive, and descriptive II studies. Case study 3 covered review-based research clarification and descriptive I studies, comprehensive prescriptive and descriptive II studies. The term “comprehensive” defines a combination of a literature review and the results obtained by researchers, e.g., empirical analysis. Descriptive study I reflects the application of the value approach and associated techniques. Application of the emergence approach, STOEP, CDMM-1, and CDMM-2 constitutes descriptive study II.

The prior knowledge analysis, which cumulatively required significant time resources, is distributed between descriptive studies. It can be done during one of these stages or prepared during the descriptive study I stage and then completed during the descriptive study II stage. As shown in Table 8, time resources spent by decision-makers during these two stages are comparable. The application of the emergence approach does not benefit in saving time resources but provides other advantages (see Chapter 2).

All innovative engineering systems used in case studies refer to the oil and gas industry and represent systems of global significance. This industry's various scientific and engineering domains are essentially divided into three sectors, as listed in Table 9 [130].

Table 9 – Sectors of scientific and engineering domains in the oil and gas industry [130].

№	Sector	Explanation	Examples
1	Upstream	Searching for oil and gas reserves, their extraction (crude oil and raw natural gas)	Petrophysical, drilling, well test systems, etc.
2	Midstream	Transportation and storage of oil and gas	Transport systems
3	Downstream	Refining of crude oil, purifying natural gas	Refining systems

ARCDS and ILPS refer to the upstream sector and touch on the global challenges of automation and the shale revolution, respectively. ALTS represents a system in midstream and faces the challenge of gas production in the Arctic. IRTA refers to upstream and touches on supporting operations in oil and gas fields from hard-to-reach locations.

The author of the thesis personally contributed significantly to the development of each case study. He managed decision making and played the role of a decision-maker in all of them. A comprehensive literature review for Case study 4 was predominantly prepared by him [131]. In Case studies 2-4, the author's main collaborator was Prof. Clement Fortin.

3.1. Case study 1: STOEP as a tool for concept selection in IRTA

The conceptual design of the airship for the oil and gas industry by "WARPA," named IRTA, started in June 2021 in France. IRTA, an innovative complex system, aims to transport equipment and spare parts required to support operations in oil and gas fields from hard-to-reach locations. Its hull envelope constitutes one of its most critical subsystems, for which preliminary concept selection was performed using the value approach (descriptive study I). Later it was repeated using the emergence approach and STOEP as a tool (descriptive study II), which showed more valuable results and allowed to save one month of the company's resources on the design of IRTA (Appendix A). The case study was supported by the general director of "WARPA" Mr. Jean-François Geneste. Textile type choice constituted concept selection of IRTA's hull envelope within preliminary decision making. It allowed, to a first approximation, an understanding of how would be the primary function of the hull envelope (keeping gas inside) converted to its form (a particular type of textile).

3.1.1. Research clarification

Case study 1 aimed to use the emergence approach for the IRTA's hull envelope concept selection and STOEP as a decision support tool for its realization, which constituted the research purpose. The tasks included identifying values, emergent properties, and alternatives, applying the value and emergence approaches for selecting between alternatives, and comparing decision-making results. The research question was given the following formulation: “How does STOEP represent itself if used separately for the realization of the emergence approach to design decision making?” Case study 1 represents preliminary decision making performed individually by a single decision-maker. However, decision validation attracted additional support for inspection by Mr. Geneste as an expert.

3.1.2. Descriptive study I

As mentioned earlier, decision-making approaches require their incorporation into decision-making processes and other design decision-making techniques and tools for practical use. Therefore, for preliminary concept selection decision-making of the IRTA’s hull envelope, the abridged decision-making process, which was based on the generalized decision-making process, was used. For descriptive study I, the value decision-making approach was chosen due to its success for design decision making of space missions and systems by NASA [7,18]. The applied decision-making process is given below (Figure 25). It does not contain ambiguity and uncertainty consideration step due to its preliminary character.

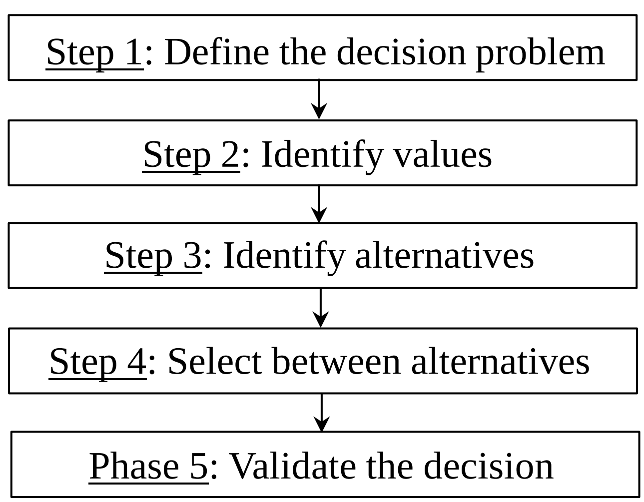


Figure 25 – Abridged value approach-based decision-making process.

As shown in Figure 25, preliminary concept selection decision-making of the IRTA's hull envelope started by defining the decision problem, for which the canonical framework "To-By-Using," described by Crawley et al., was used [4]. The decision problem was defined by "WARPA" prior to concept selection of its hull envelope and was initially provided to the decision-maker. Values and alternatives were identified through the prior knowledge analysis, which consisted of reviewing literature sources for this case study. The decision-maker performed selection between alternatives, which constituted the decision, using a decision matrix as a decision support tool. Final validation of the made decision was done through inspection by the expert in the field from "WARPA."

IRTA's innovativeness consists of its possibility to operate in all-weather conditions and allow all-terrain landing. This flight vehicle possesses the potential of disrupting the contemporary oil and gas industry. Currently, transportation of oversized or heavy equipment to the oil and gas fields, for example, located in the taiga area of Western and Eastern Siberia in the wintertime, is problematic or impossible. Implementation of IRTA would cope with this problem keeping the reasonable transportation cost. The given from the side of the "WARPA" decision problem was formulated the following way: "Provide "WARPA" with the hull envelope to allow all-weather exploitation of IRTA by selecting an appropriate type of textile using information from the available literature sources."

The decision-maker reviewed various literature sources for the prior knowledge analysis that allowed identifying values and alternatives for IRTA's hull envelope concept selection. The book "Aeronautics in inventions" by Boiko was one of the best sources [132]. The following five values were considered: all-weather exploitation, low gas penetration, low weight, resistance to ultraviolet radiation, and availability in the market. Firstly, all-weather exploitation consists of the possibility of using textiles in a wide range of temperatures (from -60°C to +70 °C), humidity, etc., with maintaining all their characteristics stable at least for a 3-year period. This value considers that the temperature of the hull envelope would be higher than the temperature of the outside air due to the heating of the gas inside by the engines. Secondly, low gas penetration assumed negligibly low gas permeability of the hull envelope. Thirdly, the surface density of the textile to be less than 100 g/m^2 constituted the low-weight value. Finally, resistance to ultraviolet radiation, which is critical for flying above the clouds, and availability in the market were defined as separate values.

Based on defined values, the following four alternatives were identified: polyamide (A1), aramid (A2), Dyneema (A3), and rubberized cotton (A4). Metals were not considered as options for preliminary decision making and can be considered for future decision making, if the total mass of the hull envelope, made of metal, would satisfy the mass budget for the airship. Values and alternatives were put into the decision matrix to select between alternatives (Table 10). According to the following grading scale, all values were assigned their weights *W*: 1 – high importance, 0.5 – medium importance, and 0.1 – low importance. Then the decision-maker assessed levels of compliance of values with alternatives *C(A)* using the following grading scale: 0.9 – high level of compliance, 0.5 – medium level of compliance, and 0.1 – low level of compliance.

Table 10 – Decision matrix for IRTA’s hull envelope concept selection (value approach).

№	Values	Weight, *W*	Alternatives			
			A1	A2	A3	A4
1	All-weather exploitation	1.0	0.9	0.9	0.9	0.5
2	Low gas penetration	1.0	0.9	0.9	0.9	0.9
3	Low weight	0.5	0.5	0.1	0.5	0.1
4	Resistance to ultraviolet radiation	1.0	0.5	0.1	0.9	0.9
5	Availability in the market	0.5	0.9	0.9	0.1	0.9
		Decision value, *DV*	3.0	2.4	3.0	2.8
		Priority	1	3	1	2

As shown in Table 10, priority setting was based on decision values *DV*, calculated according to formula (1), using weights *W* and levels of compliance *C(A)* for values instead of emergent properties. All used values were of high or medium importance; therefore, no low-importance weight ($W = 0.1$) was assigned. No full compliance ($C(A) = 1$) was considered, as defective samples could be caught or modifications of textiles within their types could be used. According to the decision matrix, polyamide (A1) and Dyneema (A3) were both selected as equitable concept options for IRTA's hull envelope. However, rubberized cotton (A4) turned out to be close to them by its *DV*.

When decision results were provided to the expert from "WARPA," he experienced difficulties in its validation as the calculated decision values *DV* did not allow clear selection between alternatives. On the one hand, it could be a matter of the low number of values used for preliminary decision making. On the other hand, it could result from the necessity to consider the combination of innovativeness and complexity of IRTA as the innovative complex system for good concept selection. Thus, an idea of using the emergence approach and STOEP as a decision support tool for this decision problem appeared.

3.1.3. Prescriptive study

The emergence approach was proposed for concept selection of IRTA's hull envelope by the author of this thesis, one of STG members. Emergent properties were expected to be used instead of values to increase the number of principles for consideration. For this, STOEP was proposed to be used as a decision support tool.

3.1.4. Descriptive study II

For descriptive study II, the decision-making process from the descriptive study I with the substitution of values on emergent properties was used. Previous prior knowledge analysis results were slightly updated. Selection between alternatives is presented in Table 11.

Table 11 – Combined STOEP-decision matrix for concept selection of IRTA's hull envelope (the emergence approach).

№	Level	Emergent properties	Clarification	Weight, *W*	Alternatives			
					A1	A2	A3	A4
1	Strategic	Benefit	The leadership of "WARPA" in the domain	0.5	0.9	0.9	0.9	0.9
2		Knowledge	Development of relevant technologies	0.5	0.9	0.5	0.9	0.5
3		Cost	A sense of quality and apparent complexity	0.5	0.9	0.9	0.9	0.5
4	Engineering	Function	Exploit at all-weather conditions	1.0	0.9	0.9	0.9	0.5
5		Performance	Exploitation at -50 –70°*C* temperature range	1.0	0.9	0.9	0.9	0.5
6		Performance	Exploitation at 0 – 100% humidity	1.0	0.9	0.9	0.9	0.5
7		Ilities (operability)	Low gas penetration	1.0	0.9	0.9	0.9	0.9
8		Ilities (operability)	Resistance to ultraviolet radiation	1.0	0.5	0.1	0.9	0.9
9		Ilities (operability)	Low weight	0.5	0.5	0.1	0.5	0.1
10		Ilities (maintainability)	Maintain stable characteristics (≈ 3 years)	1.0	0.5	0.5	0.9	0.5
11		Cost	Availability in the market	0.5	0.9	0.9	0.1	0.9
12		Emergency (high)	Mechanical damage (avoid)	0.75	0.5	0.9	0.9	0.5
				Decision value, *DV*	7.03	6.53	7.73	5.63
				Priority	2	3	1	4

According to Table 11, 12 emergent properties were identified in the descriptive study II. All these properties were listed using the STOEP structure and evaluated. For evaluation, firstly, a decision was made to combine STOEP with a decision matrix. It allowed using the ontology for the numerical comparisons of the calculated decision values *DV*. As it turned out, using "pure" STOEP as a decision support tool did not allow numerical comparisons. Secondly, similar to the descriptive study I, formula (1) with the same grading scales of its constituents was applied. Additional intermediate numerical value of weight $W= 0.75$ was used for emergency, assuming that the damage of the hull envelope does not necessarily lead to the crash of the airship, if helium inside the hull envelope, as planned by "WARPA," is used. Finally, the list of alternatives and their symbols were kept the same as in the descriptive study I phase: polyamide (A1), aramid (A2), Dyneema (A3), and rubberized cotton (A4). The decision-maker filled weights *W* and levels of compliance *C(A)* in the combined STOEP-decision matrix. Values from the descriptive study I phase were distributed among emergent properties, as listed in Table 11. Strategic-level emergent properties were assigned medium-importance weights *W* ($W = 0.5$), as they did not constitute the purpose of IRTA's design at the stage of preliminary decision making. Engineering-level emergent properties obtained various numerical values of weights *W*. Similar to descriptive study I, no cases of $W=0.1$ and $C(A) = 1$ were used. Dyneema (A3) was selected as the best concept for IRTA's hull envelope based on the calculated decision values *DV*.

Dyneema (A3) was successfully validated as the final decision by the expert from "WARPA," and polyamide (A1), which was close to it by the calculated *DV,* was left as a reserve option. The use of the emergence approach and STOEP, compared to the application of the value approach, allowed making good concept selection of IRTA's hull envelope by leading to the development of a successful innovative complex system, as further simulations in "WARPA" demonstrate. Overall, their use for preliminary decision making allowed to save one month of the company's resources on the design of IRTA (Appendix A).

As an answer to the research question, it should be noted that the separate use of STOEP as a decision support tool turned out to be imperfect for the realization of the emergence approach. During the descriptive study II phase, it became evident that as a separately applied tool, STOEP, via its schematic representation, allows supporting design decisions by providing the visualization of identified emergent properties and relationships between them. However, numerical comparisons of alternatives were possible only by combining it with a decision matrix, which mostly equals the finalized tool with MHoQ. Additionally, IRTA's hull envelope represented a subsystem of a complex system, but not the innovative complex system itself, which could serve as a factor of its success in the role of a decision support tool. Thus, the separate use of STOEP as a tool does not bring to full and comfortable decision making but can serve as an analog to values in cases when their broader list is required. More complex decision-making cases need applying CDMM-1 or CDMM-2.

3.2. Case study 2: Abridged CDMM-1 for concept selection of ARCDS

The conceptual design of ARCDS started at the beginning of 2018 in the Skoltech Center for Hydrocarbon Recovery as a Ph.D. research project of Evgeny Baraboshkin supervised by Prof. Dr. Dmitry Koroteev. Nowadays, its development continues by "Digital Petroleum," a Skolkovo start-up company, to which shareholders Skoltech belongs. ARCDS represents a medium-complexity innovative system from the upstream sector that touches on the global challenge of automation in various engineering domains. The system is applied to rock core laboratory research that consists of lithological, petrophysical, and chemical investigations of rock core samples. These are cylindrical rock samples drilled out from wells that serve as the initial and credible source of geological information [133]. ARCDS touches on rock core description, the initial phase of rock core research, which is predominantly conducted manually by geologists nowadays. This innovative system aims to improve rock core description by increasing its speed and quality through using machine learning, machine vision techniques for the analysis of rock core images, and leaving human participation only for the final control stage. The innovativeness of ARCDS consists of bringing radically new functionality to the domain of rock core research [12].

In 2018, concept selection of ARCDS was performed using the value decision-making approach in the Skoltech Center for Hydrocarbon Recovery (descriptive study I). Over time, the selected best concept revealed its inconsistence with the results of laboratory experiments. Therefore, in 2020-2021, assisted by two STG members, one more round of decision making for concept selection was performed, this time, using the emergence approach and abridged CDMM-1 (descriptive study II). The new round of decision making brought to another selected best concept, validated by the results of laboratory experiments. The application of the emergence approach for concept selection of ARCDS allowed to save ≈ 1.5 months of the “Digital Petroleum” company’s resources (Appendix B). The results of the collaborative work on concept selection of this system were published in the related research paper by Nikolaev et al. in 2021 [12]. The current case study was supported by “Digital Petroleum” staff: general director Dr. Dmitry Koroteev, development director Dr. Dmitry Orlov, and senior specialist in machine learning Evgeny Baraboshkin.

3.2.1. Research clarification

Case study 2 aimed to use the emergence approach for concept selection of ARCDS by applying the abridged version of CDMM-1, which constituted the research purpose. The case study tasks consisted of identifying values, emergent properties, and alternatives, applying the value and emergence approaches for selecting between alternatives, comparing decision-making results, and concluding the pros and cons of abridged CDMM-1. The research question was formulated the following way: “How does abridged CDMM-1 represent itself if used for the realization of the emergence approach to design decision making?” Case study 2 represents group decision making performed in the collaborative mode.

3.2.2. Descriptive study I

To apply the value approach to concept selection of ARCDS, four decision-makers from the Skoltech Center for Hydrocarbon Recovery used the generalized value approach-based decision-making model (Figure 26). They skipped Phase 5, as when descriptive study I was conducted, this subject was not clear. However, the possibility of success *P* was included in Phase 4 as an element of uncertainty/risks evaluation. The given below decision-making model is not specified as a model but provided as a process in the related paper [12].

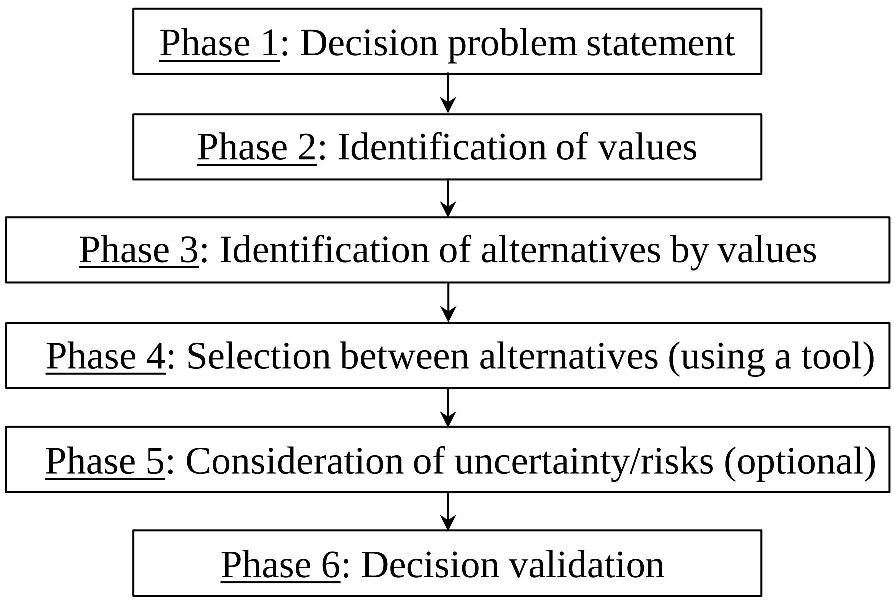


Figure 26 – Generalized value approach-based decision-making model.

Thus, the value approach-based concept selection of ARCDS started with the decision problem statement (Phase 1), continued by identifying values and alternatives by values (Phases 2-3), selecting between alternatives using a decision support tool (Phase 4), and finished by decision validation (Phase 5, as initial Phase 5 from Figure 26 was skipped). The canonical framework "To-By-Using," described by Crawley et al., was used for Phase 1 [4]. Phases 2-3 were performed through the prior knowledge analysis, which consisted of reviewing literature sources and interviewing the experts in geology, petrophysics, and information technologies. The conducted literature review later resulted in publishing its findings in the related paper by Baraboshkin et al. [134]. Decision-makers used a decision matrix tool for Phase 4 and applied the “inspection” type of validation for Phase 5.

Decision-makers formulated the decision problem the following way: “Provide customers in the domain of rock core analysis with the system to perform automated rock core description by implementing combinations of standard and improved software machine vision techniques, workflows and methods, using a set of rock core images, accompanying software applications, and petrophysical data.” They identified five values for design decision making of ARCDS: speed of description, flexibility of a system, automation level, accuracy of description, and availability of a system. Seven alternative concepts of this system were identified based on values (Table 12) [12,134].

Table 12 – List of alternative concepts of ARCDS [12,134].

Index	Alternative
A1	Rock core photographing, machine vision, human guidance
A2	Rock core photographing, unsupervised machine learning, human guidance
A3	Rock core photographing, supervised machine learning, human guidance
A4	Rock core photographing, supervised machine learning
A5	Rock core photographing, supervised deep learning
A6	Rock core photographing, manual description
A7	Manual description of rock core

As listed in Table 12, alternatives A1-A6 include initial rock core photographing and further analysis of rock core images by applying machine vision, machine learning, and deep learning in different combinations. Alternative A7 represents the traditional option of manual rock core description. Machine and deep learning can be supervised or not (alternatives A2-A5); the possibility of additional human guidance by operators is also considered (alternatives A2-A3). Operators can be represented by geologists and petrophysicists.

Values and alternatives were put into the decision matrix to select between alternatives (Table 13) [12]. The decision matrix was filled by the responsible for the ARCDS development project geologist by consulting with the experts in associated knowledge domains. It was done to diminish the probability of possible bias in assigning table parameters: weight *W*, the level of compliance *C(A)*, and the probability of success *P*. Numerical values of parameters in the decision matrix are approximate and can reflect certain subjectivity of decision-makers. This subjectivity was considered non-critical for concept selection of ARCDS, but it should be taken into account for future cases of complex systems.

Table 13 – Decision matrix for concept selection of ARCDS (the value approach) [12].

№	Values	Weight, *W*	Alternatives						
			A1	A2	A3	A4	A5	A6	A7
1	Speed of description	1.0	0.25	0.5	0.75	1.0	1.0	0.0	0.0
2	Flexibility of a system	0.75	0.75	0.75	1.0	1.0	1.0	1.0	1.0
3	Automation level	0.5	0.25	0.5	0.75	1.0	1.0	0.5	0.0
4	Accuracy of description	1.0	1.0	0.5	0.75	0.75	1.0	0.5	0.5
5	Availability of a system	1.0	0.75	0.75	0.75	0.75	0.5	0.75	1.0
	Probability of success, *P*		0.5	0.1	0.5	0.1	0.1	0.5	0.5
	Decision value, *DV*		1.34	0.26	1.69	0.38	0.38	1.13	1.13
	Priority		2	5	1	4	4	3	3

The decision matrix, shown in Table 13, was filled the following way: firstly, weights *W* of each value were assigned. The following grading scale was used: 1 – high importance, 0.75 – intermediate high-medium importance, 0.5 – medium importance, 0.25 – intermediate medium-low importance, and 0.1 – low importance. In practice, $W = 0.25$ was not used in the matrix. Secondly, the level of compliance of each value with each alternative was assessed according to the next grading scale: 1 – high level of compliance, 0.75 – intermediate high-medium level of compliance, 0.5 – medium level of compliance, 0.25 – intermediate medium-low level of compliance, 0.1 – low compliance, and 0 – no compliance. In this case, high level of compliance assumed full compliance, which was an omission, as no existing research method can guarantee complete success of work with rock core due to its diversity. However, the difference in top levels of compliance was considered in descriptive study II. Thirdly, the probability of success *P* was assigned using the following grading scale: 0.9 – high probability, 0.5 – medium probability, and 0.1 – low probability. This introduced parameter represents the estimation of overall concept success in performing the primary function of ARCDS: successful rock core describing. Finally, decision values *DV* were calculated and priority setting was performed. The calculation of *DV* for each alternative was done using the following formula:

$$DV = \sum_{i=1}^{N} W_i \cdot C(A)_i \cdot P_i, \tag{3}$$

Where: *DV* – decision value,

W_i – the weight of each value,

$C(A)_i$ – the level of compliance of each value with the alternative,

Pi – the probability of success,

N – number of values.

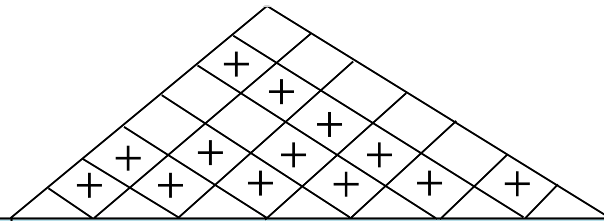
Based on the calculated decision values *DV*, alternative A3 was selected as the best concept. This decision was validated through inspection by presenting concept selection results in front of the internal expert committee. Although alternative A5 did not possess the highest priority, it was further developed due to the certain scientific interest of researchers. Over time, it turned out that laboratory experiments confirmed A5 as the best concept. Therefore, the need to conduct concept selection that considers design decision-making specifics of innovative complex and medium-complexity systems, like ARCDS, appeared.

3.2.3. Prescriptive study

The STG members proposed to the ARCDS designers to apply the emergence approach for concept selection of ARCDS. Consideration of innovativeness and complexity as complementary features of such systems through this approach and STOEP was expected to lead to good concept selection, the one that would align with the results of laboratory experiments. Abridged CDMM-1 was proposed as the means of applying the emergence approach.

3.2.4. Descriptive study II

Descriptive study II was conducted at the end of 2020 – at the beginning of 2021 by five decision-makers: three from the Skoltech Center for Hydrocarbon Recovery and two from STG. Abridged CDMM-1 that was used to realize the emergence approach in this study stage lacked Phase 5, “Mitigation of uncertainty and ambiguity,” compared to the conventional version of CDMM-1. It was an early version of the model, and this phase was at the stage of its development by the moment of decision making. Abridged CDMM-1 possesses five phases: Phase 1 “Decision problem statement,” Phase 2 “Identification of stakeholder needs and emergent properties,” Phase 3 “Identification of alternatives,” Phase 4 “Selection between alternatives,” and Phase 5 “Decision validation.” Decision-makers used the information from the descriptive study I stage for Phases 1-3 and updated previous prior knowledge analysis results to fit using stakeholder needs and emergent properties instead of values for CDMM-1. Each stakeholder need was referred to one type of emergent properties, which constitutes the distinctive peculiarity of CDMM-1. For selecting between alternatives in Phase 4, emergent properties and alternatives were put into MHoQ and evaluated, as shown in Figure 27 [12]. MHoQ was filled by the responsible for the ARCDS project geologist, attracting the participation of other decision-makers and sharing the results among them. All assigned parameters, their numerical values, and calculations were performed as described for CDMM-1 in Chapter 2.



№	Emergent properties	Weight, *W*	A1	A2	A3	A4	A5	A6	A7	Function	Performance	"Ilities"	Emergency	Benefit	Knowledge	Elegance
			Alternatives							**Emergent property**						
1	Determination of different types of rocks	1.0	0.5	0.5	0.9	0.9	0.9	0.9	0.5	•						
2	Description of rock core conditions	0.5	0.1	0.1	0.9	0.9	0.9	0.9	0.5	•						
3	Extraction of core images from the image of a box	0.5	0.1	0.5	0.5	0.5	0.9	0.9	0,0	•						
4	Description of ⩾10 lithotypes (automated mode)	1.0	0.1	0.5	0.9	0.9	0.9	0,0	0,0		•					
5	Flexibility of description with extraordinary rocks	0.5	0.9	0.9	0.1	0.1	0.1	0.5	0.5			•				
6	Use of other petrophysical data	0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.9			•				
7	Rock core damage (avoid)	1.0	0.9	0.9	0.9	0.9	0.9	0.5	0.5				•			
8	Description using internal resources	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5					•		
9	Data for geological simulation	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9						•	
10	A sense of quality and low apparent complexity	1.0	0.5	0.9	0.9	0.9	0.9	0.1	0.1							•
Decision value, *DV*			3.79	4.79	5.59	5.59	5.79	3.89	2.84	Immediate	Immediate	Life-cycle	Unanticipated	Economic	Educational	Overall
	Priority		5	3	2	2	1	4	5	**Value**						

Figure 27 – Modified house of quality for concept selection of ARCDS (the emergence approach) [12].

According to Figure 27, 10 emergent properties were identified in descriptive study II. Values from descriptive study I were distributed between them. All emergent properties were listed in the left field of MHoQ and organized according to STOEP. The link between emergent properties and values was provided in the right field. The roof of MHoQ demonstrated correlations between alternatives: alternatives A1-A5 correlate with each other by rock core photographing, A1-A3 are linked with human guidance, etc. The central field of MHoQ contained numerical values of assessed levels of compliance *C(A)* of each emergent property with each alternative. No full-compliance option ($C(A) = 1$) was included to consider the influence of rock core diversity on the success of its laboratory research. Additionally, no intermediate numerical values of weights *W* and levels of compliance *C(A)*, low-weight numerical value for weights ($W = 0.1$) were applied for MHoQ. According to the calculated decision values *DV*, alternative A5 was selected as the best one. This decision was successfully validated by the results of laboratory experiments ("test" validation type), which selected results, confirming A5 as the best concept of ARCDS, were later published in the related paper by Baraboshkin et al. [135]. Use of the emergence approach allowed to save ≈ 1.5 months of the "Digital Petroleum" company's resources (Appendix B).

Compared to the use of the value approach, application of the emergence approach brought to good concept selection or ARCDS: the selection of a concept that aligns with the results of laboratory experiments. The use of abridged CDMM-1 for this purpose was also successful. Its following advantages were noticed: firstly, the model allowed applying the emergence approach to consider the combination of innovativeness and complexity of ARCDS. Secondly, abridged CDMM-1 contained MHoQ, which turned out to be a comfortable tool for performing numerical comparisons of alternatives. Finally, its success was confirmed by "Digital Petroleum." The disadvantages of the model consisted of the lack of consideration of ambiguity, uncertainty, and associated risks, and the adopted assumption of referring each stakeholder need only to one type of emergent properties.

3.3. Case study 3: CDMM-1 for architecture selection of ALTS

Case study 3 represents a retrospective study of design decision making for a complex system. The system of interest, ALTS, refers to the midstream oil and gas industry sector and faces the challenge of gas production in the Arctic. The Russian Federation possesses considerable natural gas reserves in this region. One of the largest gas fields in Russia's Arctic is the South-Tambeyskoye gas condensate field, located in the Yamal Peninsula. It is operated by "Yamal LNG," a joint venture of four companies: "NOVATEK," "Total," "China National Petroleum Corporation," and "Silk Road Fund." "Yamal LNG" is a pilot project for the Russian Federation, initiated by a decree of our country's government in 2010. It represents an integrated project that unites LNG production, liquefaction, and transportation to its consumers in the European and Asian markets [116].

ALTS supports the transportation part of the "Yamal LNG" project. Due to the lack of existing pipeline and railway infrastructure and high costs of their building in the Arctic region, LNG transportation by sea was considered as the primary option from the beginning. For future possibilities, Merkulov claimed that the Ob-Irtysh river route could also be considered [136,137]. Since 2017, the transportation of LNG by sea started via the Northern Sea Route. Its assumed all-the-year-round transportation of approximately 17.5 mln tons of LNG per year (project capacity of the plant) from the Port of Sabetta (the Yamal Peninsula, Ob river) to destination points in Europe and Asia [116,136]. Mitrova noted that this type of transportation occurs in severe climate conditions. Therefore, the window for sending cargo using the Northern Sear Route opens in July and closes at the end of November [138]. Thus, scientists and engineers from "Yamal LNG" faced an engineering problem of designing such an innovative complex system, called ALTS by the author of the thesis, which would allow all-the-year-round safe, reliable, and sustainable transportation of LNG through the Northern Sea Route to Europe and Asia. By the time of this case study, the problem was solved by "Yamal LNG," therefore, a retrospective type of study for the thesis was conducted.

3.3.1. Research clarification

The current case study aimed to use the emergence approach for architecture selection of ALTS by applying the conventional version of CDMM-1, which constituted the research purpose. Its tasks consisted of identifying a decision-making approach used by decision-makers from “Yamal LNG,” applying the emergence approach through CDMM-1 using the information from the available literature sources, and concluding the pros and cons of the model. The research question was formulated the following way: “How does CDMM-1 represent itself if applied for the realization of the emergence approach to design decision making?” Case study 3 represents group decision making. Its mode (collaborative or co-located) is unknown for the descriptive study I stage, representing architecture selection of ALTS made by “Yamal LNG.” The descriptive study II stage was performed in a collaborative mode by two decision-makers from STG and additionally involved consultations and interviews with the experts in the field.

3.3.2. Descriptive study I

There is not much available information on how design decision making for architecture selection of ALTS was conducted. However, the main facts about it can be defined from the publications. One of the best literature sources on the topic is the relatively recent publication by Hannon [116]. Firstly, it is known that design decision making for architecture selection of ALTS was performed by decision-makers from “Yamal LNG” and could be a part of the final investment decision made at the end of 2013. Secondly, the following values can be identified: reliability, safety, sustainability, and cost. Thirdly, the selected alternative is well established. It consists of applying specially designed ice-breaking LNG carriers for transportation along the Northern Sea Route. LNG is initially transported by ice-breaking carriers to trans-shipment terminals (e.g., Zeebrugge in Belgium), transferred at these terminals to conventional carriers, and further transported to destination points with them. Finally, successful decision validation through the success of current transportation operations by the selected alternative is extensively described in publications [116,117,136,138].

Due to the available information on values and alternatives, it can be concluded that either VFT (the value approach) or AFT were used for making the architecture selection design decision of ALTS by "Yamal LNG." However, as the system of interest represents an innovative complex system, the emergence approach could also be applied to it.

3.3.3. Prescriptive study

The STG members were interested in making architecture selection of ALTS due to the high complexity and innovativeness of the system, which could serve as a solid testing example for the approbation of the emergence approach, STOEP, and CDMM-1. Radical new functionality of LNG transportation along the Northern Sea Route in the wintertime, constituting its innovativeness, is impossible without considering many elements of ALTS, constituting its complexity: vessels, navigation facilities, etc. Therefore, ALTS reveals the complementarity of its innovativeness and complexity, to which the principle of complementarity for design decision making in innovative complex systems is applicable. Thus, two STG members conducted a retrospective study of architecture selection of ALTS in 2020-2021, using the information from the available publications. The idea of this type of study was taken from contemporary retrospective studies on design decision making for Apollo missions of landing on the Moon by Simmons and Crawley et al. [4,21].

3.3.4. Descriptive study II

Descriptive study II reflects the use of the emergence approach through CDMM-1 for architecture selection of ALTS. The applied model consists of the following six phases: Phase 1 "Decision problem statement," Phase 2 "Identification of stakeholder needs and emergent properties," Phase 3 "Identification of alternatives," Phase 4 "Selection between alternatives," Phase 5 "Mitigation of uncertainty and ambiguity," and Phase 6 "Decision validation." Two decision-makers from STG went consistently through all of them.

The canonical framework "To-By-Using," described by Crawley et al., was used for Phase 1 [4]. The decision problem was given the following formulation: "Provide "Yamal LNG" with the system to perform all-the-year-round LNG transportation from Yamal LNG plant to customers in Asia and Europe by implementing existing and new transportation means using the Northern Sea Route possibilities." Information for the decision problem statement was mostly taken from Hannon's publications and aligned with the goals of the "Yamal LNG" project [116,117,138]. Due to greater demands in energy resources of the Asian market compared to the European market, it can be assumed that 80% of LNG is intended to be transported to Asia through the Bering Strait and 20% to Europe. The amount of LNG for annual transportation was not specified in the decision problem statement as different values are given in the literature. Hannon specified 16.5 mln tons of LNG and 1.2 mln tons of gas condensate transportation annually; Merkulov claimed the production capacity of the plant to be equal to 17.5 mln tons of LNG per year [116,136].

The information from the problem statement was distributed among stakeholder needs identified from the prior knowledge analysis for Phase 2. It included reviewing available literature sources and consulting with the expert from one of the companies-founders of "Yamal LNG" on the information from them. Each stakeholder need was referred to one type of emergent properties as assumed by CDMM-1. Decision-makers additionally developed the list of clarifications for emergent properties by shortening formulations of related stakeholder needs. It was done to assist in building MHoQ in Phase 4. Therefore, the list of clarifications of emergent properties could be used as an equivalent of stakeholder needs. Identified emergent properties and their clarifications are listed in Table 14, which includes types of emergent properties according to STOEP, their clarifications, representing abridged formulations of stakeholder needs, and the citations to close to them literature sources.

Table 14 – Identified emergent properties and their clarifications for ALTS.

№	Type	Clarification	Citations
1	Function	Transportation of LNG to consumers	[118]
2	Function	"Import" of building LNG carriers technology	[116,137]
3	Performance	Transportation of 20 mln tons of LNG per year	[136]
4	Ilities (maintainability)	Domestic supplier and maintenance operations	[137]
5	Ilities (reliability)	Compatibility of LNG carriers with terminals	[116]
6	Ilities (sustainability)	Regular reach of Europe and Asia (locations)	[116]
7	Ilities (safety)	Monitoring technological risk for double hull	[139]
8	Ilities (operability)	Sabetta logistics seaport support	[116]
9	Ilities (operability)	Navigation logistics support	[116]
10	Cost	Transportation to Asia (<180 USD/1000 m^3)	[137]
11	Cost	Transportation to Europe (<160 USD/1000 m^3)	[137]
12	Emergency (low)	Economic sanctions (avoid)	[140]
13	Emergency (low)	Negative change of Russia's legislation (avoid)	[140]
14	Emergency (high)	Negative environmental impact (avoid)	[139]
15	Emergency (high)	Technological accident (avoid)	[139]
16	Benefit	Leadership of Russia in Arctic presence/LNG	Expert
17	Knowledge	Technology transfer	Expert
18	Knowledge	Development of relevant technologies	[137]
19	Knowledge	Gain of Arctic LNG treatment experience	[137]
20	Elegance	Fulfillment of quality/low apparent complexity	[4]

According to Table 14, 20 emergent properties (and related stakeholder needs) were established for architecture selection of ALTS. Although STOEP assumes benefit, knowledge, and elegance to constitute the strategic level of emergent properties, their list in the current case study was prepared, starting with engineering-level emergent properties. The reason for this consists of that more information in the available literature sources is devoted to engineering questions compared to strategic ones. All the listed in Table 14 emergent properties can be conditionally divided into the following two semantic groups: leadership of the Russian Federation in LNG production, transportation of LNG to Europe and Asia, and the development of technologies. The first group covers strategic topics: leadership of our country in the Arctic presence and LNG, regular reach of European and Asian market locations, avoiding economic sanctions, etc. The second group includes engineering themes: the volume of product transportation, its cost, and associated technical aspects and risks. The numerical value of 20 mln tons of annual LNG transportation was put, assuming future possibilities to increase current transportation rates or production capacity of LNG plant as noted by Hannon and Merkulov [116,136]. The third semantic group of emergent properties covers hybrid strategic-engineering topics: gain of foreign technologies and experience of Arctic LNG treatment by the Russian Federation, development of relevant technologies, and others. All the obtained information was taken from the literature sources and discussed with the expert. Two strategic-level emergent properties were not found in the publications and resulted from this discussion; therefore, the citation to them was marked as "expert."

Established emergent properties were used to identify alternative architectures of ALTS or alternatives (Table 15). Only transportation by sea was considered, as other options (e.g., pipeline transportation) were excluded by "Yamal LNG" from the beginning.

Table 15 – List of alternative architectures of ALTS.

Index	Alternative
A1	Conventional LNG carriers assisted by ice-breakers on the Northern Sea Route
A2	Ice-breaking LNG carriers along all the route to destination points
A3	Ice-breaking carriers until trans-shipment terminals, conventional carriers after

As listed in Table 15, there were basically three options to select from: A1 and A2 assumed separate use of conventional or ice-breaking LNG carriers, A3 served as their combination. Separate use of conventional LNG carriers (A1) required additional support from the side of ice-breakers for transportation along the Northern Sea Route. Combined use of conventional and ice-breaking LNG carriers required supporting trans-shipment facilities. All the alternatives were identified using reviewed literature sources in combination. Therefore, no specific separate publications were identified. As Case study 3 represents architecture selection, a binary DSM for representation of alternatives was applied (Figure 28).

Subsystems		1	2	3	4	5	6	7	8	9	10
Ice-breakers	1		●	●							
Conventional LNG carriers	2	●		●	●			●	●	●	
Navigation facilities	3	●	●		●	●				●	
Rescue service facilities	4		●	●		●					
Authorities for navigation	5			●	●			●	●		●
LNG plant	6							●			
Loading terminal (Sabetta)	7		●			●	●				
Destination point terminals	8		●			●				●	
Ice-breaking LNG carriers	9		●	●					●		●
Trans-shipment terminals	10					●				●	

Figure 28 – The binary DSM for ALTS (A1 – blue, A2 – green, A3 – purple).

The binary DSM displayed in Figure 28 demonstrates the decomposition of ALTS into its 10 subsystems: LNG loading-unloading facilities (plant, terminals), vessels (tankers, ice-breakers), and navigation support facilities (authorities, rescue service). Relationships between pairs of subsystems are indicated in DSM with dots. Alternatives are highlighted with blue, green, and purple colors for A1, A2, and A3, respectively. According to DSM, alternative A1 incorporates loading and unloading (destination point) terminals, navigation support facilities, conventional LNG carriers, and ice-breakers. Relationships between terminals and LNG carriers are established through navigation authorities and facilities. Ice-breakers relate only to alternative A1 and, therefore, possess no relationships with ice-breaking LNG carriers and trans-shipment terminals. Opposite to A1, alternative A3 includes them but excludes ice-breakers. Therefore, no relationship between ice-breaking LNG carriers and ice-breakers is shown in Figure 28. Alternative A2 excludes conventional LNG carriers, ice-breakers, and trans-shipment terminals. It incorporates loading and unloading (destination point) terminals, navigation support facilities, and ice-breaking LNG carriers.

The binary DSM does not represent types of relationships between subsystems, which allowed keeping a high-level representation of alternative architectures. For the same reason, the decomposition of ALTS on components was omitted. Decision-makers considered the level of alternatives representation reasonably detailed to understand their architectures for the purpose of architecture selection. The more profound understanding of alternatives allowed proceeding to Phase 4 to select between them using MHoQ (Figure 29).

As shown in Figure 29, all 20 identified emergent properties were listed in the left field of MHoQ and organized according to STOEP. Abridged formulations of stakeholder needs from Phase 2 were used as their titles. However, types of emergent properties were also included in the right field, where the link between emergent properties and values was provided. The roof of MHoQ demonstrated correlations between alternatives: alternatives A1 and A3 correlate with each other by including LNG carriers, A2 and A3 are linked with ice-breaking LNG carriers. There is no correlation between A1 and A2. The central field of MHoQ contained numerical values of assessed levels of compliance *C(A)* of each emergent property with each alternative. Priority setting was performed based on the calculated decision values *DV*, for which weights *W* of emergent properties were established by decision-makers. According to *DV*, alternative A3 was selected as the best one. By saying “the best,” decision-makers assumed the most appropriate alternative as identified from MHoQ.

№	Emergent properties	Weight, *W*	Alternatives A1	A2	A3	Function	Performance	"Ilities"	Cost	Emergency	Benefit	Knowledge	Elegance
1	Transportation of LNG to consumers	1.0	0.5	0.5	0.9	●							
2	"Import" of building LNG carriers technology	0.5	0.1	0.9	0.9	●							
3	Transportation of 20 mln tons of LNG per year	0.5	0.5	0.5	0.9		●						
4	Domestic supplier and maintenance operations	1.0	0.9	0.5	0.5			●					
5	Compatibility of LNG carriers with terminals	1.0	0.9	0.5	0.5			●					
6	Regular reach of European and Asian locations	1.0	0.1	0.5	0.9			●					
7	Monitoring technological risk for double hull	1.0	0.1	0.9	0.9			●					
8	Sabetta logistics seaport support	0.5	0.5	0.9	0.9			●					
9	Navigation logistics support	0.5	0.5	0.9	0.9			●					
10	Transportation to Asia (<180 USD/1000 m^3)	0.5	0.5	0.1	0.9				●				
11	Transportation to Europe (<160 USD/1000 m^3)	0.5	0.5	0.1	0.9				●				
12	Economic sanctions (avoid)	0.1	0.5	0.5	0.5					●			
13	Negative change of Russia's legislation (avoid)	0.1	0.5	0.5	0.5					●			
14	Negative environmental impact (avoid)	0.5	0.5	0.9	0.9					●			
15	Technological accident (avoid)	1.0	0.5	0.9	0.9					●			
16	Leadership of Russia in Arctic presence/LNG	0.5	0.1	0.5	0.9						●		
17	Technology transfer	0.5	0.1	0.9	0.9							●	
18	Development of relevant technologies	0.5	0.1	0.9	0.9							●	
19	Gain of Arctic LNG treatment experience	1.0	0.5	0.9	0.9							●	
20	Fulfillment of quality/low apparent complexity	0.5	0.5	0.9	0.5								●
Decision value, *DV*			5.55	8.55	10.35								
		Priority	3	2	1								
					Value	Immediate	Immediate	Life-cycle	Life-cycle	Unanticipated	Economic	Educational	Overall

Figure 29 – Modified house of quality for architecture selection of ALTS.

Although the most appropriate alternative architecture using MHoQ was selected, the subjectivity in establishing numerical values of MHoQ, innovativeness of ALTS, and other factors serve as possible sources of ambiguity and uncertainty. Their influence on design decision making procedure may bring to that the selected alternative may turn out to be good according to the results of MHoQ but poor in reality. Therefore, the described below Phase 5, "Mitigation of ambiguity and uncertainty," was conducted in the case study.

In July 2021, the decision-makers from STG interviewed 10 experts using contemporary means for distance communication: Zoom, Skype, etc. Interviews lasted from 30 to 45 minutes and included six questions derived from the most valuable identified stakeholder needs and emergent properties. The summary table of their responses is given in Table 16. The experts represented various fields: six of them were from the oil and gas industry, two represented transportation and mining industries, and two were from educational and governmental institutions. The expert from one of the companies-founders of "Yamal LNG," involved in previous phases of CDMM-1, was excluded for interviewing in Phase 5 as he knew the subject and could bring additional subjectivity. The knowledge of all interviewed experts on oil and gas transportation, Artic navigation, and other topic-related questions was relatively equal. Therefore, no weighting for their answers was applied.

As demonstrated in Table 16, all given questions assumed proposing one alternative to each question. All 10 experts answered all questions, and the results of their responses were put in the summary table. Then the number of answers for each alternative was calculated, and the priority of alternatives was set according to it: the highest number of answers determined №1 priority. No frequency of answers or other statistical characteristics were applied as relatively low numbers of experts and interviews were included in the study. However, statistics characteristics could also be applied for more complex cases. The summary table shows that A3 turned out to be the most frequently mentioned alternative, and A2 was close to it. It allowed concluding that identifying A2 and A3 as top-level decision solutions in Phase 4 was close to reality. This way, it mitigates the influence of ambiguity and uncertainty on the final decision of A3 as the most appropriate architecture. Advanced mitigation techniques for ambiguity and uncertainty were left for future research (see Conclusion).

Table 16 – Summary table of information from expert responses from one-round expert interviews.

№	Question	Expert №									
		1	2	3	4	5	6	7	8	9	10
1	Which alternative primarily allows year-round transportation of LNG to Asia and Europe at a reasonable cost?	A3	A1	A1	A3	A3	A1	A3	A2	A1	A2
2	Which alternative primarily allows the "import" of technologies for building LNG carriers by Russia?	A2	A3	A2	A2	A3	A3	A3	A2	A3	A3
3	Which alternative primarily allows the development of relevant technologies and Russia's leadership in LNG?	A2	A2	A3	A3	A2	A3	A2	A2	A3	A2
4	Which alternative primarily allows the gain of Arctic LNG treatment experience by the Russian Federation?	A1	A2	A3	A3	A2	A3	A3	A1	A1	A1
5	Which alternative primarily seems to represent quality, robustness, and low apparent complexity?	A3	A2	A2	A1	A3	A1	A2	A2	A3	A3
	Number of answers with A1	1	1	1	1	0	2	0	1	2	1
	Number of answers with A2	2	3	2	1	2	0	2	4	0	2
	Number of answers with A3	2	1	2	3	3	3	3	0	3	2
	Total mentions	A1: 10 times			A2: 18 times			A3: 22 times			
	Priority	A1: №3			A2: №2			A3: №1			

Alternative A3, which was selected in Phase 4 and was supported by Phase 5, was successfully validated by successful operations ("demonstration" type of validation). Its success for LNG transportation in the Arctic is described in various literature and Internet sources. Case study 3 demonstrated the usefulness of the emergence approach through the use of CDMM-1 for architecture selection of ALTS. Although it represented a retrospective study, and the initially applied decision-making approach was not fully identified, it allowed testing developed decision-making techniques on a complex system. The current case study positively answered its research question by demonstrating successful design decision making for architecture selection of ALTS. Compared to Case study 2, it included all the phases of CDMM-1, revealing the possibilities of the model. However, for future research, the implementation of advanced ambiguity and uncertainty mitigation techniques could be considered. CDMM-1 was based on the assumption of referring each stakeholder need only to one type of emergent properties, which may not be true. The decision-makers from STG noted the wish of the expert from "Yamal LNG" to refer some stakeholder needs to various types of emergent properties, which was realized by CDMM-2 as described in Case study 4.

3.4. Case study 4: CDMM-2 for concept selection of ILPS

Concept selection of ILPS started at the end of 2017 in the Skoltech Center for Hydrocarbon Recovery and included the preparation of a comprehensive review paper as a part of its prior knowledge analysis [131]. Since November 2018, it was continued by two STG members assisted by an expert from the Skoltech Center for Hydrocarbon Recovery. Decision-making spread over time and consisted of different phases separated by considerable time breaks due to the continuous development of the emergence approach and decision-making models. It finished in July 2021 by obtaining feedback from six experts from the oil and gas industry. Case study 4 was possible due to the significant support from Dr. Andrey Kazak, an expert in petroleum petrophysics (formerly at Skoltech).

3.4.1. Research clarification

Case study 4 aimed to use the emergence approach for concept selection of ILPS by applying CDMM-2 and test the possibility of referring stakeholder needs to several types of emergent properties, which constituted the research purpose. ILPS represents a medium-complexity innovative system from the upstream sector that touches on the global challenge of the shale revolution. The shale revolution reflects oil and gas development from unconventional organic-rich reservoirs that started globally in 2014 and significantly influenced oil prices. Oil and gas extraction from such formations, called shale oil and shale gas, was hardly possible earlier due to the previous lower level of development of required technologies. The Russian Federation possesses one of the leading positions in shale oil reserves in the world [141]. ILPS supports their estimation by proposing relatively fast and reliable liquid (oil and water) saturation measurements of rock core samples in the laboratory. The complexity of ILPS complements its innovativeness: combinations of laboratory techniques and apparatuses (complexity) are required to measure liquid saturation of unconventional organic-rich rock core samples without the pore space destruction (innovativeness).

The case study tasks consisted of identifying values, emergent properties, and alternatives, applying the value and emergence approaches for selecting between alternatives, comparing decision-making results, and concluding the pros and cons of CDMM-2. The research question was formulated the following way: "How does CDMM-2 represent itself if used for the realization of the emergence approach to design decision making?" This case study reflects group decision making. The descriptive study I phase was performed in the co-located mode by two decision-makers from the Skoltech Center for Hydrocarbon Recovery and included consultations with an expert in nuclear magnetic resonance (NMR) physics from the Skoltech Center for Photonics and Quantum Mechanics. The descriptive study II phase was conducted in the collaborative mode by three decision-makers: two from STG and one from the Skoltech Center for Hydrocarbon Recovery.

3.4.2. Descriptive study I

For descriptive study I, decision-makers used the same generalized value approach-based decision-making model as for the descriptive study I phase of Case study 2, including skipping Phase 5 for similar reasons. Similar to Case study 2, the probability of success *P* for calculating decision values *DV* was included in Phase 4 as an element of uncertainty/risks evaluation. Value approach-based decision making for Case study 4 started with the decision problem statement (Phase 1), continued by identifying values and alternatives (Phases 2-3), selecting between alternatives using a decision support tool (Phase 4), and finished by decision validation (Phase 5). Decision-makers used a decision matrix as a decision support tool for Phase 4 and applied the “inspection” type of validation for Phase 5.

The canonical framework “To-By-Using,” described by Crawley et al., was used for Phase 1 [4]. Decision-makers prepared the following formulation of the decision problem: “Provide customers in the domain of rock core analysis with the system to perform liquid saturation evaluation in unconventional organic-rich reservoir rock core samples by implementing combinations of standard and improved petrophysical measurement techniques, workflows, and methods using a set of NMR rock core analyzers and accompanying petrophysical instruments.” It considered including NMR rock core analyzers, called NMR-analyzers for short, in ILPS due to the noted interest of several oil and gas companies in the Russian Federation to support the shale revolution with this technology. Phases 2-3 were conducted through the prior knowledge analysis, which consisted of reviewing literature sources and consulting with the expert in NMR physics. Other experts were not involved as decision-makers themselves possessed significant practical experience in laboratory rock core analysis. The prior knowledge analysis results were published in the related review paper by Nikolaev and Kazak. The following five values were identified: detection of bitumen, bound water, free water, liquid oil, and separation of fluid phases. Seven alternative concepts of ILPS were identified based on them (Table 17) [131,142–144].

Table 17 – List of alternative concepts of ILPS (adapted from [131]).

Index	Alternative
A1	Conventional 2 MHz NMR-analyzers
A2	Combination of conventional, optimized for tight rocks 2 MHz NMR-analyzers
A3	Combination of low-field NMR-analyzers at different magnetic frequencies
A4	Combination of low and high-field NMR-analyzers
A5	Combination of low-field, high-field, and ^{23}Na NMR-analyzers
A6	Combination of retorts and Dean-Stark extractors
A7	Combination of electrical resistivity and dielectric permittivity meters

As listed in Table 17, alternatives A1-A5 include NMR-analyzers in various combinations; A6-A7 represent traditional laboratory core analysis techniques. Alternative A2 combines conventional 2 MHz NMR-analyzers with its special version for measuring nanopores of tight samples. Alternative A5 includes non-hydrogen NMR measurements [131]. Selection between alternatives was performed using a decision matrix as a tool (Table 18).

Table 18 – Decision matrix for concept selection of ILPS (the value approach).

№	Values	Weight, *W*	Alternatives						
			A1	A2	A3	A4	A5	A6	A7
1	Detection of bitumen	0.5	0.1	1.0	0.5	1.0	1.0	1.0	1.0
2	Detection of bound water	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0
3	Detection of free water	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4	Detection of liquid oil	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5	Separation of fluid phases	1.0	0.5	0.5	0.75	1.0	1.0	0.5	0.5
	Probability of success, *P*		0.9	0.9	0.9	0.5	0.1	0.1	0.9
	Decision value, *DV*		2.52	2.93	2.93	2.00	0.40	0.35	3.15
	Priority		2	1	1	3	5	6	4

The decision matrix, shown in Table 18, was filled the same way, using the same grading scales for its parameters and formula for decision values *DV* calculation as the decision matrix in the descriptive study phase I of Case study 2. In the current case study, the probability of success *P* represented no occurrence of rock core samples destruction during measurements. Based on decision values *DV*, alternatives A2 and A3 were selected as the most appropriate or best concepts. The taken decision was validated through inspection by presenting concept selection results twice: in front of the internal expert committee in Russian and as a seminar in English. The given seminar was combined with presenting the results of the prior knowledge analysis including the prepared review paper.

The conducted decision making based on the value approach did not allow selecting between two high-priority alternatives A2 and A3 and did not consider the combination of innovativeness and complexity of ILPS. Therefore, the emergence approach and CDMM-2 were proposed to decision-makers for the new round of its concept selection.

3.4.3. Prescriptive study

Concept selection for ILPS using the emergence approach was proposed by STG. It was assumed that the emergence approach would allow considering the combination of innovativeness and complexity of ILPS. The use of emergent properties through STOEP was proposed to serve as an analog to a broader list of values for identifying alternatives and selecting between them. The choice of CDMM-2 as instrumentation was made to test the possibility of referring each stakeholder need to several types of emergent properties.

3.4.4. Descriptive study II

Descriptive study II followed all phases of CDMM-2 as described in Chapter 2. Phases 1-3 from the descriptive study I phase were united in Phase 1 “Preparation” of the current study, restricting Phase 2 of descriptive study I only by identifying stakeholder needs. Decision-makers adapted prior knowledge analysis results for using emergent properties instead of values. Three QFD-based phases: Phase 2 "Translation of needs," Phase 3 "Selection," and Phase 4 "Assessment" were used to identify alternatives, select between them, and perform mitigation of ambiguity and uncertainty in combination with decision validation. The results of Phases 2-4 are displayed in Appendices C, D, and E, respectively.

Decision-makers identified 18 stakeholder needs in Phase 1 and referred them to 9 types of emergent properties, given according to STOEP, in Phase 2 (Appendix C). They listed engineering-level emergent properties first to start by considering technical aspects of ILPS. Strategic-level emergent properties followed them due to their more general character. Each stakeholder need was assigned its level of compliance *C(A)* numerical value for each emergent property, leaving no-compliance fields empty. Decision-makers used the right field of the QFD-based matrix in Phase 2 for evaluating weights of stakeholder needs *WSN* using definitions of "might have," "should have," and "must have" by Crawley et al. [4]. Stakeholder needs were equated with 0.1, 0.5, and 1.0 numerical values of their weights *WSN*, respectively, which was added for better visualization. Weights of emergent properties *W* were calculated using formula (2) as described for CDMM-2 in Chapter 2.

Phase 3 included MHoQ, which was almost equal to that in CDMM-1 (Appendix D). The only difference consisted of that weights of emergent properties *W* in CDMM-2 were calculated in Phase 2. It allowed referring stakeholder needs to several types of emergent properties. According to the calculated decision values *DV*, alternative A1 was selected as the most appropriate or the best concept. A well-known petrophysicist, Dr. Vitaly Merkulov from the National Research Tomsk Polytechnic University (TPU), validated the selected concept via its inspection in October 2020. He filled the QFD-based matrix in Phase 4 by evaluating decisions for each alternative according to dimensions of decision quality (Appendix E). The spider diagram demonstrated the dominance of alternative A1 and confirmed its selection. Other experts preferred answering questions in a simplified manner (Table 19).

Table 19 – Summary table of expert responses from one-round expert interviews.

№	Question	Expert №					
		1	2	3	4	5	6
1	Which alternative is best suited by the given model?	A3	A3	A2	A2	A1	A3
2	Which alternative is mostly realizable in the industry?	A1	A3	A1	A1	A1	A1
3	Which alternative provides most useful data?	A2	A3	A2	A2	A2	A1
4	Which alternative best avoids damaging samples?	A1	A1	A1	A1	A1	A1
5	Which alternative mostly makes sense to be selected?	A1	A3	A2	A2	A1	A1
6	Which alternative would you proceed with?	A1	A3	A2	A2	A1	A1
	Total mentions, times	A1: 19		A2: 10		A3: 7	
	Priority	A1: №1		A2: №2		A3: №3	

The summary table, given in Table 19, reflects decision quality assessment due to using questions based on dimensions of decision quality. It represents the results of one-round expert interviews, which are used to mitigate ambiguity and uncertainty. Due to the apparent complexity of filling the QFD-based matrix of Phase 4, the experts refused to work with it. Instead, they answered questions based on dimensions of decision quality. Their responses considered three highest-priority alternatives and confirmed the selection of alternative A1. This alternative possessed maximum mentions in the answers of experts.

Case study 4 positively answered its research question by demonstrating successful design decision making for concept selection of ILPS. It allowed clarifying between high-priority alternatives and selecting the most appropriate one. CDMM-2 possibility of referring stakeholder needs to several types of emergent properties allowed decision-makers to consider the versatility of stakeholder needs instead of limiting them by equating them with one type of emergent properties. However, CDMM-2 turned out to be more complicated for actual use than CDMM-1, and 6 out of 7 involved experts refused to do full work with it.

3.5. Deeper representation of design research methodology elements

Chapter 3 was devoted to the practical application of the proposed in the thesis decision-making framework, which is the combination of STOEP, the emergence approach, CDMM-1, and CDMM-2. It presented four case studies that were conducted using the design research methodology by Blessing and Chakrabarti [33]. Although the generalized information on the elements of this methodology was given initially for each case study, the methodology assumes specifying success criteria, overall objectives/research questions in the research clarification stage, objectives/research questions in the following stages: descriptive study I, prescriptive study, and descriptive study II. In addition, the subsequent stages of the design research methodology should clarify what was tried to be achieved and what was achieved. This type of information except overall research questions was not added to the subsections on case studies to avoid their over-saturation with details, and was left for this particular subsection. Under the term “success criteria” one assumes those criteria that relate to the final goal, to which the research project contributes. It reveals the aim of the research and the desired influence on practice [33].

3.5.1. Design research methodology elements for Case study 1

Design research methodology elements associated with each stage for Case study 1 are given below:

1. Research clarification:
    a) Success criteria: performance and time for decision making: improve performance while reducing the time for decision making.
    b) Overall objectives:
        (i) Research purpose: use the emergence approach for the IRTA’s hull envelope concept selection and STOEP as a decision support tool for its realization.

(ii) Research tasks:

- identify values, emergent properties, alternatives
- apply the value and emergence approaches
- compare decision-making results

(iii) Type of research: review-based research clarification, comprehensive descriptive study I, comprehensive prescriptive study, and initial descriptive study II.

c) Overall research question: "How does STOEP represent itself if used separately for the realization of the emergence approach to design decision making?"

2. Descriptive study I:

a) Objectives:

(i) Research purpose: use the abridged value approach-based decision-making process for the IRTA's hull envelope concept selection.

(ii) Research tasks:

- identify values, alternatives
- apply the value decision-making approach
- conclude decision-making results

b) Research question: "How does the value decision-making approach represent itself if used for the IRTA's hull envelope concept selection via the abridged value approach-based decision-making process?"

Conclusion: Descriptive study I of Case study 1 identified the areas of weakness in current decision-making methods in achieving the success criteria: performance was low (not clear, which alternative to select), time for decision-making for this type of system was relatively long (30-35 hours, mainly goes to the prior knowledge analysis). It was identified that the division of values was very general for decision making, and no focus on considering innovativeness and complexity was made.

3. Prescriptive study:
   a) Objectives:
      (i) Research purpose: propose applying the emergence approach through using STOEP for the IRTA's hull envelope concept selection.
      (ii) Research tasks: identify what areas of weakness are to be addressed by the emergence approach and how are they to be addressed.
   b) Research question: "How to apply the emergence approach for better IRTA's hull envelope concept selection?"

   Conclusion: Prescriptive study of Case study 1 identified that the performance of decision making is the main weakness that is to be addressed through using STOEP. Time for decision making as an additional weakness can also be addressed. Application of STOEP is expected to improve performance (and possibly, time for decision making) via considering innovativeness and complexity of IRTA and using more detailed division of parameters for evaluation (emergent properties instead of values).
4. Descriptive study II:
   a) Objectives:
      (i) Research purpose: use the abridged value approach-based decision-making process through using emergent properties instead of values, turning the decision making process into the emergence approach-based.
      (ii) Research tasks:
         - identify emergent properties, alternatives
         - apply the emergence approach through STOEP
         - conclude decision-making results
         - compare decision-making results with those from descriptive study I
   b) Research question: "How does the emergence approach represent itself (compared to the value-based decision-making approach) if used for the IRTA's hull envelope

concept selection using the abridged value approach-based decision-making process, modified by STOEP?"

Conclusion: Descriptive study II of Case study 1 demonstrated, how the emergence approach was tested. Obtained results identified the improvement in performance (clear understanding, which alternative to select). No improvement in time for decision-making was noticed (the same 30-35 hours). It was noted that the time on decision making predominantly goes to the prior knowledge analysis (25-30 hours), which cannot be strictly controlled. Overall, STOEP represented itself well in Case study 1.

3.5.2. Design research methodology elements for Case study 2

Design research methodology elements associated with each stage for Case study 2 are given below:

1. Research clarification:
   a) Success criteria: performance and time for decision making: improve performance while reducing the time for decision making.
   b) Overall objectives:
      (i) Research purpose: use the emergence approach for concept selection of ARCDS by applying the abridged version of CDMM-1.
      (ii) Research tasks:
         – identify values, emergent properties, alternatives
         – apply the value and emergence approaches
         – compare decision-making results
         – conclude pros and cons of abridged CDMM-1
      (iii) Type of research: review-based research clarification, comprehensive descriptive study I, comprehensive prescriptive study, and comprehensive descriptive study II.

c) Overall research question: “How does abridged CDMM-1 represent itself if used for the realization of the emergence approach to design decision making?”

2. Descriptive study I:

a) Objectives:

(i) Research purpose: use the generalized value approach-based decision-making model for concept selection of ARCDS.

(ii) Research tasks:

– identify values, alternatives

– apply the value decision-making approach via the generalized value approach-based decision-making model

– conclude decision-making results

b) Research question: “How does the value decision-making approach represent itself if used for concept selection of ARCDS via the generalized value approach-based decision-making model?”

Conclusion: Descriptive study I of Case study 2 identified the areas of weakness in current decision-making methods in achieving the success criteria: performance was low (the selected concept was not confirmed by laboratory experiments over time), time for decision-making was extremely long (130-140 hours). It was identified that the time was primarily wasted on the prior knowledge analysis phase (120-130 hours). However, time spent on other phases was also relatively long for this type of system (8-10 hours). It was also identified that the division of values was very general for decision making, and innovativeness and complexity as complementary features of innovative complex systems were not considered.

3. Prescriptive study:

a) Objectives:

(i) Research purpose: propose using the emergence approach for concept selection of ARCDS.

(ii) Research tasks: identify what areas of weakness are to be addressed by the emergence approach and how are they to be addressed.

b) Research question: “How to apply the emergence approach via the abridged version of CDMM-1 for better concept selection of ARCDS?”

Conclusion: Prescriptive study of Case study 2 identified that the performance of decision making is the main weakness that is to be addressed via using the abridged version of CDMM-1. Time for decision making is an additional weakness that can be addressed. Application of the abridged version of CDMM-1 is expected to improve performance (and possibly, time for decision making) through considering innovativeness and complexity of ARCDS and using more detailed division of parameters for evaluation (emergent properties instead of values).

4. Descriptive study II:

a) Objectives:

(i) Research purpose: use abridged CDMM-1 for the realization of the emergence approach for concept selection of ARCDS.

(ii) Research tasks:

- identify stakeholder needs, emergent properties, alternatives
- apply the emergence approach through the abridged version of CDMM-1
- conclude decision-making results
- compare decision-making results with those from descriptive study I

b) Research question: “How does the emergence approach represent itself (compared to the value-based decision-making approach) if used for concept selection of ARCDS via the abridged version of CDMM-1?

Conclusion: Descriptive study II of Case study 2 demonstrated the results of testing the emergence approach. Obtained results identified the improvement in performance (the selected alternative was confirmed by laboratory experiments). No improvement in time for decision-making was noticed. Overall, the abridged version of CDMM-1 represented itself well for the realization of design decision making based on the emergence approach: it turned out to be comfortable and well understandable for decision-makers.

3.5.3. Design research methodology elements for Case study 3

Design research methodology elements associated with each stage for Case study 3 are given below:

1. Research clarification:
   a) Success criteria: performance and time for decision making: improve performance while reducing the time for decision making.
   b) Overall objectives:
      (i) Research purpose: use the emergence approach for architecture selection of ALTS by applying CDMM-1.
      (ii) Research tasks:
         – identify a decision-making approach used by decision-makers from "Yamal LNG"
         – apply the emergence approach through CDMM-1 using the information from available literature sources
         – compare decision-making results
         – conclude the pros and cons of CDMM-1

(iii) Type of research: review-based research clarification, review-based descriptive study I, comprehensive prescriptive study, and comprehensive descriptive study II.

c) Overall research question: “How does CDMM-1 represent itself if applied for the realization of the emergence approach to design decision making?”

2. Descriptive study I:

a) Objectives:

(i) Research purpose: identify a decision-making approach used by decision-makers from “Yamal LNG.”

(ii) Research tasks:

– analyze the information from available literature sources

– identify existing alternatives

– identify the decision-making approach that was applied by “Yamal LNG”

b) Research question: “How did decision-makers from “Yamal LNG” do architecture selection of ALTS?”

Conclusion: Descriptive study I of Case study 3 identified the value approach (VFT) or alternative-focused thinking (AFT) as possible decision-making approaches that were used by decision-makers from “Yamal LNG” for architecture selection of ALTS. Areas of weakness in current decision-making methods in achieving the success criteria are not known exactly but can be assumed: performance could be low (it was not evident that the selected architecture was the most appropriate alternative, and waiting for operations was a critical point that was extremely required for decision validation). Time for decision-making was not specified in the available literature sources but can also be assumed to be long, as the discussion on the subject continued for several years. It was also identified that innovativeness and complexity as complementary features of innovative complex systems were not considered.

3. Prescriptive study:
   a) Objectives:
      (i) Research purpose: propose using the emergence approach (through CDMM-1) for architecture selection of ALTS.
      (ii) Research tasks: identify what areas of weakness are to be addressed by the emergence approach and how are they to be addressed.
   b) Research question: “How to apply the emergence approach via CDMM-1 for better architecture selection of ALTS?”

   Conclusion: Prescriptive study of Case study 3 identified that the performance of decision making is the main weakness that is to be addressed through using CDMM-1. Time for decision making is an additional weakness that can be addressed. Application of the abridged version of CDMM-1 is expected to improve performance (and possibly, time for decision making) through considering innovativeness and complexity of ALTS (as a vivid example of an innovative complex system) and using more detailed division of parameters for evaluation (emergent properties instead of values).
4. Descriptive study II:
   a) Objectives:
      (i) Research purpose: use CDMM-1 for the realization of the emergence approach for architecture selection of ARCDS.
      (ii) Research tasks:
         – identify stakeholder needs, emergent properties, alternatives
         – apply the emergence approach via CDMM-1
         – conclude decision-making results
         – compare decision-making results with those from descriptive study I

b) Research question: “How does the emergence approach represent itself (compared to the results of descriptive study I) if used for architecture selection of ALTS via CDMM-1?

Conclusion: Descriptive study II of Case study 3 demonstrated the results of testing the emergence approach. Obtained results identified good performance (the selected alternative was confirmed by operations as reported in the available literature sources). Cumulatively spent time on decision making is 60-70 hours, from which 10-12 hours were spent on all decision-making phases except the prior knowledge analysis. As there is no information on actually spent time for architecture selection of ALTS by “Yamal LNG,” it can be compared with time losses on the application of the value approach in Case study 2 (8-10 hours). This way, it can be concluded that there is no benefit in time savings for using the emergence approach via CDMM-1. Overall, CDMM-1 represented itself well for the realization of design decision making based on the emergence approach: it turned out to be comfortable and well understandable for decision-makers.

3.5.4. Design research methodology elements for Case study 4

Design research methodology elements associated with each stage for Case study 4 are given below:

1. Research clarification:
   a) Success criteria: performance and time for decision making: improve performance while reducing the time for decision making.
   b) Overall objectives:
      (i) Research purpose: use the emergence approach for concept selection of ILPS by applying CDMM-2.
      (ii) Research tasks:

   - identify values, emergent properties, alternatives
   - apply the value and emergence approaches
   - compare decision-making results
   - conclude pros and cons of CDMM-2
  (iii) Type of research: review-based research clarification, comprehensive descriptive study I, comprehensive prescriptive study, and initial descriptive study II.

c) Overall research question: "How does CDMM-2 represent itself if used for the realization of the emergence approach to design decision making?"

2. Descriptive study I:

a) Objectives:

  (i) Research purpose: use the generalized value approach-based decision-making model for concept selection of ILPS.

  (ii) Research tasks:
   - identify values, alternatives
   - apply the value decision-making approach via the generalized value approach-based decision-making model
   - conclude decision-making results

b) Research question: "How does the value decision-making approach represent itself if used for concept selection of ILPS via the generalized value approach-based decision-making model?"

Conclusion: Descriptive study I of Case study 4 identified the areas of weakness in current decision-making methods in achieving the success criteria: performance was low (not clear, which alternative to select), time for decision-making was long (240-250 hours for the prior knowledge analysis, 10-12 hours for other decision-making phases). It was identified that the division of values was very general for decision making, and innovativeness and complexity as complementary features of innovative complex systems were not considered.

3. Prescriptive study:
   a) Objectives:
      (i) Research purpose: propose using the emergence approach for concept selection of ILPS.
      (ii) Research tasks: identify what areas of weakness are to be addressed by the emergence approach and how are they to be addressed.
   b) Research question: "How to apply the emergence approach via CDMM-2 for better concept selection of ILPS?"

   Conclusion: Prescriptive study of Case study 4 identified that the performance of decision making is the main weakness that is to be addressed via using CDMM-2. Time for decision making is an additional weakness that can be addressed. Application of the CDMM-2 is expected to improve performance (and possibly, time for decision making) through considering innovativeness and complexity of ILPS and using more detailed division of parameters for evaluation (emergent properties instead of values).
4. Descriptive study II:
   a) Objectives:
      (i) Research purpose: use CDMM-2 for the realization of the emergence approach for concept selection of ILPS.
      (ii) Research tasks:
         – identify stakeholder needs, emergent properties, alternatives
         – apply the emergence approach through CDMM-2
         – conclude decision-making results
         – compare decision-making results with those from descriptive study I

b) Research question: “How does the emergence approach represent itself (compared to the value-based decision-making approach) if used for concept selection of ILPS via CDMM-2?

Conclusion: Descriptive study II of Case study 4 demonstrated, how the emergence approach was tested. Obtained results identified the improvement in performance (clear understanding, which alternative to select). No improvement in time for decision-making was noticed. If not considering the prior knowledge analysis, 10-12 hours were spent on the value approach-based decision making, and 12-14 hours were spent on the emergence approach-based decision making. There was a negative influence of applying the emergence approach: the time for decision making increased on 2 hours. It is the result of using the decision quality chain as an additional instrument to ensure that a good decision was made for concept selection of ILPS. Overall, the abridged version of CDMM-1 represented itself well for the realization of design decision making based on the emergence approach. However, it turned out to be less comfortable and less understandable for decision-makers than CDMM-1.

3.6. Discussion on case studies’ findings

The last paragraph of each case study was devoted to case studies’ findings. It included the information on answering overall research questions for each case study, noticed advantages and disadvantages, additional recommendations. There is no need to repeat this type of information. However, in terms of achieving or not achieving the success criteria, which was set as general to all case studies, there is the need to conclude the following generalized finding: the proposed framework (STOEP, CDMM-1, or CDMM-2) do not provide benefit in the time spent on decision making. Alternatively, they allow improving the performance of decision making. Further improvement of the proposed framework will be considered through performing future research activities as given in the Conclusion section.

3.7. Conclusion on Chapter 3

Chapter 3 covered the descriptive II study stage of the dissertation's research. It touches on the information from five papers published as a result of the work on this thesis in 2018-2021 years [6,11,12,107,131]. The chapter was devoted to demonstrating the combined application of STOEP, the emergence approach, CDMM-1, and CDMM-2 in case studies from the oil and gas industry. The main findings of Chapter 3 are as follows:

1. Case study 1 was conducted that tested the possibility of applying STOEP as a tool for concept selection of the hull envelope subsystem for IRTA using the emergence approach. Its separate use turned out to be imperfect and required combining it with a decision matrix for numerical comparisons, which allowed using emergent properties instead of values for preliminary decision making and making good concept selection.
2. Case studies 2 and 3 were conducted that tested the possibility of applying CDMM-1 for the realization of the emergence approach to design decision making. CDMM-1 in Case study 2 was used in its abridged version (without the ambiguity and uncertainty mitigation phase) and covered concept selection of ARCDS. Case study 3 applied conventional CDMM-1 for the retrospective study of architecture selection of ALTS. Both case studies revealed success in applying the emergence approach compared to the results of using the value approach. CDMM-1 in both cases demonstrated reasonable efficiency and comfortability but was limited by the adopted assumption of referring each stakeholder need only to one type of emergent properties.
3. Case study 4 was conducted that tested the possibility of applying CDMM-2 for the realization of the emergence approach for concept selection of ILPS. CDMM-2 revealed itself as a solution, which allowed implementing the emergence approach and relating stakeholder needs to various types of emergent properties. However, the model turned to be more complicated than CDMM-1 for real use in organizations.

Overall findings and recommendations of the thesis are presented in the Conclusion.

4. DISCUSSION

As doing a Ph.D. research is an iterative process, new advanced questions appear during the review process that do not directly fit in Chapters 1-3 of the prepared thesis text. This section contains the discussion of such questions.

4.1. Further discussion on systems emergent properties for decision making

Although the notion of "systems emergent properties" occupy one of the central positions in the thesis, it should be noted that they are intrinsic properties of systems. Thus, one can argue that the proposed novelty "For the first time, emergent properties were used for design decision making in complex systems…" is ambiguous. One of the arguments is that the target of engineers is to make design decisions ensuring that anticipated emergent properties are exhibited. It needs additional clarification of what is meant by this term.

Although the semantics of the term "emergent properties" was analyzed in Chapter 2, still, the definition of systems emergent properties as assumed by Crawley et al. in their book "System architecture: Strategy and product development for complex systems" was used as the primary one in the thesis (see Introduction) [4]. In addition, the meaning of the notion of "systems emergent properties" in the thesis is kept the same as explained by Crawley et al. The reason for this is that the conducted research was devoted to complex engineering systems, also called complex technical or technological systems. The research predominantly operated within engineering disciplines: systems engineering, systems analysis, and design of complex systems. Therefore, other definitions that are applied to socio-technical systems or other non-engineering domains were not used as the primary definition of the term.

Emergent properties in the thesis are considered from the engineering point of view. They are applied as the type of systems "characteristics" that have the potential to improve design decision making. In contrast, values in the value-based decision making are other “characteristics” of systems that are applied for design decision making, and the target of engineers is to obtain these values, when building a system. Other types of characteristics can be proposed for making better design decisions in complex systems. However, emergent properties were selected for this particular research as no publications were found to do design decision making based on them. The possibility to evaluate whether complex engineering systems are successful based on systems emergent properties (see Introduction) or not is the advantage of their use for design decision making.

It should be mentioned that the primary applied in the thesis definition of systems emergent properties by Crawley et al., which is used for complex engineering systems, is supported by the explanation of emergence for engineering by Khasanov et al. from “Gazprom Neft” in their book “Fundamentals of systems engineering” and Glukhikh from the University of Tyumen in his book “Theory of systems and systems analysis” [4,145,146].

4.2. Boundary in applicability between traditional and new techniques and tools

There is the note in the Conclusion section on testing the applicability of the emergence approach to preliminary and detailed design stages left for future research. The thing is that the emergence approach and the proposed framework “work” only for the conceptual design stage. It is the consequence of the appearance of emergent properties during this design stage. This note establishes both the boundary between the applicability of traditional and new techniques and tools and the main limitation of the proposed framework. MHoQ “works” for the conceptual design stage, although the “traditional” HoQ “works” only for preliminary and detailed design stages as it is more on the detailed engineering side. Thus, MHoQ substitutes HoQ for the conceptual design stage. However, there is no such boundary between the value approach and the emergence approach. The value approach is not substituted by the emergence approach, but is enriched by it, as the emergence approach represents the modification of the value approach well adapted for the conceptual design stage.

4.3. Consideration of ontology development methodologies and tools

The current thesis proposes a new ontology, STOEP, as its first scientific contribution. However, it does not describe application of methodologies that were used in building STOEP. In addition, no ontology-building tools were applied, which needs clarification.

Various methodologies, platforms, and tools are used to develop ontologies. In 2019, Law et al. in their review paper provided the taxonomy of literature on ontology development aspects. According to this paper, there are three key ontology development methodologies (e.g., Uschold and King's), four ontology development platforms (e.g., Protégé), and two tools (e.g., Jena) [147]. There is no strict division between platforms and tools, therefore, platforms can also be called tools. In 2020, Aminu et al. in their review paper selected the following four most popular ontology development methodologies for description, among which is Noy and McGuiness methodology, also called "Ontology Development 101" [148]. There exist more recent reviews on the topic.

All the methodologies listed in the two aforementioned papers were initially checked for their applicability to building STOEP. However, at the time of the development of STOEP there was an urgent need to prepare an essential and practical ontological model for its application in Case studies 2 and 4. Moreover, from the practical point of view, it turned out that decision-makers felt themselves very confident with the high-level representation of ontology, exactly the way STOEP was presented. Therefore, it was decided to leave STOEP "as is", and to leave an idea of applying various methodologies and comparing their results for future research. For the same reason, Protégé as an ontology-building platform or tool was not used for the high-level representation of STOEP. An idea of its future use to verify consistency of the developed ontological model was also left for future research. However, it should be noted that STOEP will definitely need to be built using ontology-building platforms, when proceeding to the application of emergent properties for decision making at the preliminary and detailed levels of design. It will allow avoiding possible logical mistakes.

4.4. Consideration of uncertainties of the innovation process in CDMM-1 and CDMM-2

The current thesis starts with the mention of a considerable role of innovations in global technological progress and mentions the current-day 4th Industrial Revolution, called “digital transformation” (see Introduction). There is also an explanation on the necessity to consider the high degree of uncertainty induced by the innovativeness of new products and systems and associated market and technological risks in Chapter 1. However, an additional question appears on whether this type of uncertainty associated with the innovation process is considered by the proposed decision-making models, CDMM-1 and CDMM-2.

The key to answering the raised question lies in the application of the systems thinking approach for the innovation process. Khasanov and Krasnov from the Scientific-technical Center of “Gazprom Neft” in their paper on digital transformation in the scientific organization discuss stages of the digital transformation in companies as the current-day innovation process [149]. They compare the current-day “digital transformation” with the “electrical transformation” that occurred in the beginning of the 20th century. The key finding by Khasanov and Krasnov is that the innovation process, to which digitalization belongs, is a matter of trial and error. Hence, the innovation process needs the systems thinking approach for its consideration. If the world that is influenced by the innovation process is considered as a system, then different disciplines that describe it (Earth Science, information technologies, etc.) are its entities. Thus, the key to understanding the innovation process lies within the understanding of the relationships between such entities (disciplines), not just disciplines.

Returning to the thesis, it should be noted that the systems thinking approach constitutes the core of the whole proposed decision-making framework, including CDMM-1 and CDMM-2. It enters them through STOEP. Emergent properties united in STOEP reflect the result of the relationships that occur between the elements of innovative complex systems.

Therefore, trial and error in the innovation process associated with innovative complex systems are considered through emergent properties. In addition, decision-makers are given the following possibilities to adapt the results of decision making to the results of the innovation process using CDMM-1 and CDMM-2:

1. Editing the list of emergent properties in MHoQ: adding new, deleting unused.
2. Editing the contents of emergent properties in STOEP: analyzing and adapting listed emergent properties to the needs of decision-makers.
3. Using flexibility opportunities of CDMM-1 and CDMM-2 (see Chapter 2).

The combination of the systems thinking approach, which is the foundation of the proposed decision-making framework, and listed above possibilities to adapt CDMM-1 and CDMM-2 allow considering the uncertainty associated with the innovation process.

4.5. Discussion on TRIZ applicability

Although various methodologies related to the analysis of complex systems are analyzed in the thesis, TRIZ (theory of inventive problem solving) is not mentioned in it. Therefore, an additional question appears of whether these principles can or should be considered for design decision making in complex systems.

TRIZ represents a powerful approach for understanding innovative technical problems. It provides various strategies and tools for searching for inventive solutions to them. The main idea of the approach consists of that various technical problems represent contradictions, the solution to which can be found via identical methods. To find a concrete solution using TRIZ, one performs the following procedure [150]:

1. The problem is converted to the generalized form.
2. The solution to the generalized form is searched from more than 40 simple techniques, paired techniques, more than 76 standards (combinations of techniques), etc. [151]
3. Having found the solution in the generalized form, the concrete problem is solved.

TRIZ provides an appropriate solution for innovative product development and found its application in different companies. A vivid example of a world-level company, where its practices found extensive application for the development of technological innovations is the Samsung corporation [152]. However, this approach deals more with the design process itself through searching for appropriate innovative solutions, but not doing design decision making. No publications were found that use TRIZ as the approach applied to design decision making. Moreover, the applicability of this approach for the high-level design of complex systems like ALTS is under question. The reason for it is that more concrete engineering information may be required for the application of TRIZ. Therefore, the option of using this approach for design decision making for innovative complex engineering systems was not considered in the thesis. However, potentially its elements can be incorporated into the proposed decision-making framework to support design decision making for simple and medium-complexity systems like ARCDS or ILPS. Therefore, the investigation on the applicability of TRIZ was left for future research in the thesis.

4.6. Discussion on the acts of the implementation

The Appendix section presents two acts on the implementation of the constituents of the proposed decision-making framework in two different companies. These documents certify the successful application of the emergence approach and CDMM-1. They claim resulting time savings on the design of IRTA by WARPA and ARCDS by "Digital Petroleum" for ≈ 1 month and ≈ 1.5 months, respectively. There appear three questions associated with this: firstly, what would these organizations do within these time periods if they used traditional decision-making techniques instead of the proposed novel decision-making framework? Secondly, would these companies finally come to the same decision as it turned out to be with the applied emergence approach? Finally, do these organizations continue using the proposed design decision-making techniques based on emergent properties?

There is no precise answer to the formulated above questions. First of all, it should be noted that all these three raised questions are critical for the real understanding of the practical applicability of the proposed decision-making framework. There is also the need to emphasize that the collaboration on Case studies 1 and 2 with the real companies, associated with concept selection for IRTA and ARCDS, was a great success for research. Searching for the industrial partners in the systems engineering project, as the current Ph.D. project was, turned out to be a complicated task. However, as these companies represent innovation-oriented dynamic organizations, they agreed on using elements of the proposed decision-making framework for concept selection of their innovative engineering systems.

The reason for the agreement of these companies was the understanding of the need to search for more effective decision-making techniques. Estimated 1 and 1.5 months of time savings on the design of their innovative engineering systems are their expert judgments. Therefore, these numbers are not mathematically precise. However, they represent the concrete practical value in time savings that experienced these organizations by using the emergence approach and CDMM-1. The result of the initial use of the value decision-making approach for the same tasks in these companies is known and was given in Chapter 3 in the relevant subsections. If these companies did not use the proposed emergence approach or CDMM-1, they would have definitely search for other perspective techniques to improve design decision making techniques. However, it is unknown, whether these organizations would have spent time on doing experiments or data gathering instead.

There is no collaboration with “WARPA” and “Digital Petroleum” on this topic anymore. These companies proceeded from the conceptual design state to preliminary and detailed design stages. Therefore, there is the lack of information, whether the proposed emergence approach and CDMM-1 were additionally applied for other their projects. However, a recent communication with the representatives of “WARPA” and “Digital Petroleum” confirmed the possible use of these techniques in the future projects of these organizations.

4.7. Discussion on using CDMM-1 and CDMM-2 for creating new knowledge

The proposed in the thesis decision-making framework, which includes an ontological model, new decision-making approach, and decision-making models, was presented in the thesis and applied in case studies. As the thesis finishes with the descriptive study phase, it seems that the presented work is more descriptive than predictive. Thus, a question appears on whether it is possible to use the proposed models, CDMM-1 and CDMM-2, to create new scientific knowledge or not.

The raised question is very important for understanding future development paths of the proposed framework. Unfortunately, it does not have a precise answer. On the one hand, STOEP, the emergence approach, CDMM-1, and CDMM-2 are already well developed and are, therefore, described only for their future use in design decision-making purposes. There is already the identified ontological structure of emergent properties. CDMM-1 and CDMM-2 also represent well-formed sequences of decision-making phases. From this point of view, these models (as well as the whole proposed decision-making framework) can be used only for descriptive studies and do not create new knowledge. On the other hand, the proposed ontology of emergent properties allows adding modifications, the developed decision-making models are flexible (see 2.5. Flexibility of combined decision-making models) and allow "experimenting" with their different constituents. From this point of view, CDMM-1 and CDMM-2 (as well as the whole proposed decision-making framework) to some extent can be used for prescriptive studies and create new knowledge. However, on this occasion, the new knowledge is limited and represented by new data on models' optimization, statistics on the efficiency of model performance, usability of new elements, etc.

Thus, the following statement can be formulated to answer the raised question: it is possible to use the proposed models, CDMM-1 and CDMM-2, to create new scientific knowledge but only within certain boundaries. The new data that is possible to obtain using these models represent new knowledge of "incremental" nature.

4.8. Discussion on the decision quality chain

CDMM-2 incorporates the decision quality chain (Figure 23) in its Phase 4 “Decision assessment.” How does it help to improve the decision-making process?

The answer to the raised question can be concluded from the same literature source, from which the decision quality chain was taken. It is the book on making decisions for the oil and gas industry “Making good decisions” by Bratvold and Begg, where the authors provided the explanation of the framework for evaluating the quality of decisions by Matheson and Matheson [24,129]. The reason for using this framework (and the decision quality chain as its key part) is to ensure that good decisions were made as a result of the performed decision-making process. The explanation of the term “good decision” as given by Bratvold and Begg was mentioned in the Introduction section of the current thesis [24].

The understanding of whether a good decision was made appears as a consequence of using the decision quality chain. This understanding allows evaluating the efficiency the performed decision-making process and, hence, facilitates its improvement.

4.9. Discussion on emergent properties relating to innovativeness or complexity

It is not clear, which of the emergent properties relate to innovativeness and to complexity, and how novelty and complexity are addressed by turning them into requirements.

This question was partially answered in Chapter 2: innovativeness is distributed between strategic-level emergent properties, and complexity is distributed between engineering-level emergent properties (see subsection 2.2.1.). Novelty (innovativeness) and complexity are not addressed by turning emergent properties into requirements. Emergent properties just serve as “requirements” in decision-making models similar to values. Innovativeness and complexity are addressed via the principle of complementarity, when their complementarity is considered via emergence using emergent properties (see subsection 2.2.1.).

CONCLUSION

This thesis was devoted to researching possibilities of using emergent properties for design decision making in technological innovations. It focused on technological innovations of new complex systems, also called innovative complex systems, as the research object and design decision making for concept selection of such systems as the research subject. Considering the close relationship between concept and architecture as described by Crawley et al., architecture selection was also included in the thesis [4]. The relevance of the research topic consisted of correlating with the innovation policy for the strategic development of the Russian Federation, the global trend of the increasing complexity of engineering systems, the need to save energy resources, and the tendency of favoring a good-level understanding of decision-making methodology by decision-makers [2,3,9,10].

The thesis raised the current-day engineering problem that the development of successful innovative complex engineering systems must be based on design research methods and requires considering their innovativeness and complexity. It proposed the solution to adapting design decision-making techniques to innovative complex systems based on using emergent properties. This thesis aimed to develop and approbate the modified decision-making approach for good concept selection of innovative complex systems from systems engineering and systems analysis positions. By "good concept selection," the type of concept selection design decision that leads to the development of successful complex systems was assumed. Successful complex systems were defined by Crawley et al. as systems in which anticipated emergent properties occur [4]. Overall, the dissertation's research focus fell within systems engineering and systems analysis fields of knowledge, including the key aspects of complex systems design and touching on elements of the innovation theory.

The text of the thesis was built the following way: firstly, research clarification and clarification of the core research-related terms were provided. The more profound understanding of research-related terms allowed identifying keywords for the subsequent literature search. Secondly, the specific literature review of design decision-making techniques and tools applied and applicable to technological innovations was prepared. It used the literature search and allowed identifying the value approach as the most successful contemporary decision-making approach. Thirdly, STOEP was developed, and the emergence approach was formulated. STOEP allows structuring emergent properties and considering the link between emergent properties and values. The emergence approach enables to reach values through emergent properties for design decision making and consider the combination of innovativeness and complexity as complementary features of innovative complex systems. Finally, CDMM-1 and CDMM-2 were developed and successfully tested on case studies from the oil and gas industry. They represent decision-making process-based models that serve as the means for the practical application of the emergence approach. The oil and gas industry was selected as an example of a domain intensively incorporating technological innovations of national and global significance. Clarification of the core research-related terms and the specific literature review were united in Chapter 1. The development of STOEP, formulation of the emergence approach, and development of CDMM-1 and CDMM-2 constituted Chapter 2. Chapter 3 described the combined application of STOEP, the emergence approach, CDMM-1, and CDMM-2 in four case studies. Findings, recommendations, and further development prospects of the research topic were left for the conclusion.

The dissertation's research followed the design research methodology by Blessing and Chakrabarti [33]. This type of methodology was selected due to the solid credibility of the source and the proven successful applications by the leading researchers in the field. According to it, the research was divided into the research clarification, descriptive study I, prescriptive, and descriptive study II stages. Research clarification was distributed between the Introduction and clarification of the core research-related terms from Chapter 1. The specific literature review covered the descriptive study I stage. Chapter 2 and Chapter 3 described the prescriptive and descriptive study II stages of research, respectively. Case studies from Chapter 3 contained similar internal stages of research of their own. The dissertation's research complied with the type of design research primarily based on the literature review and proposing an initial or comprehensive practical application depending on a particular case study. The formulated research question demanded replying, how to modify existing design decision-making techniques and tools using emergent properties for good concept selection of innovative complex systems. The thesis answered this question by identifying the value approach as the most successful one, proposing STOEP, the emergence approach, CDMM-1, and CDMM-2, and applying them in case studies. It proposed the following four scientific contributions, which demonstrated their success in case studies:

1. The systems thinking ontology of emergent properties for complex systems (STOEP). It represents an ontological model that is based on analyzing the semantics and relationships of emergent properties, uses the systems thinking approach, unites strategic and engineering-level emergent properties, and considers the link between emergent properties and values. STOEP can be used as a separate decision support tool.
2. The emergence approach to design decision making. It is based on reaching values via emergent properties and uses STOEP as instrumentation. It includes the principle of complementarity for design decision making in innovative complex systems as a theoretical background, which reflects the possibility to consider the combination of innovativeness and complexity through emergence using emergent properties.
3. Level-one combined decision-making model (CDMM-1). It represents the realization of the emergence approach and design decision making using emergent properties. The model consists of six stages and applies various decision-making techniques. CDMM-1 assumes relating stakeholder needs only to one type of emergent properties.
4. Level-two combined decision-making model (CDMM-2). It represents the modernization of CDMM-1 and includes four phases, three from which are QFD-based. CDMM-2 allows relating stakeholder needs to several types of emergent properties.

During the research the following tasks, constituting scientific novelties of the thesis, were fulfilled for the first time: emergent properties were used for design decision making in complex systems (enhancing the applicability of HoQ for the conceptual design stage) and served as its foundation, systems thinking was used as the primary approach of the developed ontology for complex systems, HoQ was modified for making design decisions in complex systems based on emergent properties, and the principle of complementarity for design decision making in innovative complex systems was formulated.

The following main findings have been made from the dissertation's research:

1. The value approach was identified as the most successful contemporary decision-making approach. It relates both to systems engineering and systems analysis and is applicable to design decision making in technological innovations of new products and systems, including innovative complex systems.
2. Emergent properties in complex systems can be structured into two levels through the ontological model based on systems thinking, named STOEP. STOEP demonstrates the link between emergent properties and values, making it possible to modify the value decision-making approach via this link using the ontology as instrumentation.
3. Good concept selection of innovative complex systems can be achieved through considering their innovativeness and complexity. It needs the formulated principle of complementarity for design decision making in innovative complex systems that reflects the possibility to consider the combination of innovativeness and complexity as complementary features of innovative complex systems using emergent properties.
4. It is possible to apply the modification of the value approach, which uses emergent properties to consider the combination of innovativeness and complexity in innovative complex systems, named the emergence approach. However, it requires decision sup-

port in the form of decision-making processes or models. Two decision-making models were developed and tested in the thesis: CDMM-1 and CDMM-2. Their core consists of MHoQ that represents the incorporation of STOEP into HoQ.

The following recommendations could be given for future research: firstly, it is recommended to search for proof of the formulated principle of complementarity for design decision making in innovative complex systems. Secondly, further modification of STOEP by including sustainability in its strategic-level emergent properties can be considered. Although sustainability was previously included in ilities, nowadays, it becomes important for the strategic goals of systems and organizations development [153]. In addition, various ontology development methodologies can be applied for emergent properties to compare the results, and Protégé can be used as an ontology-building tool. Thirdly, enhancing types of design decisions, to which the emergence approach could be applied, is recommended. There is the potential of applying emergent properties for design decision making at other design stages than only for the conceptual design stage. Fourthly, only one-level expert interviews were applied for ambiguity and uncertainty mitigation in CDMM-1 and CDMM-2. It is recommended to consider additional techniques of mitigating ambiguity, uncertainty, and associated risks in these decision-making models. For instance, concepts of VOI (value of information) and VOF (value of flexibility), described in detail by Bratvold and Begg, could be used for this [24]. Fifthly, it is recommended to consider artificial intelligence techniques for enhancing the possibilities of CDMM-1 and CDMM-2, which constitutes the primary future research direction. Finally, additional case studies from various industries can be conducted and TRIZ applicability for additional decision support can be tested.

There were global non-engineering factors that influenced the oil and gas industry in the Russian Federation in 2022. If their influence is critical for decision makers, the flexibility of developed models allows to consider them by adapting the selection of emergent properties, re-considering weights of emergent properties, and changing alternatives.

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Appendix A: Act on the implementation by "WARPA"

September 3rd, 2021

WARPA (World Advanced Research Project Agency), a company, *SASU*, duly organized and existing under the law of France, registered on the RCS Toulouse under the number 843 654 187, having its registered office at 30 chemin Boudou. 31200 Toulouse. France. Duly represented by Jean-François Geneste, acting in his capacity as CEO

ACT
on the implementation of the dissertation results
of the Space Center Ph.D. student of Skolkovo Institute of Science and Technology
Mikhail Yurievich Nikolaev

The current act confirms that the "World Advanced Research Project Agency" (WARPA) applied the emergence approach from the dissertation by Mikhail Yurievich Nikolaev on the topic of "Concept selection of innovative complex engineering systems considering systems emergent properties" for concept selection of the hull envelope subsystem for the innovative robotized tropospheric airship (IRTA) in June-July 2021, which resulted in reducing the time of its design by 1 (one) month.

IRTA represents the all-weather flight vehicle that supports operations in oil and gas fields from hard-to-reach locations. Its hull envelope constitutes a subsystem of critical significance, which required preliminary concept selection. "WARPA" experienced problems in distinguishing a broad list of values for this purpose. Due to the innovativeness of IRTA, systems emergent properties through systems thinking ontology of emergent properties were considered instead. Implementation of the emergence approach and the ontology, which was used as instrumentation, allowed selecting the most appropriate textile for the hull envelope. "WARPA" confirms the willingness of applying the emergence approach for concept selection of innovative medium-complexity and complex engineering systems as an alternative to the value decision-making approach in cases of necessity.

Jean-François Geneste

Appendix B: Act on the implementation by “Digital Petroleum”

Digital Petroleum

Limited liability company

«Digital Petroleum»

121205, Moscow, The territory of the Skolkovo Innovation Center, Nobel Street 3, room 208

PSRN 1197746001265 TIN/IEC 9731021267/773101001

Tel.: +7 495 280-14-81 ext. 3512

Approved by
General director
LLC «Digital Petroleum»

/D.A. Koroteev
«31» March 2021

ACT

on the implementation of the dissertation results
of the Space Center Ph.D. student of Skolkovo Institute of Science and Technology
Mikhail Yurievich Nikolaev

Commission of LLC “Digital Petroleum” consisting of:

Chairman of the commission: D.A. Koroteev

Members of the commission: D.M. Orlov, E.E. Baraboshkin

drew up the current act on that the following results of the dissertation by Mikhail Yurievich Nikolaev on the topic of “Concept selection of innovative complex engineering systems considering systems emergent properties” were implemented in the practice of developing new petrophysical systems by LLC “Digital Petroleum”:

Systems thinking ontology of emergent properties is used as one of the methods of analyzing customer needs to new digital petrophysical systems;

The emergence approach for concept selection of future digital petrophysical systems is used as the alternative to the value decision-making approach in cases of developing systems with the significant innovation component.

At the end of 2020 – beginning of 2021, the systems thinking ontology of emergent properties and the emergence approach were successfully applied to approve concept selection of automated rock core description systems (ARCDS) via the combined decision-making model №1 (CDMM-1), which allowed reducing the development time of ARCDS by 1.5 months.

General director of LLC “Digital Petroleum” /D.A. Koroteev/

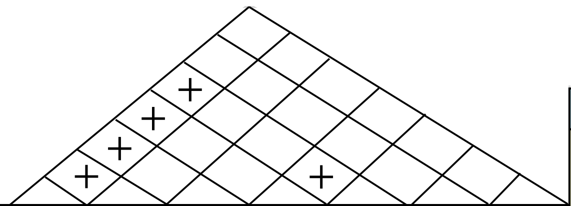
Development director of LLC “Digital Petroleum” /D.M. Orlov/

Senior specialist in machine learning /E.E. Baraboshkin/

Appendix C: Phase 2 of CDMM-2 for Case study 4

№	Stakeholder needs	Weight, *WSN*	Types of emergent properties								Evaluation of needs		
			Function	Performance	Ilities	Cost	Emergency	Benefit	Knowledge	Elegance	Might have	Should have	Must have
1	System detects kerogen	0.1	0.9	0.1					0.1		+		
2	System detects bitumen	0.5	0.9	0.1					0.1			+	
3	System detects liquid oil	1.0	0.9	0.5		0.1		0.9	0.5				+
4	System separates HC phases	1.0	0.9	0.1				0.5	0.1				+
5	System detects bound water	0.5	0.9	0.1				0.5	0.1			+	
6	System detects free water	0.5	0.9	0.5		0.1		0.9	0.5			+	
7	System separates bound from free water	1.0	0.9	0.1				0.5	0.1				+
8	System separates HC from water	1.0	0.9	0.5					0.5				+
9	System produces min 3 measurements per 24 hours	0.5	0.5	0.9	0.1			0.5				+	
10	System exhibits max ±10% measurement error	1.0	0.5	0.9	0.1			0.5	0.1				+
11	System uses cylindrical samples	1.0	0.1	0.5	0.9								+
12	System avoids damage of samples	1.0			0.1	0.1	0.9	0.9					+
13	System avoids injury to operator	1.0			0.1	0.1	0.9						+
14	System allows domestic maintenance	0.5			0.9	0.9				0.1		+	
15	System obtains data for reserves estimation	1.0	0.1		0.5	0.5			0.9				+
16	System allows no outsourcing of measurements	0.5	0.1		0.5	0.9				0.1		+	
17	System accepts broad qualifications of operator	0.5			0.1	0.9						+	
18	System embodies quality, low apparent complexity	0.5				0.5		0.1		0.9		+	
	Weight of emergent property, *W*		0.33	0.19	0.14	0.14	0.10	0.24	0.14	0.03			

Appendix D: Phase 3 of CDMM-2 for Case study 4



№	Types of emergent properties	Clarification	Weight, *W*	Alternatives A1	A2	A3	A4	A5	A6	A7
1	Function	Evaluate liquid saturation	0.33	0.75	0.9	0.9	0.5	0.5	0.5	0.5
2	Performance	Performance-efficiency	0.19	0.9	0.5	0.5	0.1	0.1	0.9	0.9
3	"Ilities"	Operability, usability, etc.	0.14	0.9	0.75	0.5	0.5	0.1	0.5	0.5
4	Cost	Cost-efficiency	0.14	0.9	0.5	0.5	0.1	0.1	0.9	0.9
5	Emergency	Damage, exploitation problems (avoid)	0.10	0.9	0.9	0.5	0.5	0.5	0.1	0.5
6	Benefit	Income (financial or other)	0.24	0.9	0.9	0.9	0.1	0.1	0.5	0.5
7	Knowledge	Obtain data for reserves estimation	0.14	0.75	0.9	0.5	0.9	0.5	0.5	0.5
8	Elegance	A sense of quality, low apparent complexity	0.03	0.9	0.9	0.5	0.5	0.1	0.5	0.5
		Decision value, *DV*		1.10	1.02	0.88	0.48	0.36	0.74	0.78
		Priority		1	2	3	6	7	5	4

Emergent property	Function	Performance	"Ilities"	Cost	Emergency	Benefit	Knowledge	Elegance
1	●							
2		●						
3			●					
4				●				
5					●			
6						●		
7							●	
8								●
Value	Immediate	Immediate	Life-cycle	Life-cycle	Unanticipated	Economic	Educational	Overall

Appendix E: Phase 4 of CDMM-2 for Case study 4

Index	Alternatives	Dimensions of decision quality, grades						Dimensions of decision quality, %					
		Helpful frame	Creative alternatives	Useful information	Clear values	Sound reasoning	Commitment to follow through	Helpful frame	Creative alternatives	Useful information	Clear values	Sound reasoning	Commitment to follow through
A1	Conventional 2 MHz NMR-analyzers	5	4	5	5	4	5	100	80	100	100	80	100
A2	Combination of conventional, designed for tight rocks 2 MHz NMR-analyzers	5	5	4	5	4	3	100	100	80	100	80	60
A3	Combination of low-field NMR-analyzers at different magnetic frequencies	5	4	4	5	4	3	100	80	80	100	80	60
A4	Combination of low and high-field NMR-analyzers	5	5	4	5	3	1	100	100	80	100	60	20
A5	Combination of low-field, high-field, and ^{23}Na NMR-analyzers	5	5	3	5	3	1	100	100	60	100	60	20
A6	Combination of retorts and Dean-Stark extractors	5	1	5	5	3	3	100	20	100	100	60	60
A7	Combination of electrical resistivity and dielectric permittivity meters	5	3	5	5	3	3	100	60	100	100	60	60