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Production planning and control enhanced with smart energy management

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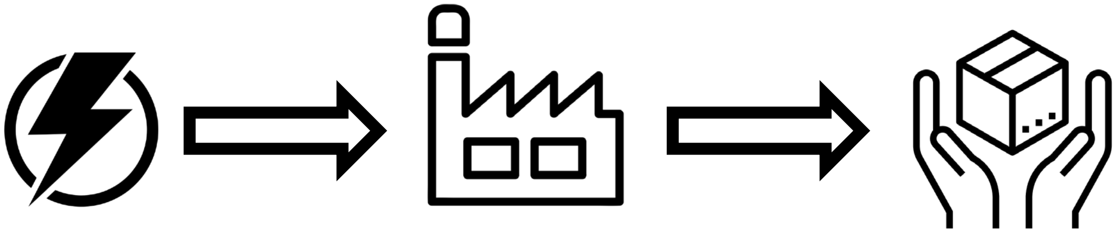
My *research topic* focuses on the activities of modelling, predicting, and improving manufacturing systems under uncertain conditions. Particular attention is devoted to sustainability of manufacturing processes, energy efficient control strategies of resources, production planning and control strategies, and data-driven modelling.

Agenda

- <u>Focus</u>
- Key aspects
- Recent approaches from the literature



Energy efficiency in manufacturing can be improved through strategies for the effective usage of production equipment while assuring a certain service level and productivity.

e.g., reduction of time for non-valuable tasks, reduction of supply excess, reduction of base-load request, optimization of process parameters.

Machine and Process Design

Energy / Heat recovery systems

Green scheduling and planning

Smart energy management (control)

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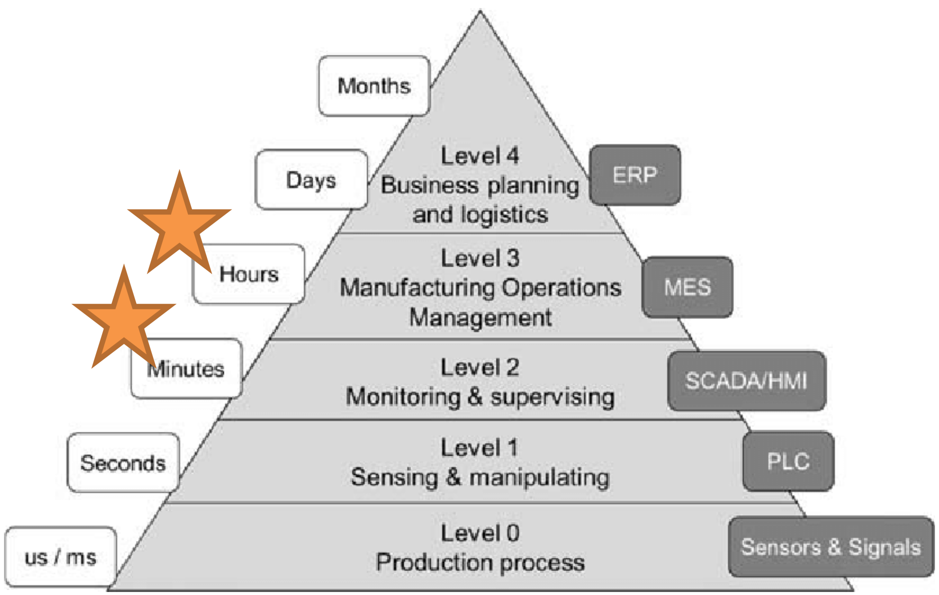

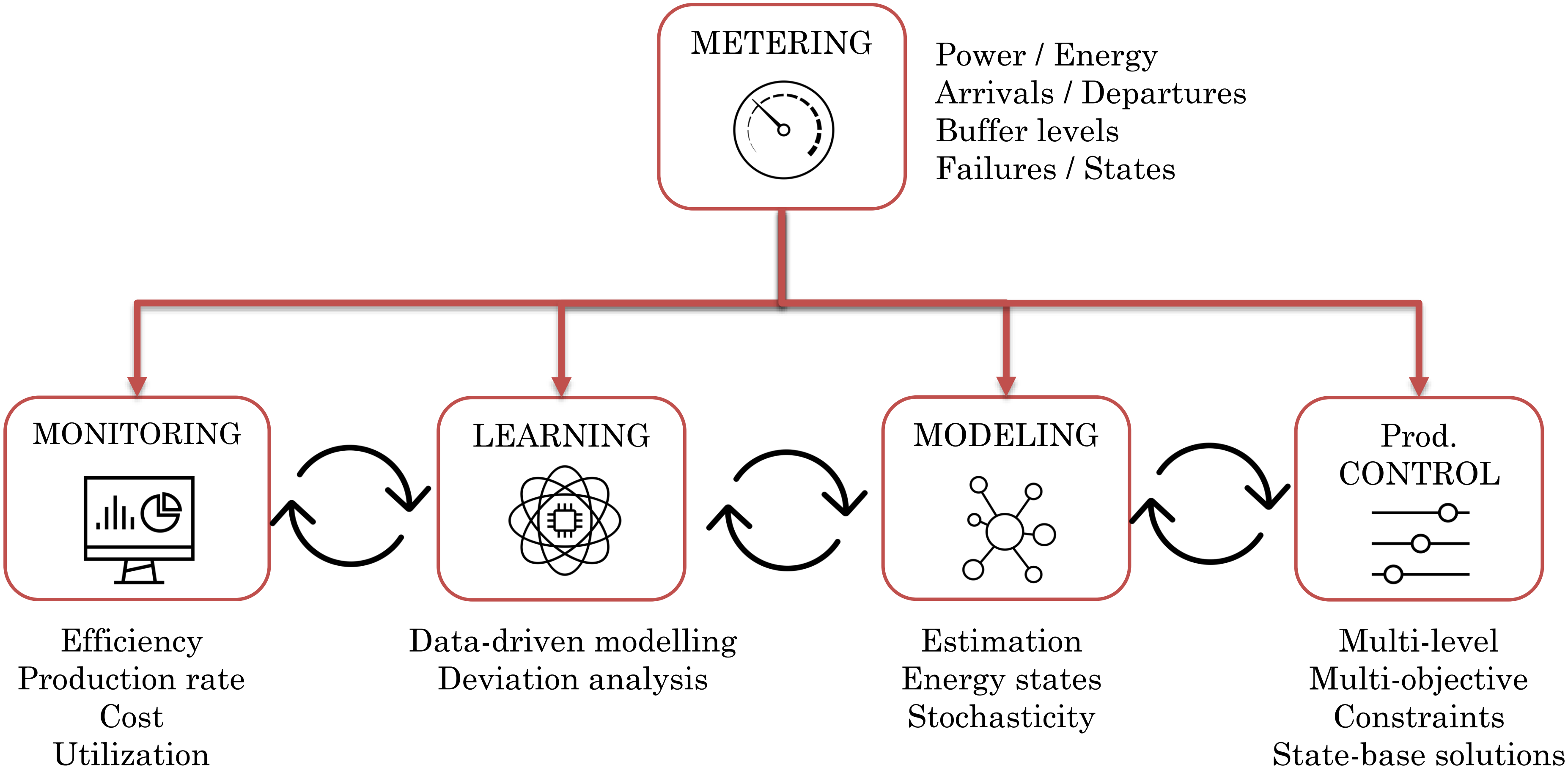

METERING
Power / Energy
Arrivals / Departures
Buffer levels
Failures / States
MONITORING
LEARNING
MODELING
Prod.
CONTROL
Efficiency
Production rate
Cost
Utilization
Data-driven modelling
Deviation analysis
Estimation
Energy states
Stochasticity
Multi-level
Multi-objective
Constraints
State-base solutions

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Key aspects

- To **reduce the energy impact and cost** of manufacturing systems
- To provide the user/client with an **augmented knowledge** about machine/systems environmental impact
- To **exploit digitalization and data-collection**
- To integrate an **energy management system** where energy-related KPIs are estimated, monitored, and improved

K1. On-line data-driven learning problem

K2. Decision-making with twin-models

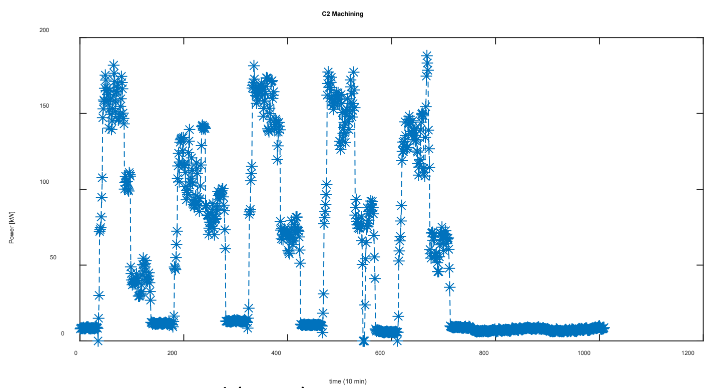
K3. Multi-criteria optimization

- Focus
- Key aspects
- Recent approaches from the literature

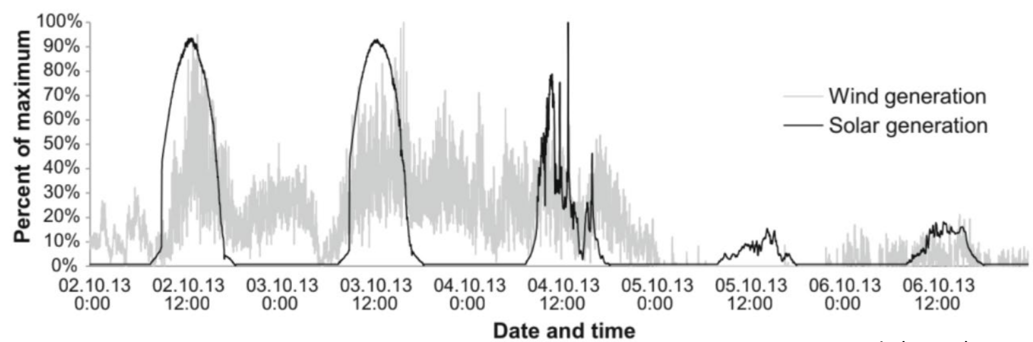
The power request of a manufacturing plant is *unbalanced* (facing peak periods) and *uncertain* (due to disruptive events interrupting the activities).

Peak Shaving → scheduling activities
Load Shedding → avoid non-critical loads during peak demands

Load Shifting → schedule considering periods where the *energy price is lower* or where *Variable Renewable Energy* are available



From: Frigerio et al (2022)



From: Beier et al. (2018).

Examples:
Beier, J., Thiede, S., & Herrmann, C. (2018). Integrating Variable Renewable Electricity Supply into Manufacturing. *Eco-Factories of the Future*, 17.
C. Gahm, F. Denz, M. Dirr, and A. Tuma, “Energy-efficient scheduling in manufacturing companies: A review and research framework,” Eur.J. Oper. Res., vol. 2, no. 3, pp. 744–757, Feb. 2016.
Frigerio, N., Matta, A., Rasella, M. Energy monitoring of manufacturing plants: a real case application (2022) Procedia CIRP (29th CIRP International Conference on Life Cycle Eng.), Elsiever B.V., Berlin,Germany, Vol. 105, pp. 770{775.

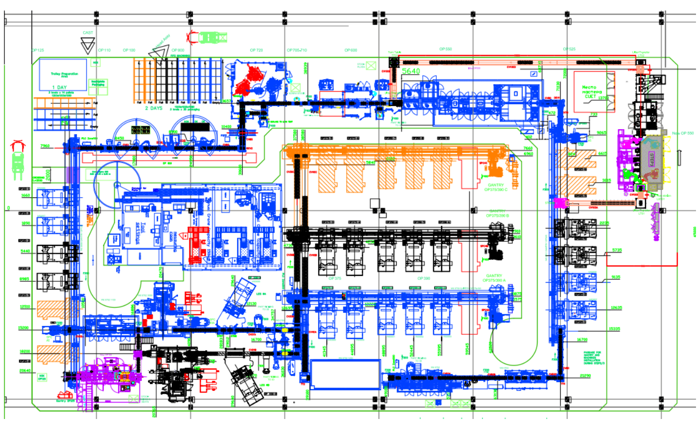
Energy efficient state control of resources

Goal of reducing the *supply exceed* to keep active resource auxiliary systems while the machine is idle (not producing).

It involves the **selection of resource/component "mode" at a given time** by using **real-time information of system state** (e.g., time, buffer level).

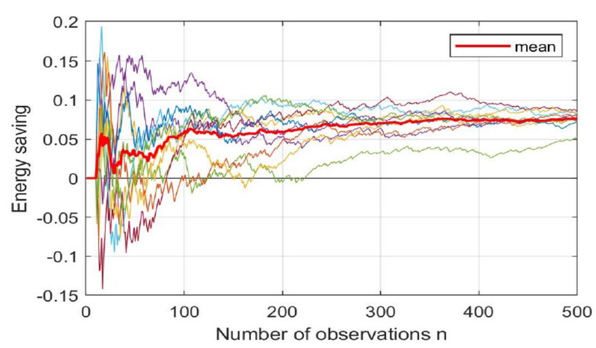
$$x^* = \quad argmin\{Energy(\boldsymbol{x}) | PR(\boldsymbol{x}) > PR^{target}; n_m \leq N_{max}\}$$

Limited knowledge of system state



estimation of energy consumption and production rate

constrained set of controllable resources

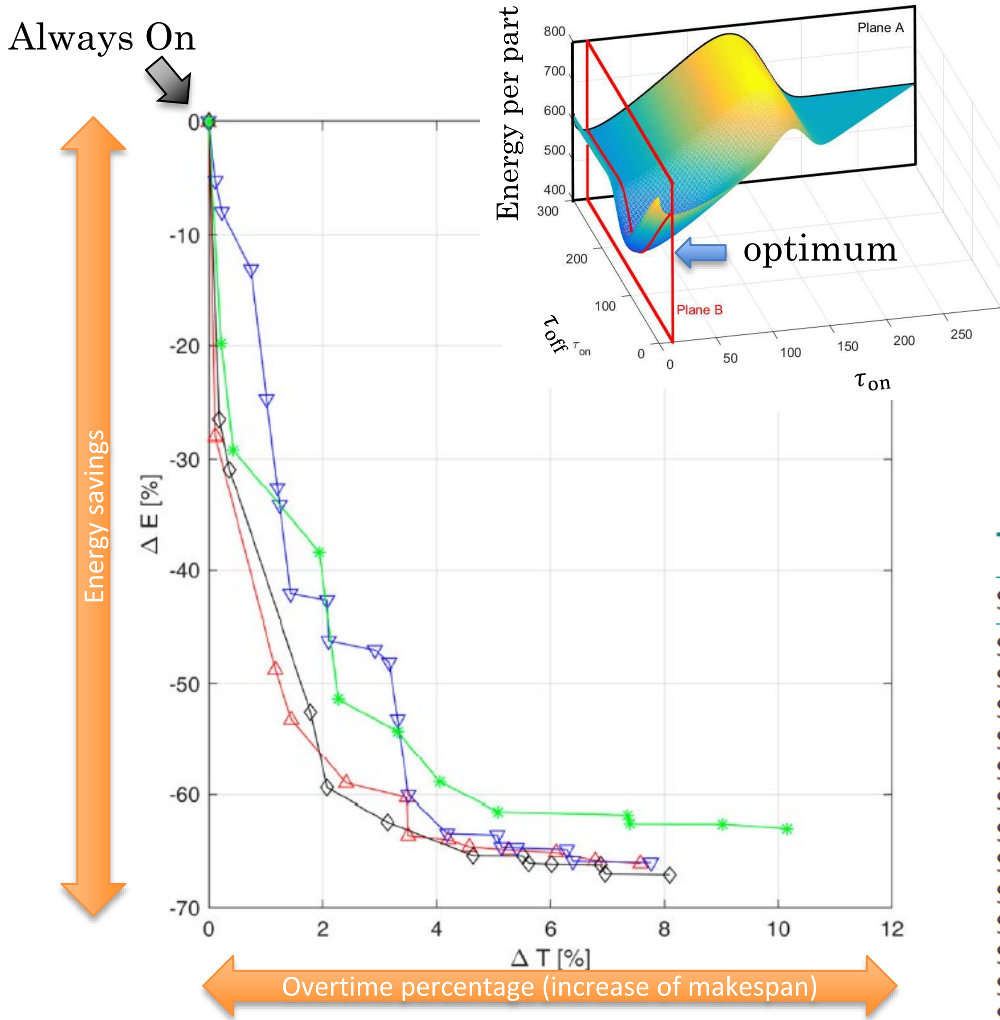


<u>Examples:</u>

Frigerio, N., Cornaggia, C.F.A., Matta, A. An Adaptive Policy for On-Line Energy-Efficient Control of Machine Tools Under Throughput Constraint (Online since 2020), Journal of Cleaner Production, 287, 125367.

Nicla Frigerio, Barış Tan & Andrea Matta (2023): Simultaneous control of multiple machines for energy efficiency: a simulation-based approach, International Journal of Production Research, DOI: 10.1080/00207543.2023.2175175

Energy efficient state control of resources



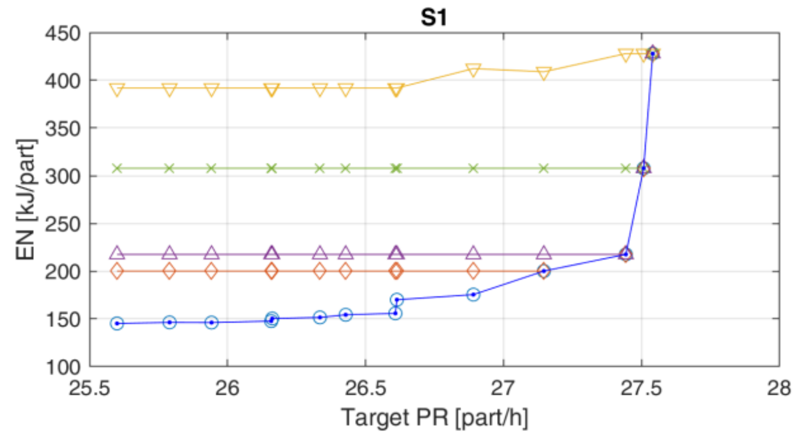


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Table 7. Mean performance obtained in the evaluated scenarios.

Scenario	Policy	ΔE	ΔP	ΔT
S1	UD	−55.2%	−3.5%	3.7%
S2	UD	−53.5%	−3.7%	3.9%
S3	UD	−42.0%	−2.8%	2.9%
S4	UD	−49.1%	−4.4%	4.7%
S5	UD	−54.7%	−3.8%	4.0%
S6	UD	−39.9%	−5.9%	6.5%
S7	UD	−42.2%	−5.4%	5.9%
S4+ 0.2	UD	−48.9%	−7.1%	7.9%
S4+ 0.3	UD	−46.3%	−6.9%	7.7%
S4+ 0.5	UD	−48.7%	−9.2%	10.5%
S2+ 1	UD	−53.5%	−3.7%	3.9%
S2+ 0.68	UD	−48.1%	−1.5%	1.6%
S2+ 0.52	UD	−48.6%	−0.9%	0.9%
S2+ 0.38	UD	−51.6%	−0.3%	0.3%

* Values include load independent energy only

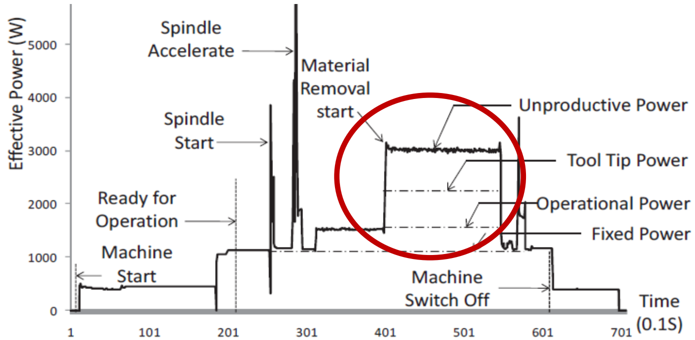
Green process re-design (parameters optimization)

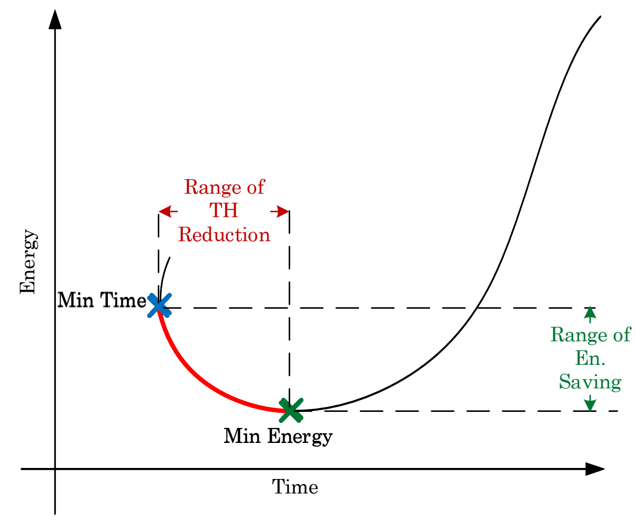
The optimization problem involves the selection of **process parameters** to reduce the load-dependent energy consumption.

Green process selection might include cost, productivity, and sustainability criteria in the same optimization problem.

$$\min_{\boldsymbol{p}} \{cost(\boldsymbol{p}), energy(\boldsymbol{p}), time(\boldsymbol{p})\}$$

$$\textit{Subject to}: \quad \text{technologic constraint}$$
$$\text{feasibility constraint}$$





<u>Examples for machining processes:</u>

Albertelli, P., A. Keshari, and A. Matta. 2016. “Energy Oriented Multi Cutting Parameter Optimization in Face Milling.” *Journal of Cleaner Production*.

Li, C., Li, L., Tang, Y., Zhu, Y., Li, L. A comprehensive approach to parameters optimization of energy-aware CNC milling (2019) Journal of Intelligent Manufacturing, 30 (1), pp. 123-138.

Take aways

- To extract *knowledge* from data and effectively use such knowledge
- To obtain and use *dynamic and constantly validated digital models*
- To use *multi-objective* and *fast responsive* algorithms supporting decisions

⇩

- Autonomous generation and update of digital twins by the use of monitored data and prior knowledge
- New methods to recognize system models and states such that proper decision can be applied
- New models to integrate sustainable criteria in complex multi-objective decision making processes
- New algorithms to solve the joint learning & optimizing problem

Thank you for your attention

Any question or comment?

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References for further reading

- International Energy Agency Website, http://www.iea.org/topics/energyefficiency/
- ISO14955. The International Organization for Standardization, ISO Standards, http://www.iso.org/iso/home/standards.htm
- Albertelli, P., A. Keshari, and A. Matta. 2016. "Energy Oriented Multi Cutting Parameter Optimization in Face Milling." *Journal of Cleaner Production*.
- Carlucci, D., Renna, P., Materi, S. A Job-Shop Scheduling Decision-Making Model for Sustainable Production Planning With Power Constraint (2021) IEEE Transactions on Engineering Management, DOI: 10.1109/TEM.2021.3103108
- Chen, X., Li, C., Tang, Y., Li, L., Du, Y., Li, L. Integrated optimization of cutting tool and cutting parameters in face milling for minimizing energy footprint and production time (2019) Energy, 175, pp. 1021-1037.
- J. B. Dahmus and T.G. Gutowski. An Environmental Analysis of Machining. In Manufacturing Engineering and Materials Handling Engineering ASME, pages 643–652, November 2004.
- A. Dietmair and A. Verl, "Energy consumption modeling and optimization for production machines," 2008 IEEE International Conference on Sustainable Energy Technologies, Singapore, 2008, pp. 574-579.
- T. G. Gutowski, J. B. Dahmus, A. Thiriez, "Electrical Energy Requirements for Manufacturing Processes", in Proc. of 13th CIRP International Conf. on Life Cycle Eng. (LCE), Leuven, 2006.
- Frigerio, N., Cornaggia, C.F.A., Matta, A. An Adaptive Policy for On-Line Energy-Efficient Control of Machine Tools Under Throughput Constraint (Online since 2020), Journal of Cleaner Production, 287, 125367. DOI: 10.1016/j.jclepro.2020.125367
- Nicla Frigerio, Barış Tan & Andrea Matta (2023): Simultaneous control of multiple machines for energy efficiency: a simulation-based approach, International Journal of Production Research, DOI: 10.1080/00207543.2023.2175175
- Frigerio, N., Matta, A. Analysis on Energy Efficient Switching of Machine Tool with Stochastic Arrivals and Buffer Information (2016) IEEE Transactions on Automation Science and Engineering, 13 (1), pp. 238-246. DOI: 10.1109/TASE.2015.2492600
- Frigerio, N., Matta, A. Energy-Efficient Control Strategies for Machine Tools with Stochastic Arrivals (2015) IEEE Transactions on Automation Science and Engineering, 12 (1), pp. 50-61. DOI: 10.1109/TASE.2014.2344507
- Frigerio, N., Matta, A. Energy Efficient Manufacturing Systems: Current Research and Future Challenges (2017) Matta A., Biller S., Tang Y., Lennartson B., Lin J. (eds) Sustainable Production Automation, Momentum Press, Jan. 2017. ISBN: 9781606509050

- C. Gahm, F. Denz, M. Dirr, and A. Tuma, “Energy-efficient scheduling in manufacturing companies: A review and research framework,” Eur.J. Oper. Res., vol. 2, no. 3, pp. 744–757, Feb. 2016.
- Loffredo, A., Frigerio, N., Lanzarone, E., Matta, A. Energy-Efficient Control Policy for Parallel and Identical Machines with availability constraint (2021), in IEEE Robotics and Automation Letters, vol.6, no. 3, pp. 5713-5719. DOI: 10.1109/LRA.2021.3085169.
- Jia, Z., Zhang, L., Arinez, J. and Xiao, G., 2016. Performance analysis for serial production lines with Bernoulli machines and real-time WIP based machine switch-on/off control. IJPR, 54(21), 6285-6301.
- Li, G., Qiao, F., Wang, J., Ma, Y., Lu, K. Parallel machine batching scheduling considering energy constraints (2017) Zhongnan Daxue Xuebao (Ziran Kexue Ban)/Journal of Central South University (Science and Technology), 48 (8), pp. 2063-2072.
- Li, C., Li, L., Tang, Y., Zhu, Y., Li, L. A comprehensive approach to parameters optimization of energy-aware CNC milling (2019) Journal of Intelligent Manufacturing, 30 (1), pp. 123-138.
- W. Li, A. Zein, S. Kara, and C. Herrmann. An Investigation into Fixed Energy Consumption of Machine Tools. In Glocalized Solutions for Sustainability in Manufacturing, pages 268–273. Springer Berlin Heidelberg, 2011.
- Mativenga, P., and M. Rajemi. 2011. “Calculation of Optimum Cutting Parameters Based on Minimum Energy Footprint.” CIRP Annals-Manufacturing Technology 60, no. 1, pp. 149–52.
- Rajemi, M., P. Mativenga, and A. Aramcharoen. 2010. “Sustainable Machining: Selection of Optimum Turning Conditions Based on Minimum Energy Considerations.” Journal of Cleaner Production 18, nos. 10–11, pp. 1059–065.
- Renna, P., Materi, S. A literature review of energy efficiency and sustainability in manufacturing systems (2021) Applied Sciences (Switzerland), 11 (16), art. no. 7366.
- Wen Su, Xiaolei Xie, Jingshan Li & Li Zheng (2016) Improving energy efficiency in Bernoulli serial lines: an integrated model, International Journal of Production Research, 54:11, 3414-3428,
- Su, W., Xie, X., Li, J., Zheng, L., Feng, L., (2017). Reducing energy consumption in serial production lines with Bernoulli reliability machines, IJPR 55(24), 7356-7379.

References for further reading

- Yoon, H.S., Kim, E.S., Kim, M.S., Lee, J.Y., Lee, G.B. and Ahn, S.H., 2015. Towards greener machine tools a review on energy saving strategies and technologies. Renewable and Sustainable Energy Reviews, 48, 870-891.
- Wang, J., Du, H., Xing, J., Qiao, F., Ma, Y. Novel Energy- And Maintenance-Aware Collaborative Scheduling for A Hybrid Flow Shop Based on Dual Memetic Algorithms (2020) IEEE Robotics and Automation Letters, 5 (4), art. no. 9128049, pp. 5613-5620.
- Wang, J., Qiao, F., Zhao, F., Sutherland, J.W. A Data-Driven Model for Energy Consumption in the Sintering Process (2016) Journal of Manufacturing Science and Engineering, Transactions of the ASME, 138 (10), art. no. 101001
- Wang, J., Qiao, F., Zhao, F., Sutherland, J.W. Batch scheduling for minimal energy consumption and tardiness under uncertainties: A heat treatment application (2016) CIRP Annals - Manufacturing Technology, 65 (1), pp. 17-20.
- Wang, J., Qiao, F., Zhu, J., Ni, J. SVR-based predictive models of energy consumption and performance criteria for sintering (2014) Tongji Daxue Xuebao/Journal of Tongji University, 42 (8), pp. 1256-1260.
- Zhou, L., Li, J., Li, F., Meng, Q., Li, J., and Xu, X., 2016. Energy consumption model and energy efficiency of machine tools: a comprehensive literature review, J. of Cleaner Prod., 112(5), 3721-3734.
- Xiao, Q., Li, C., Tang, Y., Li, L., Li, L. A knowledge-driven method of adaptively optimizing process parameters for energy efficient turning (2019) Energy, 166, pp. 142-156.