Copula 熵的多学科应用

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理论

Jian Ma and Zengqi Sun. "Mutual Information Is Copula Entropy". In: *Tsinghua Science & Technology* 16.1 (2011). See also arXiv preprint arXiv:0808.0845 (2008), pp. 51–54

$$H_c(\mathbf{x}) = -\int_{\mathbf{u}} c(\mathbf{u}) \log c(\mathbf{u}) d\mathbf{u}$$
 (1)

综述论文

马健. "Copula 熵: 理论和应用". In: ChinaXiv:202105.00070 (2021)

摘要

统计独立性是统计学和机器学习领域的基础性概念,如何表示和度量统计独立性是该领域的基本问题。Copula 理论提供了统计相关关系表示 的理论工具,而 Copula 熵理论则给出了度量统计独立性的概念工具。本文综述了 Copula 熵的理论和应用,概述了其基本概念定义、定理和 性质、以及估计方法。介绍了 Copula 熵研究的最新进展,包括其在统计学的九个基本问题(结构学习、关联发现、变量选择、因果发现、系 统辨识、时延估计、域自适应、正态性检验和双样本检验等)上的理论应用。讨论了前四个理论应用之间的关系,以及其对应的深层次的相 关性和因果性概念之间的联系,并将 Copula 熵的 (条件) 独立性度量框架与基于核函数和距离相关的同类框架进行了理论对比,又通过仿真 和实际数据实验评估验证了 Copula 熵的实际优越性。简述了 Copula 熵在理论物理学、天体物理学、理论化学、化学信息学、材料学、水文 学、气候学、气象学、环境学、生态学、动物形态学、农学、认知神经学、运动神经学、计算神经学、心理学、系统生物学、生物信息学、临 床诊断学、老年医学、精神病学、公共卫生学、经济学、管理学、社会学、教育学、计算语言学、新闻传播学、法学、政治学、军事学、情报 学,以及能源工程、食品工程、土木建筑、交通运输、制造工程、可靠性工程、化学工程、航空航天、车辆工程、电子工程、通信工程、高性 能计算、测绘谣感和金融工程等领域的实际应用。

天体物理学

- 测光红移
 - 测光红移准确度提升¹
 - 斯隆类星体巡天观测数据

¹ Jian Ma. "Photometric Redshifts with Copula Entropy". In: arXiv preprint arXiv:2310.16633 (2023).

相关粒子系统
平衡态相关粒子系统中熵的推导和计算²

² Jian Ma. "On Thermodynamic Interpretation of Copula Entropy". In: arXiv preprint arXiv:2111.14042 (2021).

理论化学

- 变构效应研究
 - 变构效应配位点和激活点热力学耦合模型³
 - 丙氨酸二肽的 C 端和 N 端

³ Michel A. Cuendet, Harel Weinstein, and Michael V. LeVine. "The Allostery Landscape: Quantifying Thermodynamic Couplings in Biomolecular Systems". In: Journal of Chemical Theory and Computation 12.12 (2016), pp. 5758–5767. DOI: 10.1021/acs.jctc.5600841.

- 分子设计
 - 设计具有特定属性的分子结构⁴
 - 有机分子属性 QM9 数据库

 $^{^{4} \}text{Mario Wieser. "Learning Invariant Representations for Deep Latent Variable Models". PhD thesis. University of Basel, 2020.}$

• 耐热型含能材料分子设计

- 含能材料热分解温度预测⁵
 - 含能材料化合物分子结构和量子化学性质数据集

⁵田杰."基于机器学习的耐热型含能材料设计方法研究".硕士学位论文.西南科技大学, 2023.

- 洪水预报
 - 金沙江流域洪水预报⁶
- 河流相关性
 - 长江上游河段(金沙江、岷江、沱江、嘉陵江)相关性⁷
 - 长江上游河段复合洪水事件分析⁸
- 水沙关系分析
 - 黄河西柳沟河流域径流量和输沙量数据分析⁹

⁶Lu Chen, Vijay P. Singh, and Shenglian Guo. "Measure of Correlation between River Flows Using the Copula-Entropy Method". In: Journal of Hydrologic Engineering 18.12 (2013), pp. 1591–1606, Lu Chen et al. "Copula entropy coupled with artificial neural network for rainfall—unoff simulation". In: Stochastic Environmental Research and Risk Assessment 28.7 (2014), pp. 1755–1767.

⁷Lu Chen and Shenglian Guo. Copulas and its application in hydrology and water resources. Springer, 2019.

⁸Xu Wang and Yong-Ming Shen. "A Framework of Dependence Modeling and Evaluation System for Compound Flood Events". In: Water Resources Research 59.8 (2023), e2023WR034718. DOI: 10.1029/2023WR034718.

⁹Longxia Qian et al. "A New Estimation Method for Copula Parameters for Multivariate Hydrological Frequency Analysis With Small Sample Sizes". In: Water Resources Management 36.4 (2022), pp. 1141–1157. DOI: 10.1007/s11269-021-03016-w.

- 干旱研究
 - 黄河流域(河南和甘肃)干旱分析和预测¹⁰
 - 印度达布蒂(Tapti)河流域干旱指数设计¹¹
 - 伊朗城市(扎黑丹、恩泽利和马什哈德)干旱数据分析¹²
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- 中长期径流预报
 - 长江上游水文站月径流预测¹⁴

¹⁰ 温云亭 et al. "基于 Copula 嫡理论的干旱驱动因子选择". In: 华北水利水电大学学报 (自然科学版) 40.4 (2019), pp. 51-56, C.Y. Huang and Y.P. Zhang. "Prediction based on Copula Entropy and General Regression Neural Network". In: Applied Ecology and Environmental Research 17.6 (2019), pp. 14415-14424, 黄春艳. "黄河流域的干旱驱动及评估预测研究". 博士学位论文. 西安理工大学, 2021.

¹¹ P. Kanthavel, C.K. Saxena, and R.K. Singh. "Integrated Drought Index based on Vine Copula Modelling". In: International Journal of Climatology (2022), DOI: 10,1002/joc.7840.

¹² M. Mohammadi, M. Emadi, and M. Amini. "Bivariate Dependency Analysis using Jeffrey and Hellinger Divergence Measures based on Copula Density Estimation by Improved Probit Transformation", In: Journal of Statistical Sciences 15.1 (2021), pp. 233-254, DOI: 10.29252/iss.15.1.233

¹³ Lingling Ni et al. "Vine copula selection using mutual information for hydrological dependence modeling". In: Environmental Research 186 (2020), p. 109604.

¹⁴ Xiao Li et al. "Predicting Monthly Runoff of the Upper Yangtze River Based on Multiple Machine Learning Models". In: Sustainability 14.18 (2022), p. 11149. DOI: 10.3390/su141811149.

水文学 III

- 中长期径流预报
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- 流域分区¹⁷
- 多站点径流生成
 - 巴西雅瓜拉比-大都市水库系统¹⁸

¹⁵ 黄朝君 et al. "基于 Copula 熵-随机森林的中长期径流预报研究"。In: 人民长江 52.11 (2021), pp. 81-85.

¹⁶Ran Mo et al. "Long-term probabilistic streamflow forecast model with "inputs-structure-parameters" hierarchical optimization framework". In: *Journal of Hydrology* (2023), p. 129736. DOI: 10.1016/j.jhydrol.2023.129736.

¹⁷ 刘磊 et al. "基于非线性相关性和复杂网络的径流相似性分区". In: 水科学进展 33.3 (2022), pp. 442-451.

¹⁸ Victor Costa Porto et al. "A GLM copula approach for multisite annual streamflow generation". In: Journal of Hydrology 598 (2021), p. 126226.

水文学 IV

- 水文观测网络选址和优化
 - 上海雨量观测网¹⁹
 - 伊洛河流域水文观测网²⁰
 - 北京市区水文观测网; 汾河流域观测网; 太湖盆地流域雨量观测网²¹
 - 淮河流域雨量观测网22
 - 美国查克托哈奇 (Choctawhatchee) 河流域水文观测网²³

¹⁹Pengcheng Xu et al. "A two-phase copula entropy-based multiobjective optimization approach to hydrometeorological gauge network design". In: *Journal of Hydrology* 555 (2017), pp. 228–241.

²⁰ 王栋 et al. "一种基于 Copula 熵的水文站网优化模型的优化方法". Pat. CN106897530B. 2019.

²¹ Heshu Li et al. "Developing a dual entropy-transinformation criterion for hydrometric network optimization based on information theory and copulas". In: Environmental Research 180 (2020), p. 108813.

²² 徐鹏程 et al. "基于 C-Vine Copula 熵多目标优化模型的水文气象站网优化研究". In: 中国农村水利水电 2 (2022), pp. 16-21. DOI: 10.12396/znsd.220702.

²³ 杨惜岁."多目标准则下流域水文站网的优化与评价".硕士学位论文.武汉理工大学,2019.

水文学-国内应用地图

应用



- 气候变化对水文气象变量相关性的影响
 - 美国德州达拉斯地区降水和气温相关性关系分析²⁴
 - 达拉斯市沃斯堡 (Fort Worth) 地区降水和气温观测数据
- 气候评估
 - 欧洲城市气候分类²⁵
 - 欧洲 25 座城市气温和降水数据

²⁴Zengchao Hao and Vijay P. Singh. "Integrating Entropy and Copula Theories for Hydrologic Modeling and Analysis". In: Entropy 17.4 (2015), pp. 2253–2280. DOI: 10.3390/e17042253.

²⁵ Francesca Condino. "La divergenza di Jensen-Shannon nell'algoritmo di clustering dinamico per dati descritti da distribuzioni multivariate". PhD thesis. Università degli Studi di Napoli Federico II, 2009.

大气污染气象成因分析

- 北京地区气象因素对 PM2.5 浓度的因果关系分析²⁶
 - 北京地区 PM2.5 和气象观测数据
- PM2.5 浓度预测²⁷
 - 北京地区 PM2.5 和气象观测数据
- 上海和广州大气污染预测预警²⁸
 - 上海和广州 PM2.5 和气象观测数据

气象灾害预测

- 广西地区台风灾情预测类²⁹
 - 广西地区台风灾害数据

²⁶ Jian Ma. "Estimating Transfer Entropy via Copula Entropy". In: arXiv preprint arXiv:1910.04375 (2019).

²⁷ Xiaoxuan Wu et al. "Research on PM2.5 Concentration Prediction Based on the CE-AGA-LSTM Model". In: Applied Sciences 12.14 (2022), p. 7009, DOI: 10.3390/app12147009, Jievin Chen, "Short-Term Prediction of PM2.5 Concentration based on Self-Attention Mechanism Improved Temporal Convolution Network", In: 2023 International Seminar on Computer Science and Engineering Technology (SCSET), 2023, pp. 528-534, DOI: 10.1109/SCSET58950.2023.00121.

²⁸ Jujie Wang et al. "A novel air quality prediction and early warning system based on combined model of optimal feature extraction and intelligent optimization". In: Chaos, Solitons & Fractals 158 (2022), p. 112098. DOI: 10.1016/j.chaos.2022.112098.

²⁹ 陈燕璇, 刘合香, and 倪增华. "基于 Copula 熵因子选取的 PSO-ELM 台风灾情预测模型". In: 气象研究与应用 40.2 (2019), pp. 7-11.

- 大气污染传播路径分析
 - 兰州市大气污染传播路径预测³⁰
 - 兰州市环境气象检测网络 2017 年 PM2.5 观测数据
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 - 火电厂氮氧化物排放浓度预测31
 - 宁夏某燃煤电厂运行数据

³⁰ 呈京鵬,"基于图嵌入表示的节点无特征网络链路预测研究"。硕士学位论文、西北师范大学、2022、

³¹ 金秀章, 乔鹏, and 史德金. "基于 VMD-Bayes-Lasso 算法带误差补偿的火电厂 NOx 浓度软测量". In: 华北电力大学学报 (自然科学版) (2023).

- 动物运动轨迹分析
 - Cylcop 算法包³²

³² Florian H. Hodel and John R. Fieberg. "Cylcop: An R Package for Circular-Linear Copulae with Angular Symmetry". In: bioRxiv (2021), p. 2021.07.14.452253, Florian Hodel. cylcop: Circular-Linear Copulas with Angular Symmetry for Movement Data. CRAN. R package version 0.2.0. 2022. URL: https://cran.r-project.org/package=cylcopackage/sylcopac

动物学

- 动物形态学
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 - GatorBait 海洋鱼类外形数据库
 - 鲍鱼生长过程的形态学研究34
 - UCI 鲍鱼数据集

³³ Francisco Escolano et al. "The mutual information between graphs". In: Pattern Recognition Letters 87 (2017), pp. 12–19. DOI: 10.1016/j.patrec.2016.07.012.

³⁴ Soumik Purkayastha and Peter X.K. Song. "Asymmetric predictability in causal discovery: an information theoretic approach". In: arXiv preprint arXiv:2210.14455 (2022).

- 作物产量预测
 - 气候变化对我国南方两季稻产量的影响及对策35
 - 南方(江南和华南)54个地点未来气候变化数据和作物数据

³⁵ Ziya Zhang et al. "Impact of climate change and planting date shifts on growth and yields of double cropping rice in southeastern China in future". In: Agricultural Systems 205 (2023), p. 103581. DOI: 10.1016/j.agsy.2022.103581.

认知神经学

- 分析大脑认知活动的多模态数据³⁶
 - 人脸检测任务 EEG 数据
 - 听觉语音刺激任务和认知行为映射任务 MEG 数据
 - 奖惩学习任务前脑岛 (anterior Insula)SEEG 数据
- 语音信息的编码和解析³⁷
 - 故事讲述语音及相应的 EEG 数据
- 因果关系脑连接网络分析³⁸
 - 注意缺陷多动障碍患者 EEG 数据
 - 葡萄牙老年人静息态 fMRI 数据

³⁶ Stephanie J. Kayser et al. "Irregular Speech Rate Dissociates Auditory Cortical Entrainment, Evoked Responses, and Frontal Alpha". In: The Journal of Neuroscience 35,44 (2015), pp. 14691-14701, Robin A. A. Ince et al. "The Decentively Simple N170 Reflects Network Information Processing Mechanisms Involving Visual Feature Coding and Transfer Across Hemispheres". In: Cerebral Cortex 26.11 (2016). pp. 4123-4135, Robin A.A. Ince et al. "A statistical framework for neuroimaging data analysis based on mutual information estimated via a gaussian copula". In: Human Brain Mapping 38.3 (2017), pp. 1541-1573. Etienne Combrisson et al. "Group-level inference of information-based measures for the analyses of cognitive brain networks from neurophysiological data". In: NeuroImage (2022), p. 119347, DOI: 10.1016/j.neuroimage.2022.119347.

³⁷ Pieter De Clercq et al. "Beyond linear neural envelope tracking: a mutual information approach". In: Journal of Neural Engineering 20.2 (2023), p. 026007, DOI: 10.1088/1741-2552/acbe1d.

³⁸ Paolo Victor Redondo, Raphaël Huser, and Hernando Ombao. "Measuring Information Transfer Between Nodes in a Brain Network through Spectral Transfer Entropy". In: arXiv preprint arXiv:2303.06384 (2023), 汪方毅 et al. "基于静息态 fMRI 区分健康老年人认知水平 的 MVPA 方法研究". In: 磁共振成像 14.6 (2023), pp. 18-25.

神经科学Ⅱ

• 运动神经学

- 分析运动的肌肉组合协同策略³⁹
 - 伸手运动时肌肉 sEMG 数据
 - 自主运动肌肉疲劳状态 sEMG 数据
- 计算神经学
 - 神经元可塑性建模⁴⁰
 - 神经网络信息传输关系分析⁴¹

^{3&}lt;sup>9</sup>吴亚婷 et al. "多尺度肌间耦合网络分析". In: 生物医学工程学杂志 38.4 (2021), pp. 742–752, Yating Wu et al. "R-Vine Copula Mutual Information for Intermuscular Coupling Analysis". In: Proceedings of the 11th International Conference on Computer Engineering and Networks. 2022, pp. 526–534, David O' Reilly and Ioannis Delis. "A network information theoretic framework to characterise muscle synergies in space and time". In: Journal of Neural Engineering 19.1 (2022), p. 016031. DOI: 10.1088/1741–2552/ac5150, Shaojun Zhu et al. "Intermuscular coupling network analysis of upper limbs based on R-vine copula transfer entropy". In: Mathematical Biosciences and Engineering 19.9 (2022), pp. 9437–9456, 金国美 et al. "基于小波包-Copula 互信息的肌间耦合特性". In: 传感技术学报 35.10 (2022), pp. 1348–1353.

⁴⁰ Johannes Leugering and Gordon Pipa. "A Unifying Framework of Synaptic and Intrinsic Plasticity in Neural Populations.". In: Neural Computation 30.4 (2018), pp. 945–986.

⁴¹ Ari Pakman et al. "Estimating the Unique Information of Continuous Variables in Recurrent Networks". In: Advances in Neural Information Processing Systems (2021).

心理学

- 生物心理学
 - 情绪刺激下心跳诱发脑电位的时间交互现象42
 - 用于情绪分析的生理信号 DEAP 数据集

 $^{^{42}} Liesa \ Ravijts. \ "Revealing \ temporal \ interactions \ around \ the \ heartbeat-evoked \ potential \ modulated \ by \ emotional \ perception".$ MA thesis. Ghent University, 2019.

- 系统生物学
 - 生物信号调控和传导⁴³
 - 癌症分子机制数据
 - 生物现象动态网络结构和功能⁴⁴
 - 酵母细胞周期数据
- 生物信息学
 - 分析基因数据,研究生命和疾病机理⁴⁵
 - 肝炎病毒感染治疗基因表达谱数据
 - 筛选与癌症有关的变异基因⁴⁶
 - cBioPortal 癌症基因组数据
 - 美国亚利桑那州立大学癌症基因组数据

⁴³ Agata Charzyńska and Anna Gambin. "Improvement of the k-NN Entropy Estimator with Applications in Systems Biology". In: Entropy 18.1 (2015), p. 13.

⁴⁴ Farzaneh Farhangmehr et al. "An information-theoretic algorithm to data-driven genetic pathway interaction network reconstruction of dynamic systems". In: 2013 IEEE International Conference on Bioinformatics and Biomedicine, 2013, pp. 214-217.

⁴⁵ Mario Wieser et al. "Inverse Learning of Symmetries". In: Advances in Neural Information Processing Systems. Vol. 33. 2020, pp. 18004-18015.

⁴⁶ Oiang Wu and Dongxi Li. "CRIA: An Interactive Gene Selection Algorithm for Cancers Prediction Based on Copy Number Variations". In: Frontiers in Plant Science 13 (2022), p. 839044. DOI: 10.3389/fpls.2022.839044.

临床医学

- 心脏病诊断⁴⁷
 - UCI 心脏病数据

应用

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 - 美国 Health Facts 糖尿病救治网络数据
- 癌症预后⁴⁹
 - UCI 肺癌数据
 - SEER 数据库乳腺癌临床数据

⁴⁷ Jian Ma. "Variable Selection with Copula Entropy". In: Chinese Journal of Applied Probability and Statistics 37.4 (2021). See also arXiv preprint arXiv:1910.12389 (2019), pp. 405-420.

⁴⁸ Radko Mesiar and Ayyub Sheikhi. "Nonlinear Random Forest Classification, a Copula-Based Approach". In: Applied Sciences 11.15 (2021), p. 15. DOI: 10.3390/app11157140.

⁴⁹ Jian Ma. "Copula Entropy based Variable Selection for Survival Analysis". In: arXiv preprint arXiv:2209.01561 (2022), 付金露. "基于 特征选择的乳腺癌患者预后模型研究"。硕士学位论文。江西财经大学、2023。

临床医学

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 - 临床白内障超声乳化手术患者数据
- 主动脉瓣置换手术射血分数分析⁵¹
 - 临床主动脉瓣置换手术前后射血分数数据
- 脑肿瘤医学影像组学诊断模型构建⁵²
 - 重庆医科大学附属医院、西南医院和四川省肿瘤医院脑肿瘤患者数据

⁵⁰Yu Luo et al. "Research on Establishing Corneal Edema after Phacoemulsification Prediction Model Based on Variable Selection with Copula Entropy". In: Journal of Clinical Medicine 12.4 (2023), p. 1290. DOI: 10.3390/jcm12041290.

⁵¹ S.M. Sunoi and N. Unnikrishnan Nair. "Survival Copula Entropy and Dependence in Bivariate Distributions". In: REVSTAT-Statistical Journal (2023). URL: https://revstat.ine.pt/index.php/REVSTAT/article/view/560.

⁵² 潘红字."基于影像组学与深度学习的脑肿瘤图像分类研究".硕士学位论文.西南大学, 2023.

认知医学

- 认知能力评估/痴呆症筛查⁵³
 - 北京和天津痴呆症老年人数据
- 运动医学
 - 运动能力评估/跌倒风险预测⁵⁴
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- 精神病学
 - 抑郁症患者识别⁵⁶
 - 江苏常州抑郁症青少年患者 EEG 数据

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- 新冠肺炎流行病 (COVID19)
 - 发热症状疑似病人筛查诊断⁵⁷
 - 新冠临床数据
- 高血压
 - 高血压关联基因研究58
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• 经济学

- 扶贫政策效果评估,用于政策目标人口鉴别⁵⁹
 - 2018 年政府贫困家庭状况普查数据(四川省和河南省)
- 议价机制中的互惠行为和时间效应⁶⁰
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- 产业链内部相关性分析61
 - 国内畜禽养殖产业链主要上市企业股票价格数据
- 投资者情绪分析⁶²
 - 中国新能源汽车上市公司的百度搜索数据

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• 管理学

- 商品期货价格预测⁶³
 - 国家统计局猪肉价格数据和大连商品交易所大豆期货价格数据
- 单周期库存管理⁶⁴
 - 大众朗逸汽车销售数据
- 中国企业海外并购影响因素分析⁶⁵
 - Wind 数据库经济数据
- 社会学
 - 分析教育、职业和收入上的性别不平等问题66
 - 美国国家成年人收入调查数据(1994年)

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- 教育学
 - 高中数学成绩与其他学科成绩相关性分析⁶⁷
 - 某市 2013 级理科学生高一、高二期末成绩和高三两次模考成绩
- 计算语言学
 - 城市热线派单系统知识图谱构建⁶⁸
 - 济南市民热线数据
- 新闻传播学
 - 上海新冠疫情下的公众情绪变化⁶⁹
 - 微博平台"上海疫情"主题数据
- 法学
 - 社区属性与社区犯罪关系分析⁷⁰
 - 美国社区与犯罪数据集

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政治学

- 分析政权领导力因素和政权危机之间关系⁷¹
 - 雪城大学莫伊尼汉全球事务研究所国际政治领导力数据集

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- 军事学
 - 目标意图识别⁷²
 - 空中飞行目标示例
- 情报学
 - 颠覆性技术科学-技术-产业互动模式分析⁷³
 - 再生医学(干细胞)和白血病治疗相关资料数据

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• 能源工程

- 能源网络管理,研究天气因素与能源网络的耦合⁷⁴
 - 北方某地区能源系统运行数据
- 光伏发电功率预测⁷⁵
 - 澳大利亚 Yulara 地区光伏电站数据
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 - 某工业园区风光火储联合发电系统

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工程学上

能源工程

- 电网频率稳定性预测⁷⁹
 - 贵州电网数据
- 用户线损贡献分析⁸⁰
 - 辽宁电网数据
- 电价预测⁸¹
 - 2017 年美国 PJM 电力市场电价数据
- 锂电池容量估计⁸²
 - NASA 锂电池退化数据
- 电力系统宽频振荡影响因素和传播路径分析⁸³

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工程学川

- 食品工程
 - 葡萄酒质量与理化成分关系分析⁸⁴
 - 葡萄牙绿酒葡萄酒理化成分与质量评价数据
- 土木建筑
 - 建筑能源系统节能技术⁸⁵
 - 大连某教学楼供热监测数据
 - 工程变形监测⁸⁶
 - 某隧道工程施工段围堰监测数据

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 - 大件货物运输案例数据
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- 城市轨道交通客流分析和预测89
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工程学 ٧

• 制造工程

- 制造质量管理,研究优化制造过程参数,预测产品质量⁹⁰
 - 富士康生产线制造过程数据
- 装配质量控制⁹¹
 - 江淮汽车某型汽油发动机关键零部件装配过程数据
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 - 田纳西伊斯曼过程数据
- 钢铁工艺过程碳排放预测⁹³
 - 某钢铁厂烧结过程数据
- 液晶显示器质量预测⁹⁴
 - 薄膜晶体管液晶显示器生产数据

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- 可靠性工程
 - 系统退化过程建模⁹⁵
 - 微波电子组件数据
 - 风电机组健康状态评估⁹⁶
 - 内蒙古某风场的风机 SCADA 数据
- 化学工程
 - 化学过程故障监测和诊断⁹⁷
 - Tennessee Eastman 讨程数据
 - 化工过程因果网络构建⁹⁸
 - 连续搅拌槽式反应器数据和 Tennessee Eastman 过程数据

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航空航天

- 飞行器总体参数分析和优化⁹⁹
 - 美国喷气战斗机总体设计参数数据
- 卫星在轨健康状态监测¹⁰⁰
 - 真实卫星遥测数据
 - NASA 公开的 SMAP 和 MSL 数据集
- 涡扇发动机健康状态监测¹⁰¹
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- 车辆工程
 - CAN 总线入侵检测¹⁰³
 - 现代汽车 YF 索纳塔 CAN 数据

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- 电子工程
 - 集成电路封装材料物理性能预测¹⁰⁴
 - CuNi 合金体系材料强度和稳定性计算数据
- 通信工程
 - 通讯网络加密技术研究¹⁰⁵
 - 6G 网络语义通信技术研究¹⁰⁶
 - ImageNet-1k 数据集和 VOC2012 数据集
- 高性能计算
 - 高性能计算能源效率优化¹⁰⁷
- 测绘谣感
 - 高光谱遥感数据分析¹⁰⁸
 - 美国印第安纳 Indian Pine 高光谱遥感数据

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- 投资组合优化
 - 股票资产相关性网络分析¹⁰⁹
 - 沪深 A 股指数、沪深 300 指数数据
 - ST 股票分类¹¹⁰
 - A 股市场 ST 股票数据
- 金融问题建模
 - Copula 函数模型选择¹¹¹
 - 标普 500 指数数据
- 股票相关性建模
 - R-vine copula 结构建模¹¹²
 - 德国 DAX 指数数据
 - 中证五大行业指数数据

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- 量化金融工具箱 MLFinLab¹¹³
- 金融系统性风险
 - 行业风险溢出效应分析¹¹⁴
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 - 金融脆弱性度量¹¹⁵
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- 信用风险评价
 - 信用风险卡模型建立¹¹⁶
 - 信用卡客户数据
- 金融产品价格预测
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 - 国际主要金融指数、能源期货价格和农产品价格数据

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Enjoy the Power of Copula Entropy!