

PAMETNE TOVARNE

UČNI NAČRT PREDMETA/COURSE SYLLABUS

Predmet:	Pametne tovarne
Course title:	Smart Factories
Članica nosilka/UL Member:	UL FS

Študijski programi in stopnja	Študijska smer	Letnik	Semestri	Izbirnost
Strojništvo - Razvojno raziskovalni program, druga stopnja, magistrski	Proizvodno strojništvo (smer)	2. letnik	1. semester	obvezni

Univerzitetna koda predmeta/University course code:	0566844
Koda učne enote na članici/UL Member course code:	6053-M

Predavanja /Lectures	Seminar /Seminar	Vaje /Tutorials	Klinične vaje /Clinical tutorials	Druge oblike študija /Other forms of study	Samostojno delo /Individual student work	ECTS
30		30			65	5

Nosilec predmeta/Lecturer:	prof. dr. Niko Herakovič, doc. dr. Miha Pipan, izr. prof. dr. Marko Šimic
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Izvajalci predavanj:	
Izvajalci seminarjev:	
Izvajalci vaj:	
Izvajalci kliničnih vaj:	
Izvajalci drugih oblik:	
Izvajalci praktičnega usposabljanja:	

Vrsta predmeta/Course type:	Obvezni strokovni predmet na smeri Proizvodno strojništvo, ki je izbirni strokovni predmet na ostalih smereh./Compulsory specialised course in the study of Production Engineering, which is an elective specialised course in other fields of study.
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Jeziki/Languages:	Predavanja/Lectures:	Slovenščina
	Vaje/Tutorial:	Slovenščina

Pogoji za vključitev v delo oz. za opravljanje študijskih obveznosti:	Prerequisites:
Izpolnjevanje pogojev za vpis v Magistrski študijski program II. stopnje Strojništvo - Razvojno raziskovalni program.	Meeting the enrollment conditions for the Master's study programme of Mechanical Engineering - Research and Development program.

Vsebina:	Content (Syllabus outline):
1. Uvod v industrijo 4.0 - Značilnosti industrijskih revolucij - Orodja za povečanje konkurenčnosti tovarne	1. Introduction to Industry 4.0 - Characteristics of industrial revolutions - Tools for the increase of competitiveness of the

- Industrijske in socialne spremembe ter spremembe kompetenc - Definicija pametne tovarne, stanje v svetu na področju pametnih tovarn 2. Opredelitev konceptov pametne tovarne - Digitalizacija in povezana veriga vrednosti - Gonila, omogočitelji in izzivi za I 4.0 - Značilnosti tradicionalne tovarne - Značilnosti pametne tovarne 3. Discipline, sistemi in tehnologije za I 4.0 - Omogočitvene tehnologije I 4.0 - Ključne tehnologije za pametno tovarno - Viri in podatki - Nove tehnologije - Umetna inteligenca 4. Ključni pristopi razvoja pametnih tovarn - Hierarhična struktura - Mrežna – distribuirana struktura - Internet stvari, Industrijski internet stvari in Internet storitev - Vertikalna integracija, horizontalna integracija 5. Ključni pristopi razvoja pametnih tovarn - Pametna proizvodnja, sledljivost in povezljivost preko oblaka - Pametna naprave – M2M komunikacija, pametni izdelki, pametna logistika materiala in informacij - Velepodatki in prediktivna analitika, dinamično planiranje 6. Referenčni arhitekturni modeli pametne tovarne - RAMI 4.0, tri-dimenzijska struktura, značilnosti, povezljivost, prednosti in slabosti - LASFA, dvo-dimenzijska struktura, transparentnost povezljivosti, prednosti 7. Koncepti pametne tovarne - Modularnost, povezljivost - Centralizirani, decentralizirani in distribuirani sistemi - Virtualizacija procesov in sistemov - Vizualizacija proizvodnega plana in aktivnosti - Usmerjenost na kupce in dobavitelje 8. Koncept distribuiranih sistemov - Distribuirani sistemi in njihove značilnosti - Omogočitvene tehnologije distribuiranih sistemov - Povezljivost med objekti in subjekti - Komunikacijski protokoli, delovanje v realnem času, fleksibilnost in agilnost 9. Top-down pristop pri uvajanju rešitev I 4.0 - Razvoj strategije - Implementacija strategije - Ovrednotenje strategije - VDMA Toolbox – proizvodni procesi in izdelki 10. Bottom-up pristop pri uvajanju rešitev I 4.0 - Sedem tipov porat - Dodajanje vrednosti - Pretočni čas, metoda VSM - Delovni cikel in balansiranje proizvodnega procesa - Modeliranje in simulacijski model procesa 11. Koncept digitalnih dvojčkov (DD) proizvodnih	- factory - Industrial and social changes and competency changes - Definition of a smart factory, the global state of the art of smart factories 2. Definition of smart factory concepts - Digitalization and linked-up value chain - Drivers, enablers and challenges for I 4.0 - Features of a traditional factory - Features of a smart factory 3. Disciplines, systems and technologies for I 4.0 - Enabling technologies for I 4.0 - Key technologies for smart factories - Resources and data - New technologies - Artificial intelligence 4. Key approaches to smart factory development - Hierarchical structure - Network - distributed structure - Internet of Things, Industrial Internet of Things and Internet of Services - Vertical integration, horizontal integration 5. Key approaches to smart factory development - Smart production, traceability and connectivity across the cloud - Smart devices - M2M communication, smart products, smart logistics of material and information - Big data and predictive analytics, dynamic planning 6. Referential architectural models of smart factories - RAMI 4.0, three-dimensional structure, features, connectivity, strengths and weaknesses - LASFA, two-dimensional structure, transparency of connectivity, advantages 7. Smart factory concepts - Modularity, connectivity - Centralized, decentralized and distributed systems - Virtualization of processes and systems - Visualization of production plan and activities - Focus on customers and suppliers 8. The concept of distributed systems - Distributed systems and their characteristics - Enabling technologies for distributed systems - Connectivity between objects and subjects - Communication protocols, real-time operation, flexibility and agility 9. Top-down approach when implementing solutions of I 4.0 - Strategy development - Implementation of the strategy - Evaluation of the strategy - VDMA Toolbox - manufacturing processes and products 10. Bottom-up approach in implementing solutions of I 4.0 - Seven types of waste - Adding value - Flow time, VSM method
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procesov pametne tovarne - Definicija, vrste in koncept DD - Pomen DD - Digitalni dvojček v življenjskem ciklu proizvodnega procesa - Izzivi in implementacija v proizvodnem procesu - off-line in on-line simulacija 12. Pet-dimenzionalno modeliranje DD in njegove ključne tehnologije - Tradicionalni tri-dimenzionalni digitalni dvojček - Razširjeni pet-dimenzionalni digitalni dvojček - Ključne tehnologije za modeliranje DD - Osem pravil modeliranja DD 13. Krmiljenje pametne proizvodnje z digitalnim dvojčkom - Koncept krmiljenja pametne proizvodnje z DD in ključne tehnologije, digitalni agenti - Optimiranje porabe energije proizvodnih sredstev - Kibernetško-fizična spojitve v proizvodnji, krmiljeni z DD (fizični elementi, modeli, podatki, storitve) - Prognostika delovanja pametne proizvodnje z DD 14. Digitalni dvojčki (DD) in nove tehnologije - Računanje v oblaku, „Edge computing“ - DD in Velepodatki - DD in storitve - DD in virtualna ter razširjena resničnost - DD in kibernetško-fizični sistemi 15. Pametna tovarna v produktronsko-preoblikovalnih procesih - Arhitekturni model pametne hidravlične stiskalnice, ki bo primerna za integracijo v pametno tovarno - Pametne/inteligentne komponente hidravličnih in pnevmatičnih sistemov - Povezljivost in komunikacija med komponentami in podsistemi stiskalnice, pametna adaptivna orodja - Modeliranje in simulacija stiskalnice kot osnova za digitalnega dvojčka, arhitekturni model digitalnega dvojčka stiskalnice	- Work cycle and the balancing of production process - Modeling and a simulation model of a process 11. The concept of digital twins (DT) of manufacturing processes of a smart factory - Definition, types and a concept of DT - The meaning of a DT - Digital twin in the life cycle of the production process - Challenges and implementation in the production process - off-line and on-line simulation 12. Five-dimensional modeling of a DT and its key technologies - Traditional three-dimensional digital twin - Expanded five-dimensional digital twin - Key technologies for DT modeling - Eight DT modeling rules 13. Control of a smart production with a digital twin - The concept of controlling smart manufacturing with a DT and key technologies, digital agents - Optimization of energy consumption of means of production - Cyber-physical coupling in DT-controlled production (physical elements, models, data, services) - Prognostics of operation of smart production with DT 14. Digital twins (DT) and new technologies - Cloud computing, "Edge computing" - DT and Big Data - DT and services - DT and virtual and augmented reality - DT and cyber-physical systems 15. A smart factory in productronic-transformation processes - Architectural model of smart hydraulic press that will be suitable for integration into a smart factory - Smart/intelligent components of hydraulic and pneumatic systems - Connectivity and communication between components and subsystems of the press, smart adaptive tools - Modeling and simulation of a press as a basis for a digital twin, architectural model of a digital twin of the press
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Temeljna literatura in viri/Readings:

1. Gao, Vincent: Smart manufacturing principles and applications, knjiga, [S. l.: V. Gao], cop. 2021, [COBISS.SI-ID [146626819](#)].
2. Accialini, Nicola: Introduction to the smart factory: and practical tips for its implementation, neleposlovje za odrasle, [S. l.: N. Accialini], cop. 2021, [COBISS.SI-ID [146615043](#)].
3. Groover, Mikell P.: Fundamentals of modern manufacturing: materials, processes, and systems, neleposlovje za odrasle, 7th ed., Hoboken (NJ) : John Wiley & Sons, cop. 2020, [COBISS.SI-ID [146641667](#)].
4. Soloman, Sabrie: Sensors and control systems in manufacturing, priročnik, New York [etc.]: McGraw-Hill, 1994, [COBISS.SI-ID [843291](#)].

5. Abdi, M. Reza: Integrated reconfigurable manufacturing systems and smart value chain: Sustainable infrastructure for the factory of the future, pregledna monografija; neleposlovje za odrasle, Springer, 2018, [COBISS.SI-ID [16110619](#)].
6. Hopkinson, N.: Rapid manufacturing: an industrial revolution for the digital age, neleposlovje za odrasle, Chichester, England; Hoboken, NJ: John Wiley, cop. 2006, [COBISS.SI-ID [11614258](#)].

Cilji in kompetence:

Cilji: 1. Spoznati pomen, osnove in bistvo pametnih tovarn 2. Usvojiti osnovne koncepte in pristope pri koncipiranju pametnih tovarn 3. Spoznati ključne tehnologije I 4.0 in koncept distribuiranih sistemov 4. Usvojiti osnove izdelave digitalnih dvojčkov procesov v pametni tovarni na osnovi modeliranja diskretnih in delno zveznih dogodkov 5. Usvojiti osnove krmiljenja pametnih tovarn s pomočjo digitalnih dvojčkov in digitalnih agentov Kompetence: 1. Sposobnost ocene stopnje digitalizacije obstoječih tovarn 2. Razumevanje konceptov in pristopov pri koncipiranju novih pametnih tovarn ali pri transformaciji obstoječih tovarn v smeri pametne tovarne 3. Razumeti ključne tehnologije I 4.0 in njihovo vlogo ter uporabnost v pametni tovarni 4. Razumevanje in izdelava digitalnih dvojčkov procesov v pametni tovarni na osnovi diskretnih in delno zveznih dogodkov 5. Sposobnost uporabe digitalnih dvojčkov in digitalnih agentov pri krmiljenju pametne tovarne
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Objectives and competences:

Objectives: 1. To know the meaning, basics and essence of smart factories 2. To gain basic concepts and approaches to design of smart factories 3. To learn about key technologies of I 4.0 and the concept of distributed systems 4. To gain the basics of development of digital twins of processes in a smart factory based on the modeling of discrete and partially continuous events 5. To learn the basics of control of smart factories with the help of digital twins and digital agents Competencies: 1. Ability to estimate the level of digitalization of existing factories 2. Understanding the concepts and approaches to designing new smart factories or for transforming existing factories towards a smart factory 3. Understanding the key technologies of I 4.0 and their role and usefulness in a smart factory 4. Understanding and creation of digital twins of processes in a smart factory based on discrete and partially continuous events 5. Ability to use digital twins and digital agents for control of a smart factory
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Predvideni študijski rezultati:

Znanja: Študent pozna in razume: vsebino in poslanstvo pametne tovarne v primerjavi s tradicionalnimi tovarnami. Pridobljena znanja uporabi študent za koncipiranje in načrtovanje procesov v pametnih tovarnah in njihovo povezovanje v celotni koncept pametne tovarne, za učinkovito uporabo tehnologij I 4.0 v pametni tovarni ter za izdelavo digitalnih dvojčkov procesov in celotne pametne tovarne, kakor tudi za krmiljenje celote. Spretnosti: 1. Uporaba orodij za oceno stanja digitalizacije v tradicionalni tovarni 2. Uporaba računalniško podprtih orodij za koncipiranje učinkovite pametne tovarne za različne namene 3. Prepoznavanje uporabnosti tehnologij I 4.0 v pametni tovarni 4. Uporaba simulacijskih orodij za izdelavo digitalnega dvojčka pametne tovarne z različnimi podprocesii
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Intended learning outcomes:

Knowledge: The student knows and understands: the content and mission of a smart factory compared to traditional factories. The acquired knowledge is used by the student to draft and design processes in smart factories and to integrate them into the whole concept of a smart factory, to make effective use of I 4.0 technologies in a smart factory, and to produce digital twins of processes and the entire smart factory, as well as to control the whole system. Skills: 1. The use of tools to evaluate the status of digitization of a traditional factory 2. The use of computer-aided tools for drafting an efficient smart factory for various purposes 3. The recognition of the usefulness of I 4.0 technologies in a smart factory 4. The use of simulation tools for building a digital twin of a smart factory with different subprocesses

Metode poučevanja in učenja:	Learning and teaching methods:
1. P1, P2 Avditorna predavanja podprta z interaktivnim prikazom praktičnih primerov 2. P3 Avditorne vaje z reševanjem praktičnih primerov 3. P4 Laboratorijske vaje s timskim reševanjem aplikativnih problemov in uporabo programske opreme ter njihova predstavitev z razpravo. 4. P5 Uporaba študijskega gradiva v e-obliki, skripta in e-verzija predavanj. 5. P6 Interaktivna predavanja 6. P7 Študij literature in razprava 7. P9 Skupinsko delo	1. P1, P2 Lectures supported by interactive presentation of practical examples 2. P3 Tutorials solving practical examples 3. P4 Laboratory exercises with team solving of application problems, using software and presenting them with discussion. 4. P5 Use of study material in e-form, lecture notes and e-version of lectures. 5. P6 Interactive lectures 6. P7 Literature review and discussion 7. P9 Team work

Načini ocenjevanja:	Delež/Weight	Assessment:
Teoretične vsebine (predavanja, timsko delo): Kolokviji, prezentacija/zagovor timskega dela, pisni in/ali ustni izpit.	60,00 %	Theoretical contents (lectures, team work): Cllouquium, team work presentation/defense, writing and/or oral exam.
Samostojno delo na avditornih in laboratorijskih vajah (vključno s poročili).	40,00 %	Individual work in exercises, individual laboratory work (including reports).

Ocenjevalna lestvica:	Grading system:
5 - 10, pri čemer velja, da je pozitivna ocena od 6 - 10	5 - 10, a student passes the exam if he is graded from 6 to 10

Reference nosilca/Lecturer's references:

Niko Herakovič:

1. RESMAN, Matevž, PIPAN, Miha, ŠIMIC, Marko, **HERAKOVIČ, Niko**. A new architecture model for smart manufacturing : a performance analysis and comparison with the RAMI 4.0 reference model. *Advances in production engineering & management*. Jun. 2019, vol. 14, no. 2, str. 153-165, ilustr. ISSN 1854-6250. http://apem-journal.org/Archives/2019/APEM14-2_153-165.pdf, DOI: 10.14743/apem2019.2.318. [COBISS.SI-ID [16766235](#)]
2. RESMAN, Matevž, DEBEVEC, Mihael, **HERAKOVIČ, Niko**. Using digital twin technology to improve the organization of the supply chain in piece type of production. *Systems*. 2025, vol. 13, issue 7, [article no.] 505, 10 str., ilustr. ISSN 2079-8954. <https://www.mdpi.com/2079-8954/13/7/505>, DOI: [10.3390/systems13070505](#). [COBISS.SI-ID [240994051](#)]
3. ZUPAN, Hugo, **HERAKOVIČ, Niko**, STARBEK, Marko, KUŠAR, Janez. Hybrid algorithm based on priority rules for simulation of workshop production. *International journal of simulation modelling*. Mar. 2016, vol. 15, nr. 1, str. 29-41, ilustr. ISSN 1726-4529. http://www.ijsimm.com/Full_Papers/Fulltext2016/text15-1_29-41.pdf, <http://www.ijsimm.com/Abstracts/Abstracts15-1.pdf>, DOI: 10.2507/IJSIMM15(1)3.319. [COBISS.SI-ID [14542875](#)]
4. DEBEVEC, Mihael, **HERAKOVIČ, Niko**. Digital twin of unique type of production for innovative training of production specialists. V: ZADNIK STIRN, Lidija (ur.), et al. SOR '19 proceedings. Ljubljana: Slovenian Society Informatika, Section for Operational Research, 2019. Str. 245-250, ilustr. ISBN 978-961-6165-55-6. [COBISS.SI-ID [16809499](#)]
5. **HERAKOVIČ, Niko** (avtor, vodja projekta), ZUPAN, Hugo, DEBEVEC, Mihael, PIPAN, Miha. YER - smart factory proposal - i [sup] 3 approach : zaključno poročilo o rezultatih raziskovalno razvojnega dela. Ljubljana: Fakulteta za strojništvo, Laboratorij LASIM, 2018. 12 f., ilustr. [COBISS.SI-ID [16026139](#)]

Marko Šimic:

1. JANKOVIČ, Denis, **ŠIMIC, Marko**, HERAKOVIČ, Niko. A comparative study of machine learning regression models for production systems condition monitoring. *Advances in production engineering & management*. Mar. 2024, vol. 19, nr. 1, str. 78–92, ilustr. ISSN 1854-6250. https://apem-journal.org/Archives/2024/APEM19-1_78-92.pdf, DOI: [10.14743/apem2024.1.78-92](#). [COBISS.SI-ID [259224051](#)]

journal.org/Archives/2024/Abstract-APEM19-1_078-092.html, DOI: 10.14743/apem2024.1.494. [COBISS.SI-ID [201874947](#)]

2. RESMAN, Matevž, PROTNER, Jernej, **ŠIMIC, Marko**, HERAKOVIČ, Niko. A five-step approach to planning data-driven digital twins for discrete manufacturing systems. *Applied sciences*. Apr. 2021, vol. 11, iss. 8, str. 1-25, ilustr. ISSN 2076-3417. <https://www.mdpi.com/2076-3417/11/8/3639>, DOI: 10.3390/app11083639. [COBISS.SI-ID [61630723](#)]
3. GHEDINI, Lorenzo, POLENGHI, Adalberto, RODA, Irene, **ŠIMIC, Marko**, JANKOVIČ, Denis, HERAKOVIČ, Niko. A preliminary investigation on DDPSS requirements to provide process quality as a service : example on laboratory scale. V: ARENA, Simone (ur.). 6th IFAC Workshop on Advanced Maintenance Engineering, Services and Technology AMEST 2024 : proceedings : Cagliari, Italy, June 12 – 14, 2024. [Laxenburg]: International Federation of Automatic Control (IFAC), 2024. Iss. 8, vol. 58, str. 335-340, ilustr. IFAC papersOnline, vol. 58, iss. 8. ISSN 2405-8963. <https://www.sciencedirect.com/science/article/pii/S2405896324008656>, DOI: 10.1016/j.ifacol.2024.08.143. [COBISS.SI-ID [207255299](#)]
4. DEBEVEC, Mihael, **ŠIMIC, Marko**, HERAKOVIČ, Niko. Digital factory to support deadlines prediction in small volume production. V: BERNARD, Alain (ur.). 10th IFAC Conference on Manufacturing Modelling, Management and Control MIM 2022 : Nantes, France, 22-24 June 2022. [S. l.]: Elsevier, 2022. Vol. 55, iss. 10, str. 2306-2311, ilustr. IFAC-PapersOnLine (Kidlington. Online), vol. 55, iss. 10. ISSN 2405-8963. <https://www.sciencedirect.com/science/article/pii/S2405896322020614>, DOI: 10.1016/j.ifacol.2022.10.052. [COBISS.SI-ID [127758851](#)]
5. **ŠIMIC, Marko**, KOS, Andrej, DEBEVEC, Mihael, ADROVIČ, Edo, PIPAN, Miha, ZUPAN, Hugo, RESMAN, Matevž, TURK, Maja, PROTNER, Jernej, HERAKOVIČ, Niko. Koncipiranje demonstracijskega centra Pametne tovarne LASIM (Industrija 4.0) : zaključno poročilo o rezultatih raziskovalno razvojnega dela. Ljubljana: Fakulteta za strojništvo, Laboratorij za strego, montažo in pnevmatiko, 2018. 84 f., ilustr. [COBISS.SI-ID [16226843](#)]

Miha Pipan:

1. TURK, Maja, **PIPAN, Miha**, ŠIMIC, Marko, HERAKOVIČ, Niko. A smart algorithm for personalizing the workstation in the assembly process. *Applied sciences*. Dec. 2020, vol. 10, iss. 23, f. 1-19, ilustr. ISSN 2076-3417. <https://www.mdpi.com/2076-3417/10/23/8624/htm>, [Repozitorij Univerze v Ljubljani – RUL](#), DOI: 10.3390/app10238624. [COBISS.SI-ID [40663299](#)].
2. RESMAN, Matevž, **PIPAN, Miha**, ŠIMIC, Marko, HERAKOVIČ, Niko. A new architecture model for smart manufacturing : a performance analysis and comparison with the RAMI 4.0 reference model. *Advances in production engineering & management*. Jun. 2019, vol. 14, no. 2, str. 153- 165, ilustr. ISSN 1854-6250. http://apem-journal.org/Archives/2019/APEM14-2_153-165.pdf, Digitalna knjižnica Slovenije - dLib.si, DOI: [10.14743/apem2019.2.318](#). [COBISS.SI-ID [16766235](#)].
3. HERAKOVIČ, Niko, ZUPAN, Hugo, **PIPAN, Miha**, PROTNER, Jernej, ŠIMIC, Marko. Distributed manufacturing systems with digital agents. *Strojniški vestnik*. Nov.-Dec. 2019, vol. 65, no. 11/12, str. 650-657, si 84, ilustr. ISSN 0039-2480. <https://www.sv-jme.eu/sl/article/distributed-manufacturing-systems-with-digital-agents/>, [Repozitorij Univerze v Ljubljani – RUL](#), Digitalna knjižnica Slovenije - dLib.si, DOI: [10.5545/sv-jme.2019.6331](#). [COBISS.SI-ID [16942875](#)].
4. DEBEVEC, Mihael, ZUPAN, Hugo, **PIPAN, Miha**, ŠIMIC, Marko, KOS, Andrej, ADROVIČ, Edo, TURK, Maja, RESMAN, Matevž, PROTNER, Jernej, HERAKOVIČ, Niko. *Modeliranje in simulacija ter optimizacija procesa varjenja, vključno z delovnimi mesti in tlorisom (razvito za podjetje Agromehanika d. d.) : poročilo o rezultatih raziskovalno razvojnega dela na projektu*. Ljubljana: Fakulteta za strojništvo, Laboratorij za strego, montažo in pnevmatiko, 2018. 38 str., ilustr. [COBISS.SI-ID [16236059](#)].
5. **PIPAN, Miha**, PROTNER, Jernej, HERAKOVIČ, Niko. Distributed manufacturing node control with digital twin. V: ZADNIK STIRN, Lidija (ur.), et al. *SOR '19 proceedings*. Ljubljana: Slovenian Society Informatika, Section for Operational Research, 2019. Str. 257-262, ilustr. ISBN 978-961-6165-55-6. [COBISS.SI-ID [16810523](#)].