DR.01 DOCTORAL THESIS PROPOSAL APPLICATION[1]	
DOCTORAL CANDIDATE	
First and last name:	Zvonimir Lipšinić, mag. ing. mech.
Registration number:	35003393
Address:	Zajačko Selo 34, 47280 OZALJ, Croatia
Phone / mobile number:	00385913038791
E-mail:	zvonimir.lipsinic@fsb.unizg.hr
GENERAL INFORMATION ABOUT THE STUDY PROGRAMME	
Institution responsible for organizing the studies:	University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture
Name of study programme:	Mechanical Engineering, Naval Architecture, Aeronautical Engineering, Metallurgical Engineering
Name of partner institution *(in case of dual doctorate)***:**	/
Name of doctoral study programme at partner institution *(in case of dual doctorate)***:**	/
Area / field / branch *(if the doctoral study programme is performed within a branch)***:**	Engineering / Mechanical Engineering / General Mechanical Engineering (Design)
Form amended after public thesis defence proposal:	☐ yes X no
CV OF DOCTORAL CANDIDATE	
Education *(chronologically, most recent first)***:**	10/2022 - Present Postgraduate Doctoral Study, Major: Theory of Structures University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture Scientific field: Technical Sciences, Discipline: Mechanical Engineering, Branch: General Mechanical Engineering 3/2019 - 7/2021 Graduate Study, Major: Mechanical Engineering, Specialization: Design and Product Development University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture 9/2015 - 3/2019 Undergraduate Study, Major: Mechanical Engineering, Specialization: Design and Product Development University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture 9/2011 - 6/2015 Four-Year Vocational Education, Major: Mechatronics Technician Polytechnic School Karlovac

[1] Please rename file as: DR.01 – *Last_Name_First_Name of doctoral candidate*.pdf
Forward the completed and signed DR.01 form to the appropriate Student Office in digital and print format.

Work experience *(chronologically, most recent first)*:	10/2022 - Present Teaching and Research Assistant University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture 9/2021 - 10/2022 Technology and Development Engineer Flammifer Ltd.
List of papers and active participation in scientific conferences or publicly presented artistic works:	Lipšinić, Zvonimir; Husung, Stephan; Pavković, Neven; Weber, Christian; Supporting circular economy strategies for design of sustainable mechatronic systems using MBSE; Proceedings of the Design Society,4,2645-2654,2024,Cambridge University Press Martinec, Tomislav; Valjak, Filip; Horvat, Nikola; Goudswaard, Mark; Ege, Daniel Nygård; Ballantyne, Robert; Berg, Martin Francis; Glaser, Tobias; Grosse, Cornelius; Lipšinić, Zvonimir; Virtual design hackathons: a data collection framework; Proceedings of the Design Society,4,,45-54,2024,Cambridge University Press Lipšinić, Zvonimir; Pavković, Neven; Integrating life cycle assessment in model-based systems engineering;Engineering for a Changing World: Proceedings 60th ISC, Ilmenau Scientific Colloquium, Technische Universität Ilmenau, September 04-08, 2023

DOCTORAL THESIS TITLE PROPOSAL

Thesis language	English
Title in Croatian	Integracija SysML modela s grafovima znanja za poboljšanu analizu funkcionalne sigurnosti u razvoju održivih sustava
Title in English	Integrating SysML models with knowledge graphs for enhanced functional safety analysis in development of sustainable systems
Title in the language of the doctoral thesis *(if not Croatian or English)*:	/

PROPOSED MENTOR(S)

(specify additional mentor in case of interdisciplinary research or other reason for dual mentorship)

	Full name, title:	**Institution, country:**	**E-mail:**
Mentor:	Prof. dr. sc. Neven Pavković, dipl. Ing.	University of Zagreb Faculty of Mechanical Engineering and Naval Architecture, Croatia	neven.pavkovic@fsb.unizg.hr
Mentor:	/	/	/

MENTOR'S COMPETENCES

Mentor	*List of up to five published relevant works in the past five years*	Lipšinić, Zvonimir; Husung, Stephan; Pavković, Neven; Christian, Weber: Supporting circular economy strategies for design of sustainable mechatronic systems using MBSE, Proceedings of the 18th International DESIGN conference DESIGN 2024; Cambridge University Press; svibanj 2024; DOI: 10.1017/pds.2024.267 Lipšinić, Zvonimir; Pavković, Neven: Integrating Life Cycle Assessment in Model-Based Systems Engineering, Proceedings of the 60th Ilmenau Scientific Colloquium; studeni 2023; DOI: 10.22032/dbt.58905 Škec Stanko, Beccatini Niccolo; Cascini Gaetano: Pavković, Neven: "E-Learning Infrastructure Prototype for Geographically Distributed Project-Based Learning", Proceedings of the 16th International DESIGN conference DESIGN 2020; Cambridge University Press; svibanj 2020, pp.

		1667-1676, DOI: 10.1017/dsd.2020.282 Juranić, Jasmin, Pavković, Neven, Jurinić, Dominik: "Management of design iterations on coupled parameters in design teamwork using multiple domain matrix and Coloured Petri Nets", Proceedings of the 16th International Design Conference (DESIGN 2020), Cambridge University Press; svibanj 2020, (pp. 617-626). DOI:10.1017/dsd.2020.264
Mentor	*List of up to five published relevant works in the past five years*	/

JUSTIFICATION FOR DUAL MENTORSHIP

/

THESIS TOPIC OUTLINE

Summary in Croatian *(max 1000 characters with spaces)***:**	Inženjerstvo sustava na bazi modela (MBSE) je učinkovita metodologija za razvoj kompleksnih sustava jer omogućuje strukturirano modeliranje (pomoću SysML-a) i rano prepoznavanje potencijalnih problema putem analiza i simulacija. Analize provedene tijekom razvojnog procesa rezultiraju znanjem koje čini temelj za donošenje konstrukcijskih odluka. Literatura ističe kako pravilno zapisivanje i korištenje tog znanja može značajno doprinijeti procesu konstruiranja. Analize funkcionalne sigurnosti pritom su iznimno zahtjevne i podložne pogreškama. Ipak, integracija SysML modela sustava i zapisa znanja u svrhu poboljšanja tih analiza još uvijek nije dovoljno istražena. Stoga je cilj ovog istraživanja razviti teorijski okvir koji će objasniti i omogućiti integraciju modela sustava i zapisa znanja, u kontekstu funkcionalne sigurnosti. Dodatno, istraživanje ima za cilj razviti metodu za mjerenje indikatora kvalitete analize funkcionalne sigurnosti u takvom integriranom okruženju.
Summary in English *(max 1000 characters with spaces)***:**	Model-Based Systems Engineering (MBSE) is an effective methodology for developing complex systems, enabling structured modeling (using SysML) and early identification of potential errors through analysis and simulation. Analyses performed during the development process result in knowledge that supports design decision making. The literature highlights that the correct recording and use of this knowledge can significantly contribute to the design process. Functional safety analyses are extremely demanding and error-prone. However, the integration of SysML models and knowledge records to improve these analyses has not yet been sufficiently explored. Therefore, the aim of this research is to develop a theoretical framework that will explain and enable the integration of system models and knowledge records in the context of functional safety. In addition, the research aims to develop a method for measuring quality indicators of functional safety analysis in such an integrated environment.

Introduction and overview of prior research *(suggested length: 7000 characters with spaces)***:**

The trend of developing modern products as mechatronic or cyber-physical systems is significantly increasing. Such development integrates mechanical, electrical, and software domains into tightly coupled architectures. This integration creates complex interdependencies across system levels and lifecycle stages. Non-linear interactions and emergent behavior further complicate the development process, requiring a holistic, systems thinking [1] approach to product design and analysis. At the same time, sustainability has become a critical requirement in engineering, driven by increasing regulatory pressure and stakeholder demand for environmental accountability [2]. As a result, sustainability considerations must be embedded into the earliest phases of development. Initial research was focused on such sustainability considerations, resulting in a case study of a complex product lifecycle analysis [3]. Furthermore, emerging business models such as leasing and product-as-a-service require systems that are not only durable and adaptable but also designed for long-term value retention [4].

In response to the need for sustainable products and extended life cycles, the Circular Economy (CE) offers a strategic framework for development that promotes narrowing, slowing, and closing resource loops [5]. These strategies are realized through R-strategies such as reuse, remanufacturing, and recycling, each introducing additional complexity to the design process. Initial research has investigated

the CE implementation which requires system-level considerations across multiple lifecycle paths, including product updates, reused components, component compatibility and degraded subsystems [6]. Circular systems, however, present unique and less explored safety challenges. Such systems are commonly subjected to changes in their architecture through the application of R-strategies. Changes in the architecture may lead to new unintended emergent behavior. The reuse or remanufacturing of components also introduces risks associated with degradation, component compatibility and altered interfaces [7]. The literature indicates that new technologies, such as Digital Twins (DT) [8] can improve sustainability. In the context of CE, DT based monitoring can reduce uncertainties regarding system states by enabling more precise degradation estimations. The reduction of such uncertainties also has an impact on reverse logistics [9]. Ensuring safety over multiple system's lifecycle iterations is particularly demanding, especially when systems evolve through upgrade or reuse. In such cases, when periodic exchanges of system components are executed for the purpose of increasing sustainability, the demand for functional safety reevaluation becomes evident. Current design practices offer limited methods for addressing safety validation in such dynamic and uncertain CE scenarios. Traditional safety assessment methods, such as Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA), and System Theoretic Process Analysis (STPA) remain the industry standard but are typically manual (labor-intensive), document-based, and prone to human errors [10]. Such analyses are typically disconnected from the system model. These practices are often inefficient and poorly suited to capture evolving system configurations or trace risks across newly created product variants (architectures). Consequently, there is a growing need for integrated, model-based approaches that support traceability, knowledge reuse, and lifecycle-aware functional safety assessment.

Model-Based Systems Engineering (MBSE) has emerged as a promising methodology to manage the complexity of modern product development [11]. The International Council on Systems Engineering (INCOSE) defines MBSE as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation (V&V) activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases." The MBSE methodology is based on three pillars: the modeling approach (method), the modeling language, and the supporting tool environment. SysML [12], a widely adopted semi-formal modeling language, enables structured representations of system structure, behavior, requirements, and parameters. Modeling approaches such as MagicGrid [13] provide a structured process for development which includes key engineering processes like requirements engineering, architecture definition, and validation and verification. Meanwhile, MBSE tools offer environments for model creation, variant and configuration management, and integration with simulation, database, and lifecycle tools. In addition to supporting system development, MBSE can also embed safety assessment directly into the system model [14]. Using SysML diagrams, designers can represent risk sources [15], propagation paths [16], and mitigation strategies as part of the system architecture. This enables traceability between hazards, safety requirements, and specific components, ensuring that safety is considered from the earliest design stages. Such practices also lay the groundwork for automation and tighter integration with simulation and testing workflows, enabling more efficient, consistent, and proactive functional safety analysis (FSA) and validation.

The conducted systematic literature review revealed a significant increase in research papers addressing the integration of safety analysis with the MBSE methodology. In the past, a major part of the literature addressed the problem of transforming system models into safety models with the purpose of enabling safety experts to complete the safety analysis. Model Based Safety Assessment (MBSA) coupled with MBSE provides a way to integrate such models without the need for transformations [17]. The trade-off in this case is that safety experts now need to acquire SysML modeling skills in order to effectively perform analyses within the new environment. Therefore, research has further aimed at automating such MBSA processes [18]. The goal is to reduce the effort needed for MBSA, while also reducing potential errors, resulting in an overall shorter development cycle and increased competitiveness and system reliability. When considering the periodic changes of systems under the influence of R-strategies, the duration of each development cycle has an impact on the overall product success. Especially when stricter safety regulations are asserted on the system specification. Approaches to assess the quality of the conducted safety analysis have been explored. For example, authors in [19] use the general IQ-framework presented in [20] to evaluate the FMEA outputs on an information content level. On the other hand, the author in [21] defines FMEA quality objectives that can be used as evaluation criteria, e.g. the FMEA outputs should result in actionable, design driving recommendations. In general, terms such as completeness (both in the identification of risks and their causes) and consistency (regarding to the values for severity, detectability, occurrence) have been used to describe risk assessment outputs. Literature [22] states that one way of increasing the efficiency of functional safety analyses is with the utilization of expert knowledge. Explicit safety related knowledge lies in both system and safety models. In most cases, legacy documentation (e.g. FMEA tables) from previous projects include useful knowledge. The challenge that remains with the reuse of such knowledge is the heterogeneous structure of the knowledge and the distribution of sources. A framework to harmonize such knowledge into searchable databases is required. Knowledge graphs (KG) provide a solution for this challenge [23]. In addition to the harmonization benefit, KG enable flexible search options and advanced reasoning based on asserted rules. The reasoning capabilities of KG, which are currently not supported with MBSE tools, enable the creation of new knowledge by discovering new (previously not known) relations between knowledge or system elements. Such newly created reasoning paths and relations cannot be directly extracted from the SysML models. The application of KG in MBSE has been explored by Faheem et al. [23] and Schummer et al. [24]. This application was also further investigated in collaboration with the authors from [23] during a research visit. The current joint research efforts demonstrates the transformation of SysML models into KG and the feasibility of advanced searches through SPARQL queries. During the collaboration, the feasibility of transforming safety information stored in legacy documentation has been investigated and confirmed. This research addresses the challenge of recurring functional safety reassessment in evolving system architectures shaped by R-strategies. The originality lies in developing an integrated framework that connects SysML-based system models with graph-based knowledge records to enhance reasoning and knowledge reuse. Additionally, by defining and applying measurable quality indicators, the research aims to measurably improve the quality of functional safety analyses in complex technical systems.

Objective and research questions and/or research hypotheses[2] *(suggested length: 700 characters with spaces)*:

Objectives:

1. Develop a theoretical framework that defines how system models created using MBSE tools (SysML) can be systematically integrated with knowledge records stored in graph databases, supporting enhanced reasoning and reuse during functional safety analysis (FSA). This integration should provide a valuable complement enabling more comprehensive and error-resilient FSA.
2. Determine quality indicators (such as completeness, risk reduction measures, increased traceability, error reduction) of the functional safety analysis of a system in development processes based on the MBSE approach. Develop a method for measuring the determined indicators.
3. Validate the proposed integration framework of SysML-based system models and knowledge records through a case study involving the development of a complex technical system requiring frequent functional safety reassessments. The validation will include qualitative (expert knowledge) and quantitative (performance) metrics.

The hypothesis of the described research is:

The integration of SysML models of complex technical systems and knowledge record elements (stored in graph databases) will improve the quality indicators of the system functional safety analysis.

Materials, participants, methodology and research plan *(suggested length: 6500 characters with spaces)*:

The purpose of this research is to improve the quality of functional safety analysis of complex technical systems through the integration of system model elements realized with MBSE tools (and the SysML programming language) and knowledge records stored in graph databases. A prerequisite for this is a theoretical understanding of the functional safety analysis process in the context of a development process based on the MBSE approach. This process concerns the development of complex technical systems that require periodic functional safety analysis. Another prerequisite for improving the functional safety analysis quality is the understanding of the quality indicators and the ways in which they are measured and quantified. The research will integrate the general methodology of design research (Design Research Methodology) [25], the Design Science Research framework [26], and the principles of Experimental Design Research [27], organized into four main phases: Research Clarification, Descriptive Study I (including a systematic literature review and preliminary empirical studies), Prescriptive Study (which proposes a theoretical model and measuring method), and Descriptive Study II (which validates the developed theoretical model and method).

Research clarification

The initial phase, aimed at defining the research objective, includes a review of literature related to model-based systems engineering (MBSE) methods and models, with an emphasis on the functional safety analysis processes. This includes analysis of the development process of sustainable complex technical systems. Furthermore, the literature review in the area of knowledge records involves researching methods for creating, manipulating, and using knowledge records in various forms. The research will primarily focus on knowledge records stored in graph databases (knowledge graphs), though other potentially suitable forms for integration will also be explored. The literature review also includes the current state of implementation of the studied methods and the realization of system models and knowledge records using software tools and languages. In this phase, available (academically licensed) tools were used, including CAPELLA, CATIA Systems of Systems Architect, Protege and Ontograph TextDB. This phase is crucial for acquiring competencies in modeling complex systems and knowledge graphs, which will enable a better understanding of the current state and implementation possibilities while also enabling the future validation of the proposed research. A comprehensive review of the stated fields is essential for setting research objectives, questions, and hypotheses.

Descriptive Study I

Descriptive Study I expands upon the knowledge gained from the initial literature review in the first phase of the research, which defined the research objectives. The goal of this second phase is to deepen the understanding of the acquired knowledge by investigating more specialized literature through a systematic literature review and conducting preliminary experimental studies. The purpose is to further confirm the possibilities for integrating system models realized using MBSE tools and knowledge records in the context of functional safety analysis, and to identify quality indicators of the analysis. This phase also includes the exploration of various metrics, methods, methodologies, and tools for measuring the identified indicators. A combination of quantitative and qualitative research methods will be used, including subjective elements such as self-assessment scales, questionnaires, and interviews, as well as approaches related to the performance of specialized functional safety analyses such as Failure Mode and Effect Analysis (FMEA). Furthermore, preliminary

[2] Order of objectives and hypotheses / research questions depends on the field of research.

experimental research will be conducted at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb (UNIZG FAMENA), using the available equipment at the Chair of Design and Product Development (CADLab). The experimental studies will involve students and industry professionals to provide a comprehensive perspective that accounts for various levels of expertise and knowledge of the individuals involved in the research.

Prescriptive Study

The third phase of the research methodology builds on the insights gained in Descriptive Study I. In this phase, the focus is on developing a theoretical model that defines the integration of system models realized with MBSE tools and knowledge records stored in graph databases. The model will reflect the current theoretical understanding and knowledge in the field, including key mechanisms, elements, and influential factors. The theoretical model will serve as a basis for developing a method to measure the identified quality indicators. In addition, the model and method will be key in assessing the improvement in the functional analysis proposed through the integration of the system model and knowledge records. This phase will also consider and propose an implementation process for the integration, with a focus on the necessary transfer and transformation of knowledge records forms based on the previously studied methods and tools in this area. Furthermore, theoretical understanding of the current situation will be used as a foundation for developing experimental studies to validate the developed model and method. The definition of experimental studies will include setting experimental conditions and applying existing frameworks for data collection, processing, and analysis.

Descriptive Study II

The Descriptive Study II represents the final phase of the research. This phase focuses on validating the theoretical model through experimental studies, with the aim of exploring the contribution of the proposed integration in improving the quality indicators of functional safety analysis. In addition to validating the theoretical model, this phase includes testing the developed method for measuring the identified indicators. The validation results will provide insight into the advantages and limitations of the proposed integration, stating opportunities for further improvements. The ultimate goal of this phase is to confirm or refute the main research hypothesis based on the results of the conducted experiment. The outcomes of this research are highly relevant for industry, aiming to reduce both the time and errors in functional safety analysis. This is especially valuable for the automotive sector [28], where complexity and strict safety and sustainability requirements demand more efficient processes.

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Expected scholarly or artistic contribution of the proposed research *(suggested length: 500 characters with spaces)***:**

1. A theoretical framework for integrating (complementing) system models realized through MBSE tools (in the SysML language) with knowledge records stored in graph databases.
2. Definition of the process for integrating SysML models and knowledge graphs with potential for automation within MBSE-compatible tool environments, including guidelines for transforming SysML model elements into a format suitable for representation as knowledge graphs.
3. A method for quantifying key quality indicators (such as completeness, risk reduction measures, increased traceability, error reduction) of the functional safety analysis for systems in development processes based on the MBSE approach.

Cited literature / artistic works *(max 30 references)***:**

[1] R. Jonkers and K. E. Shahroudi, “CONNECTING SYSTEMS SCIENCE, THINKING, DYNAMICS AND ENGINEERING TO SYSTEMS PRACTICE FOR MANAGING COMPLEXITY,” in Proceedings of the 65th Annual Meeting of the International Society for the Systems Sciences, ISSS 2021 - The Art and Science of the Impossible: The Human Experience, 2021.
[2] Z. Lipšinić and N. Pavković, “INTEGRATING LIFE CYCLE ASSESSMENT IN MODEL-BASED SYSTEMS ENGINEERING,” 2023. Accessed: Nov. 10, 2023.
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[4] A. Urbinati, S. Franzò, and D. Chiaroni, “Enablers and Barriers for Circular Business Models: an empirical analysis in the Italian automotive industry,” Sustain Prod Consum, vol. 27, pp. 551–566, Jul. 2021, doi: 10.1016/J.SPC.2021.01.022.
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[9] C. M. Lee, W. S. Woo, and Y. H. Roh, "Remanufacturing: Trends and issues," International Journal of Precision Engineering and Manufacturing - Green Technology, vol. 4, no. 1, pp. 113–125, Jan. 2017, doi: 10.1007/S40684-017-0015-0.
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[11] R. Cloutier, B. Sauser, M. Bone, and A. Taylor, "Transitioning Systems Thinking to Model-Based Systems Engineering: Systemigrams to SysML Models," IEEE Trans Syst Man Cybern Syst, vol. 45, no. 4, pp. 662–674, Apr. 2015, doi: 10.1109/TSMC.2014.2379657.
[12] S. Friedenthal, A. Moore, and R. Steiner, "A Practical Guide to SysML: The Systems Modeling Language, Third Edition," A Practical Guide to SysML: The Systems Modeling Language, Third Edition, pp. 1–606, Jan. 2014, doi: 10.1016/C2013-0-14457-1.
[13] A. Morkevicius, A. Aleksandraviciene, D. Mazeika, L. Bisikirskiene, and Z. Strolia, "MBSE Grid: A Simplified SysML-Based Approach for Modeling Complex Systems," INCOSE International Symposium, vol. 27, no. 1, pp. 136–150, Jul. 2017, doi: 10.1002/J.2334-5837.2017.00350.X.
[14] R. Krishnan and S. V. Bhada, "Integrated System Design and Safety Framework for Model-Based Safety Assessment," IEEE Access, vol. 10, pp. 79311–79334, 2022, doi: 10.1109/ACCESS.2022.3193495.
[15] M. Hecht, A. Chuidian, T. Tanaka, and R. Raymond, "Automated generation of FMEAs using SysML for reliability, safety, and cybersecurity," in Proceedings - Annual Reliability and Maintainability Symposium, 2020. doi: 10.1109/RAMS48030.2020.9153708.
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[17] X. Xu, R. Wei, and H. Wang, "Model-based Automated Safety Analysis Method for Safety-critical System," 2024 5th International Conference on Mechatronics Technology and Intelligent Manufacturing, ICMTIM 2024, pp. 55–59, 2024, doi: 10.1109/ICMTIM62047.2024.10629307.
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[20] M. Helfert and O. Foley, "A context aware information quality framework," 4th International Conference on Cooperation and Promotion of Information Resources in Science and Technology, COINFO 2009, pp. 187–193, 2009, doi: 10.1109/COINFO.2009.65.
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[28] G. Xie, Y. Li, Y. Han, Y. Xie, G. Zeng, and R. Li, "Recent Advances and Future Trends for Automotive Functional Safety Design Methodologies," IEEE Trans Industr Inform, vol. 16, no. 9, pp. 5629–5642, Sep. 2020, doi: 10.1109/TII.2020.2978889.

Total cost estimate of proposed research *(in euros)*:

50 000

Proposed sources of research funding:

Type of funding	Project title	Project leader	Signature
National funding:	Funds of the DATA-MATION project (Croatian Science Foundation)	Prof. dr. sc Mario Štorga	
International funding:	Funds of the DETAILLs project (ERASMUS)	Prof. dr. sc Mario Štorga	
Other project types:	Funds of the Chair of Design and Product Development, FAMENA (industry collaboration, organization of the international DESIGN conference)	Prof. dr. sc Mario Štorga	
Own funds:	/		
Session of Ethics Committee at which consent was given to the research proposal[3]:	/		

Consent of proposed mentor and doctoral candidate to doctoral thesis application proposal

I agree with the submitted thesis proposal.

Signature
(Prof. dr. sc. Neven Pavković, dipl. Ing.)

Signature
(full name of second proposed mentor)

Signature
(Zvonimir Lipšinić, mag. ing. mech.)

DECLARATION

I declare that I did not submit an application for a doctoral thesis with the same topic to a different study programme of the University or to a different university[4].

In Zagreb, on 12.05.2025.
(place and date)

Signature
(Zvonimir Lipšinić, mag. ing. mech.)

Additional comments *(optional)*

[3] Specify only if necessary.
[4] Ignore in case of dual doctorate (*cotutelle de thèse*).