MECHATRONICS AND AUTONOMOUS SYSTEMS RESEARCH GROUP

ENERGY-EFFICIENT INDUSTRIAL ROBOTICS
TRENDS AND METHODS

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Outline

1. Why energy efficiency matters
2. Energy use in industrial robot systems
3. Measurement methods
4. Current trends
    - Software-based methods
    - Hardware-based methods
5. Conclusion and group discussions

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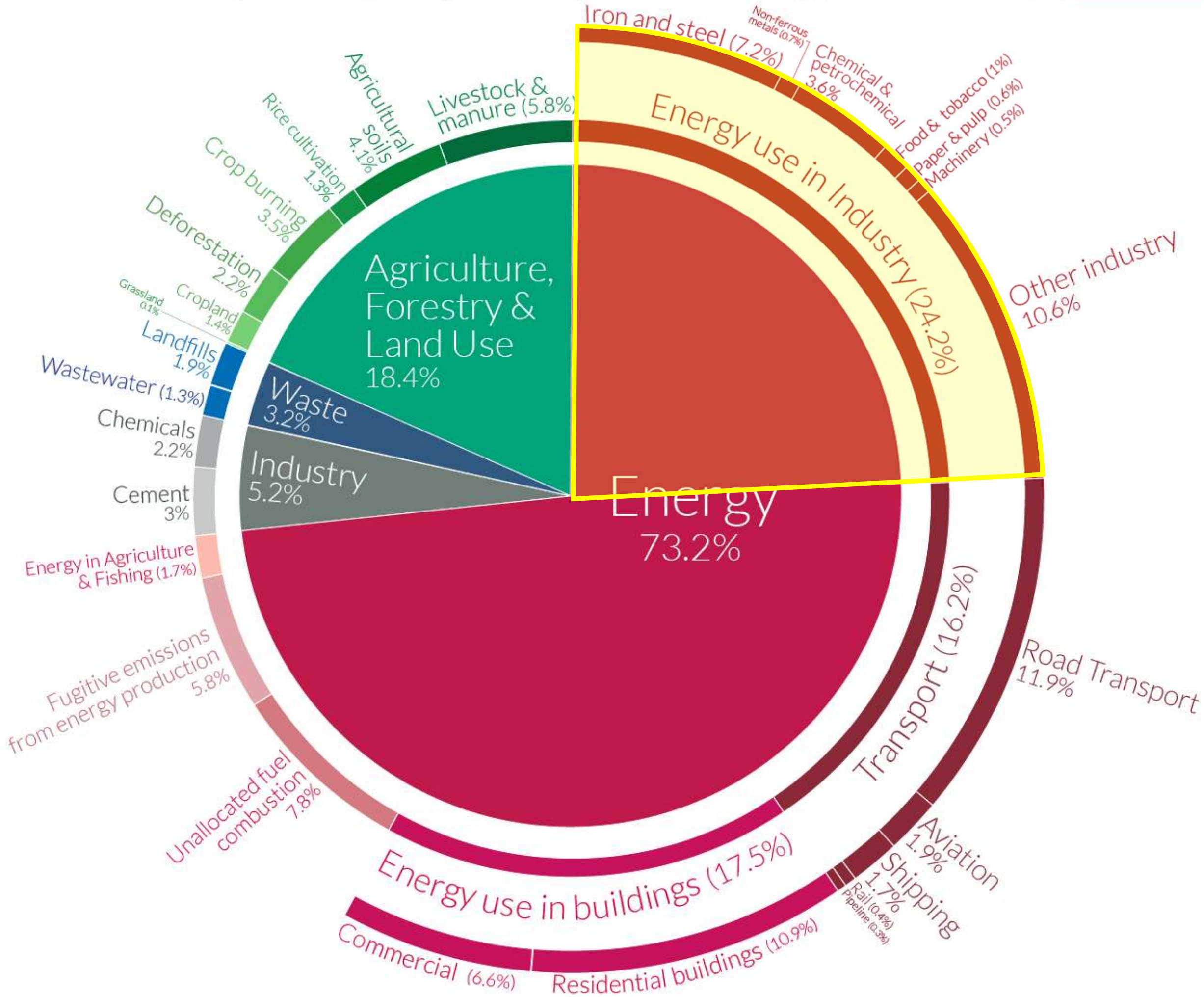
Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO_2eq.

Our World in Data



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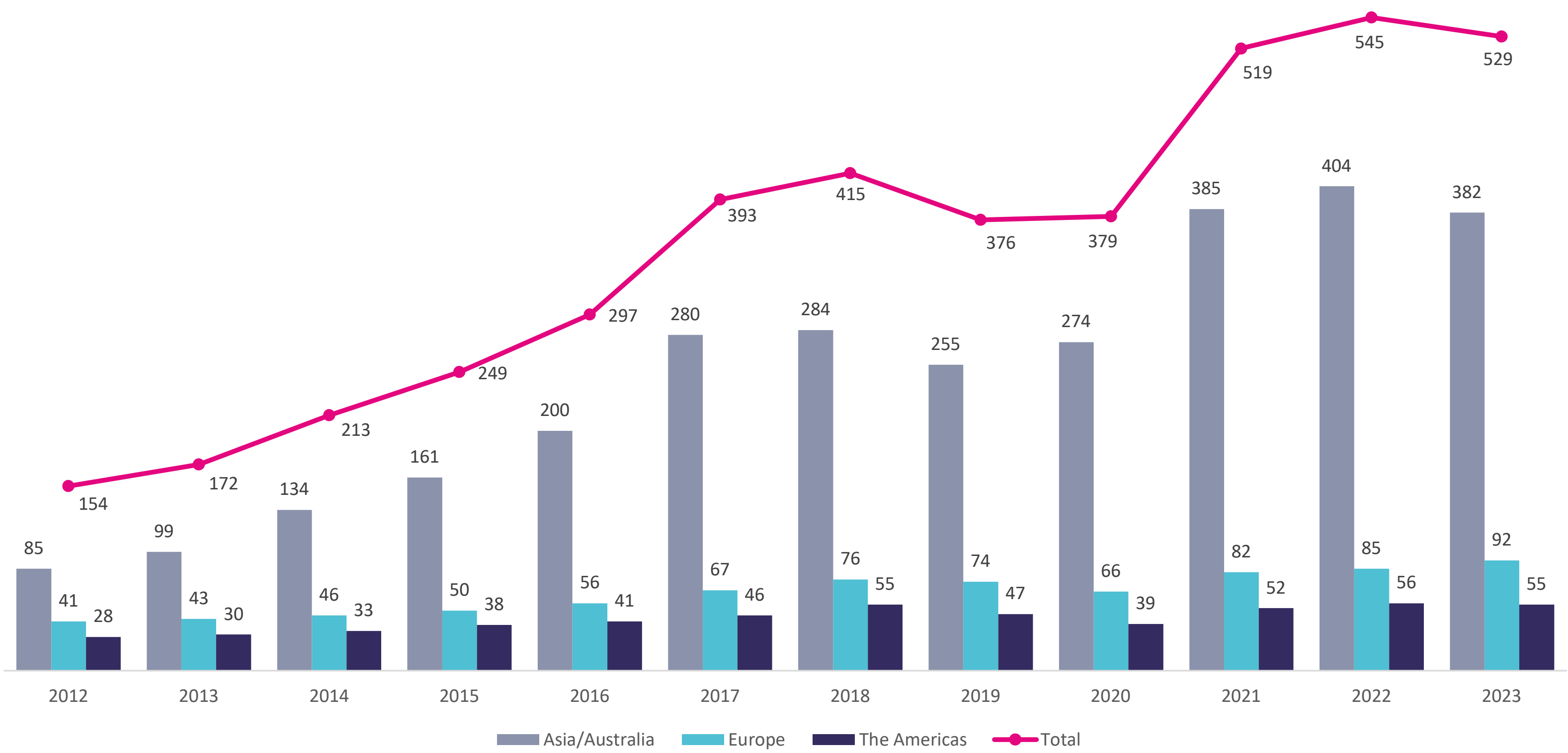
OurWorldinData.org – Research and data to make progress against the world's largest problems.

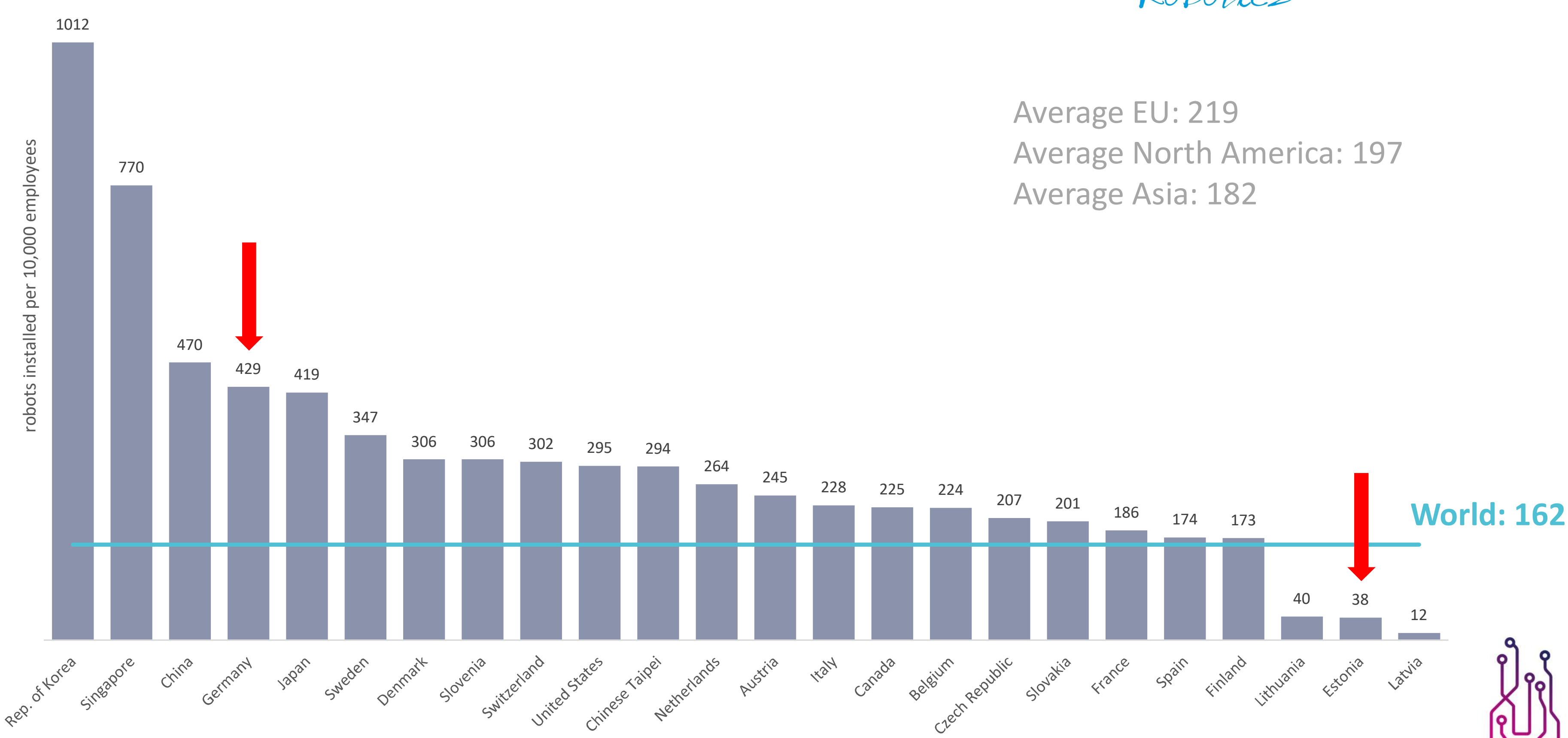
Source: Climate Watch, the World Resources Institute (2020).

Annual installation of industrial robots ('000 of units)



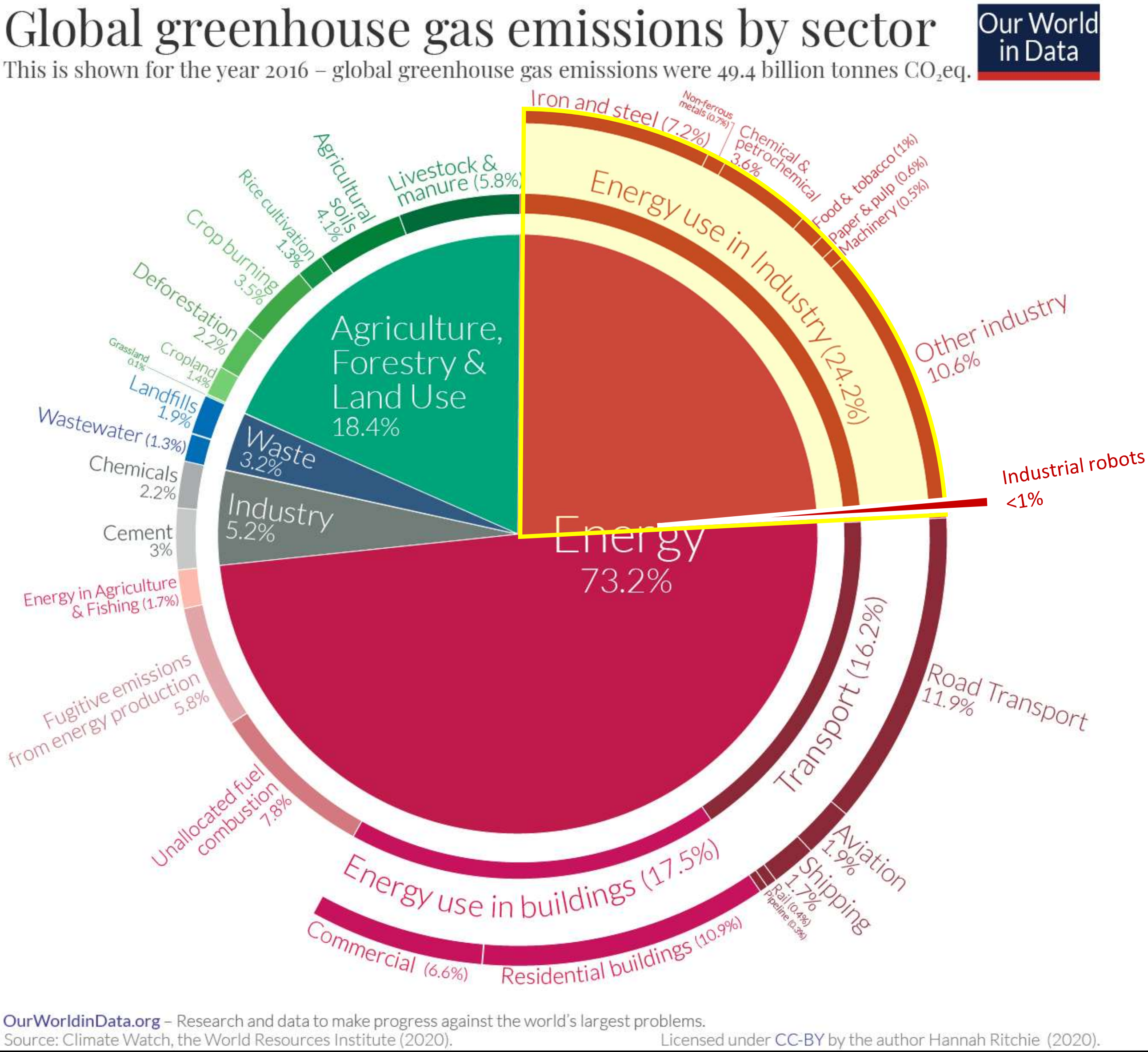
International Federation of Robotics, World Robotics – Industrial Robots, https://ifr.org/wr-industrial-robots/

Robot density in the manufacturing industry 2023



Average EU: 219
Average North America: 197
Average Asia: 182

International Federation of Robotics, World Robotics – Industrial Robots, https://ifr.org/wr-industrial-robots/



- Multiple sources say that industrial robots account for **8%** of energy consumption in the **automotive industry.**

- Industrial robots are used in other industries as well
- **The estimate is that robots contribute less than 1% in the total energy consumption**

The problem

Increasing adoption of industrial robots is driving the need for **energy-efficient** automation

Energy efficiency is critical for **reducing** operating **costs** and **improving sustainability**

- Total Cost of Ownership by reducing energy and maintenance costs
- Enabling smarter and resource-efficient plant design

Various **energy consumption optimization (ECO)** strategies

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Industrial Robot

Mechanical manipulator

- Automatic
- Programmable in three or more axes
- Reprogrammable
- Multipurpose
- **Automation applications in industrial environment**

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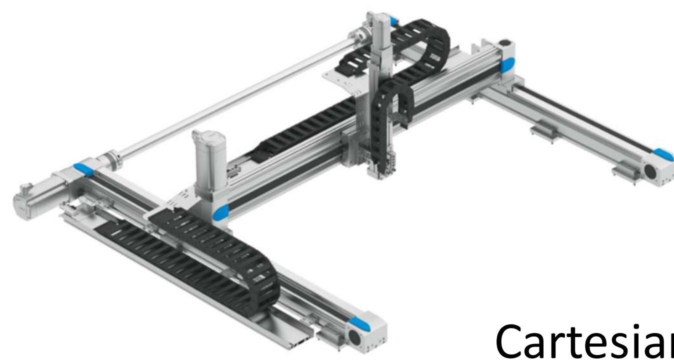
Source: ISO 8373:2021 Robotics — Vocabulary

Industrial Robot

Articulated

SCARA

Delta



Cartesian

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Source: ISO 8373:2021 Robotics — Vocabulary

Power flow

1. **Cabinet**
   - AC/DC conversion
   - Control electronics
   - DC-bus
2. **Servo drives**
3. **Manipulator**
   - Joint motors
   - Payload

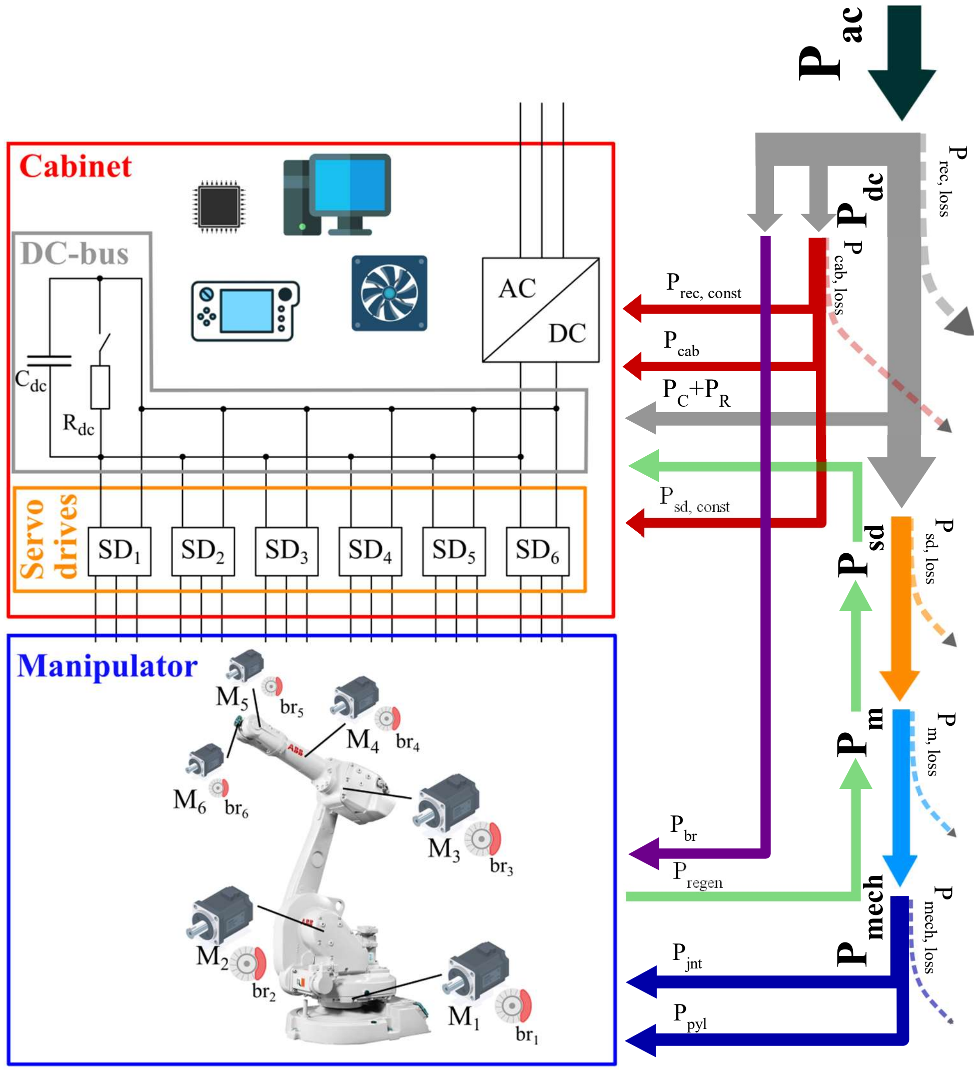
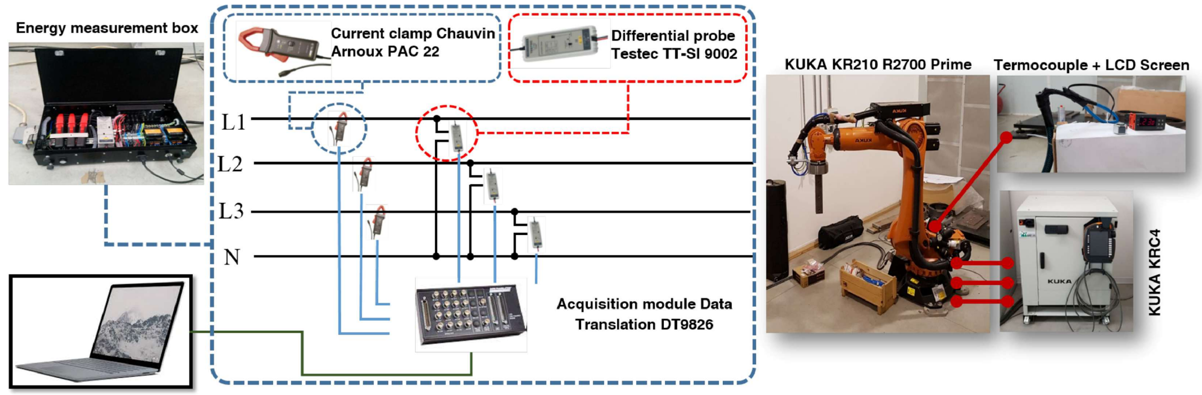


Fig 7: Power distribution from the grid to the subsystems of a 6-DOF industrial robot.

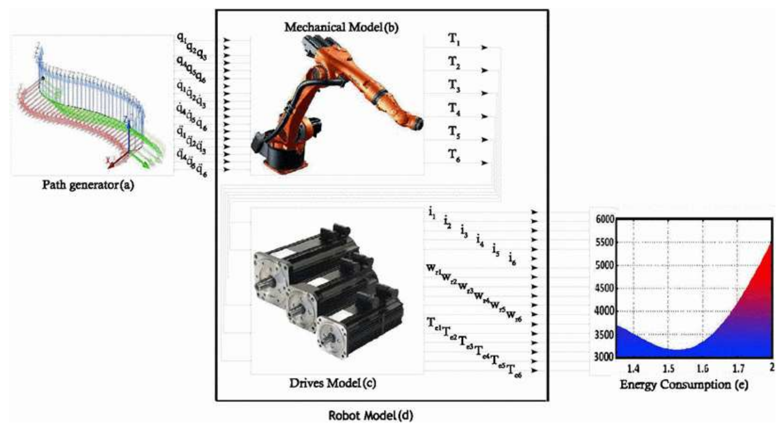
Muru, J.; Rassõlkin, A. A Scoping Review of Energy Consumption in Industrial Robotics. Machines 2025, 13, 542. https://doi.org/10.3390/machines13070542

Measurement and modelling methods

- Power meters
- Controller data
- Energy models
  - Empirical
  - Physics based
  - Data-driven
- Key metrics
  - Energy per cycle
  - Energy by produced part
  - Idle energy
  - Peak power
  - Regenerative energy



M. Gadaleta, G. Berselli, M. Pellicciari, and F. Grassia, "Extensive experimental investigation for the optimization of the energy consumption of a high payload industrial robot with open research dataset," *Robotics and Computer-Integrated Manufacturing*, vol. 68, p. 102 046, Apr. 2021.



A. Othman, K. Belda and P. Burget, "Physical modelling of energy consumption of industrial articulated robots," *2015 15th International Conference on Control, Automation and Systems (ICCAS)*, Busan, Korea (South), 2015, pp. 784-789

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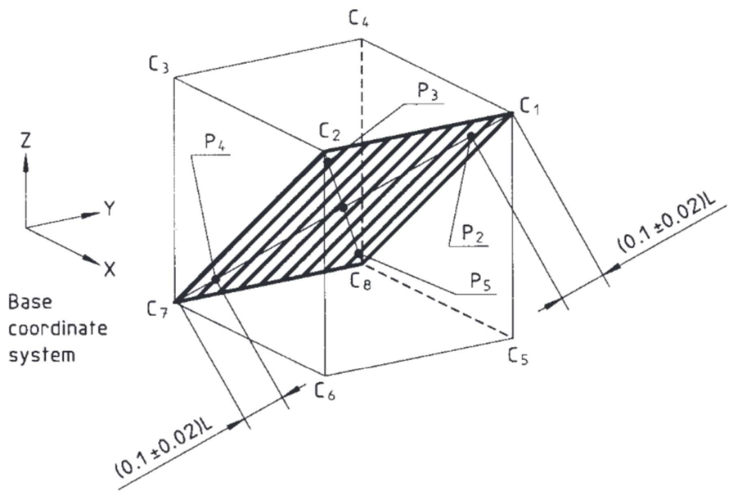
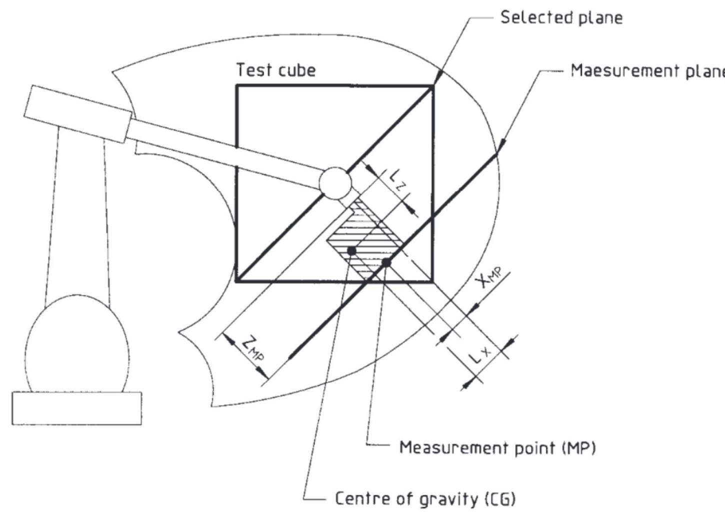
How to assess?



(a)



(b)

- **ISO 9283:1998**
  - Accuracy
  - Repeatability
- Greatest anticipated use
- Largest possible volume
- Motion parameters?

- **VDMA 24608:2013-11**
- Side length multiple of 200 mm
- Static and dynamic tests
- 30 x (P2-P3-P4-P5-P2) at max speed and nominal load

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ABB Robotics leads global effort to standardize measurement of industrial robots' energy consumption

IFR International Federation of Robotics

Mar 04, 2026 — ABB Robotics is leading the development of a technical specification for the International Standardization Organization (ISO), along with 11 other countries, to measure the energy consumption and efficiency of an industrial robot.

"With no global standard currently in place, it's a challenge for customers to compare the energy consumption of different robots and choose the most energy efficient solution. Unlike other products such as fridges, TVs, washing machines and motors, which have clearly defined standards for how to measure and compare energy efficiency, there is no standard for measuring the energy consumption of a robot. This initiative will empower customers to make informed decisions and help the industry reduce its carbon footprint."

-Gianluca Brotto, Head of Sustainability, ABB Robotics

Due to be completed by August 2026

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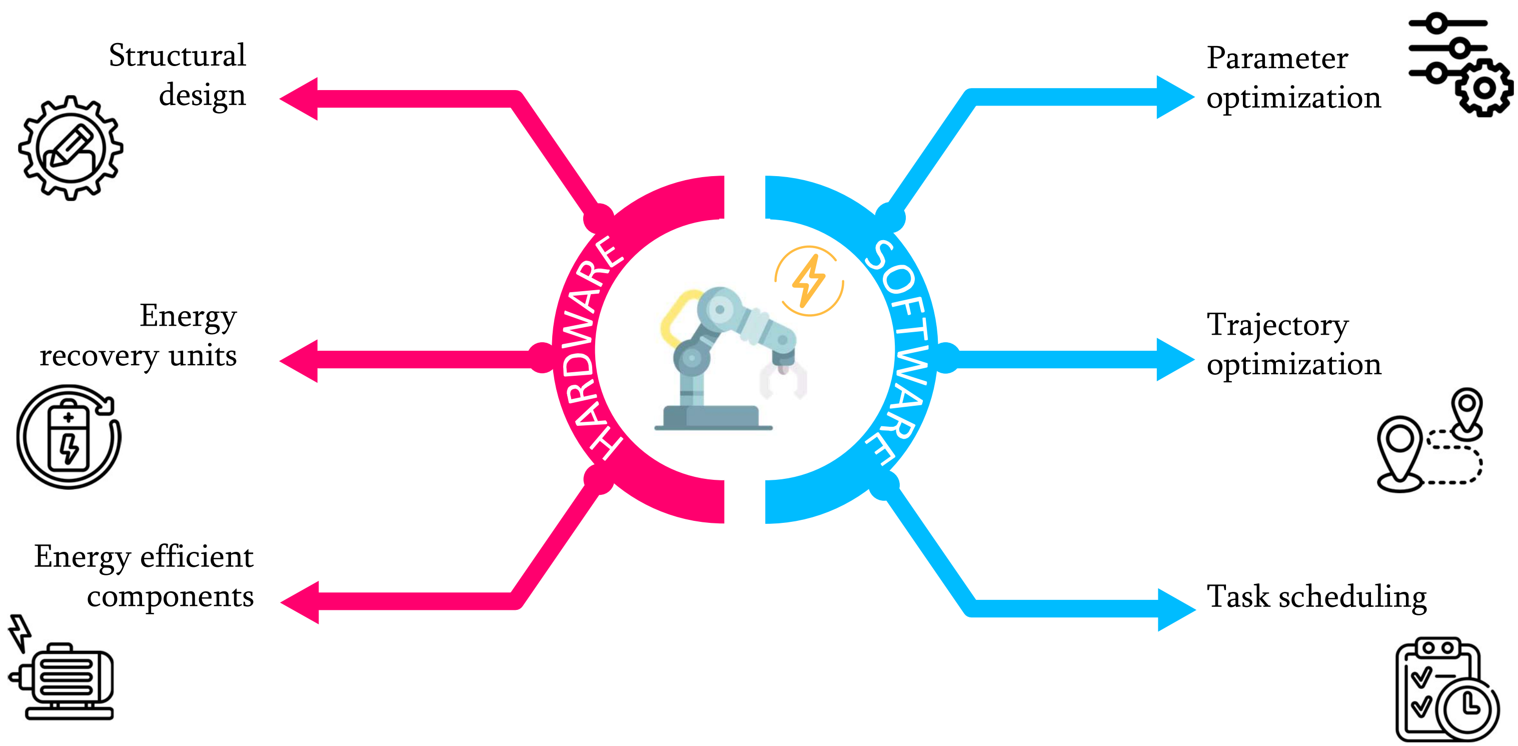
https://ifr.org/ifr-press-releases/news/abb-robotics-leads-global-effort-to-standardize-measurement-of-industrial-robots-energy-consumption

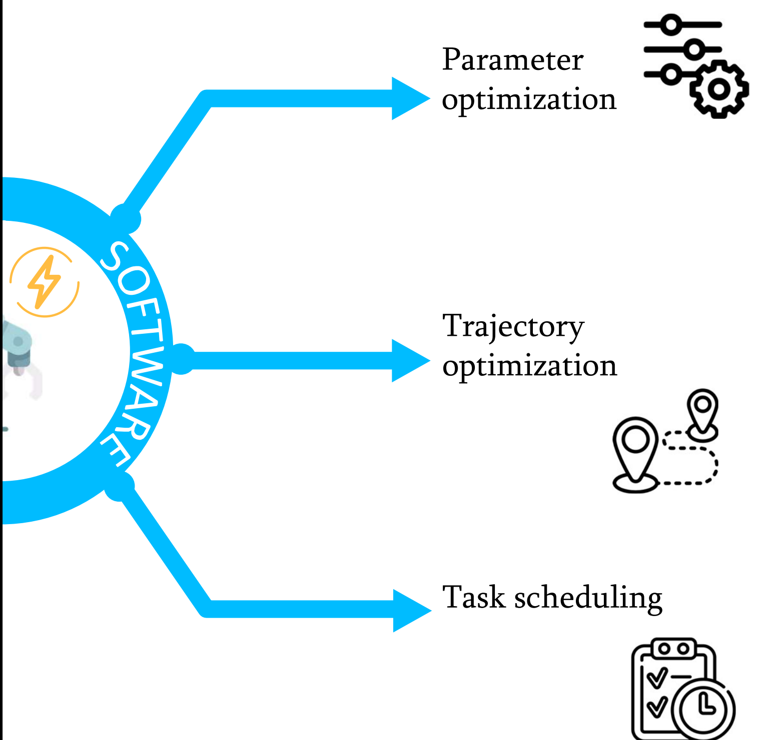
Energy Consumption Optimization (ECO)



Classification of energy optimization strategies.

Muru, J.; Rassõlkin, A. A Scoping Review of Energy Consumption in Industrial Robotics. Machines 2025, 13, 542. https://doi.org/10.3390/machines13070542

Software ECO



- Velocity
- Acceleration
- Load conditions

- Robot kinematics and dynamics
- Robot placement
- Data driven methods for path planning

- Sequence and timing of tasks
- Multi-robot systems
- Data driven methods for task planning

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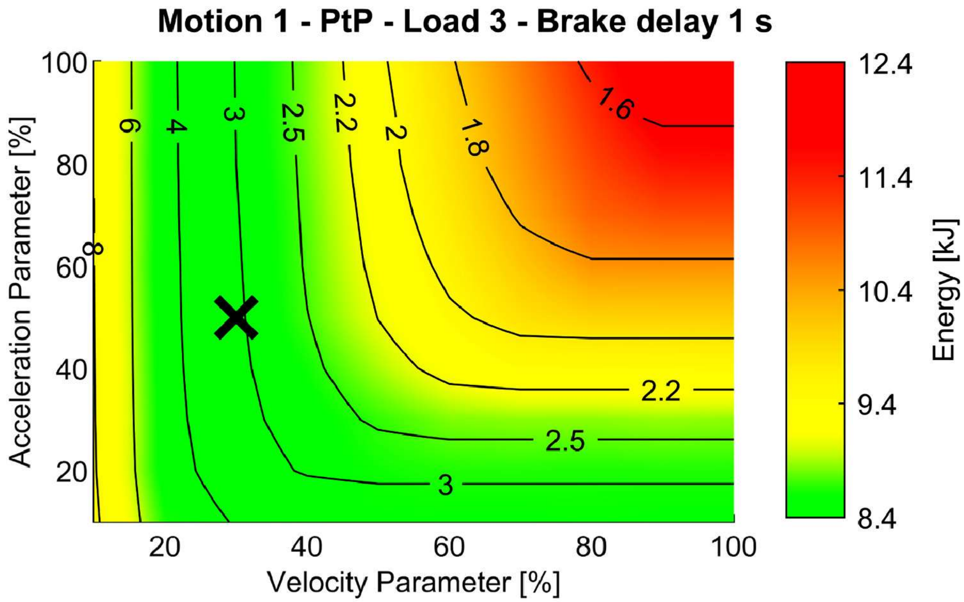
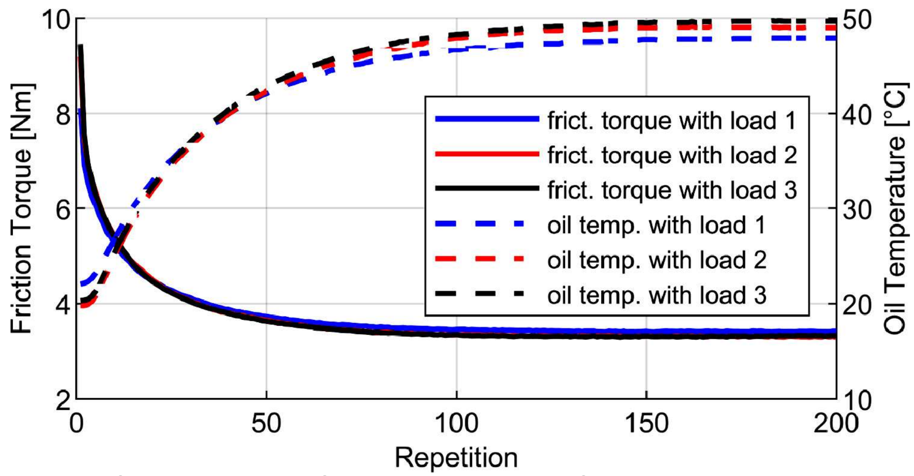
Muru, J.; Rassõlkin, A. A Scoping Review of Energy Consumption in Industrial Robotics. Machines 2025, 13, 542. https://doi.org/10.3390/machines13070542

Parameter optimization

- Identify the optimal motion parameters
  - Velocity
  - Acceleration
- Typically, between 50 – 80 % of maximum

- Secondary parameters
  - Payload
  - Lubricant temp





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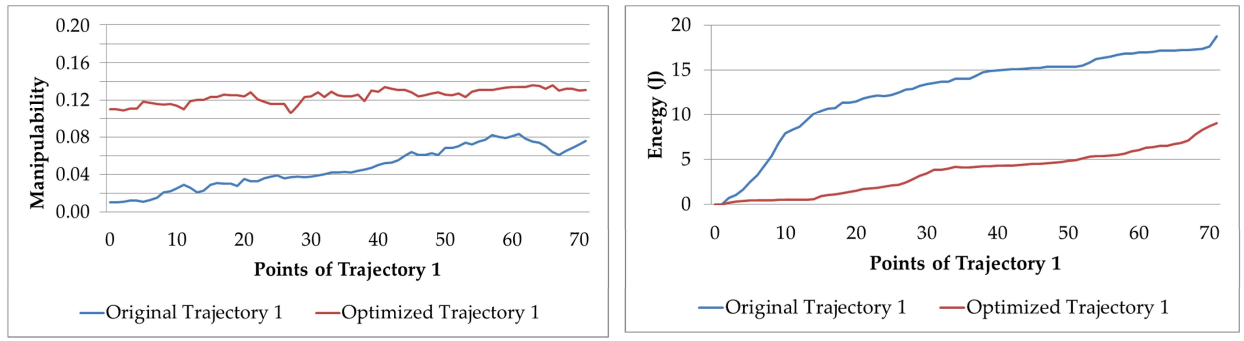
Gadaleta, M.; Berselli, G.; Pellicciari, M.; Grassia, F. Extensive experimental investigation for the optimization of the energy consumption of a high payload industrial robot with open research dataset. *Robot. Comput.-Integr. Manuf.* **2021**, *68*, 102046.

Trajectory optimization

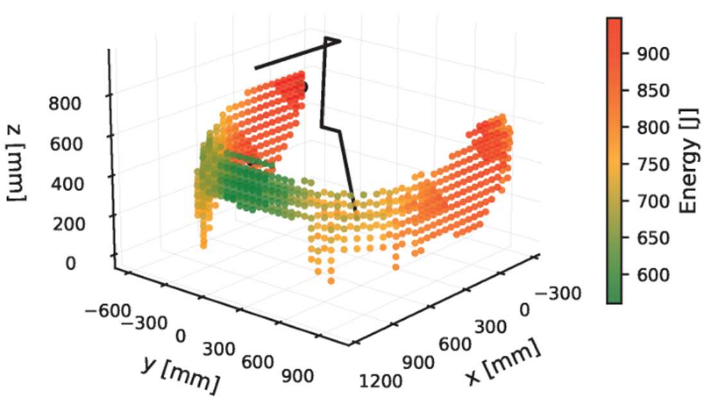
- Closely related to motion parameter tuning
- Smoother paths
- Avoid unnecessary joint motion
- Reduce excessive acceleration and deceleration
- Path and robot placement



Garriz, C.; Domingo, R. Trajectory Optimization in Terms of Energy and Performance of an Industrial Robot in the Manufacturing Industry. *Sensors* **2022**, *22*, 7538.

Manipulability index – metric to quantify robot's ability to move

$$w = \det \sqrt{J(q) \times J^T(q)}$$



Wierbica, R.; Krejčí, J.; Babjak, J.; Kot, T.; Krys, V.; Bobovský, Z. Automatic Optimization of Industrial Robotic Workstations for Sustainable Energy Consumption. *AI* **2026**, *7*, 17

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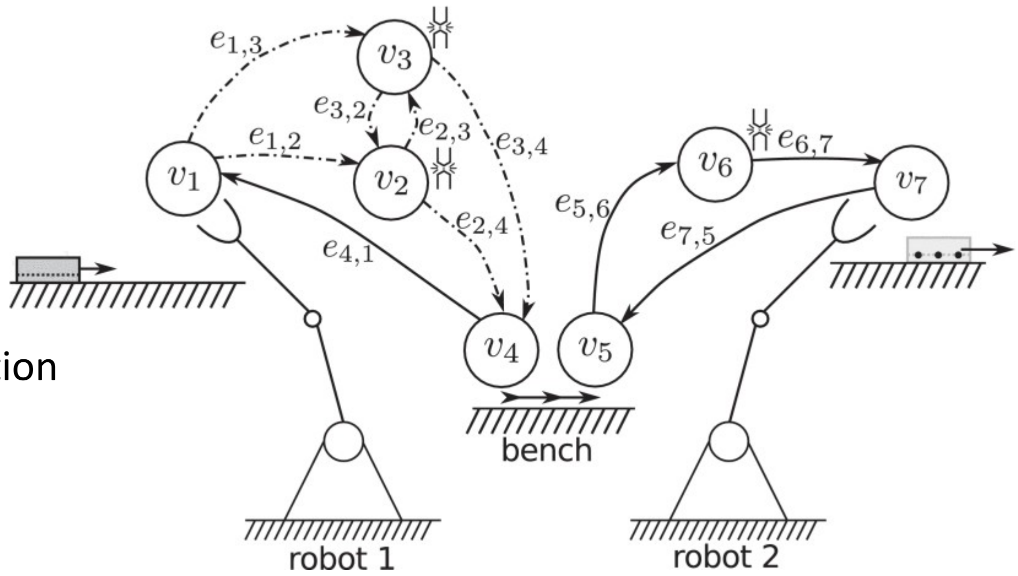
Task scheduling

- Multi robot manufacturing cells
- Human-Robot collaboration
- Coordination between several machines
  - Minimize idle times
  - Sequence tasks to reduce unnecessary motion
  - Balance cycle time and throughput



- Algorithms
  - Genetic algorithms
  - Conflict-Based Search

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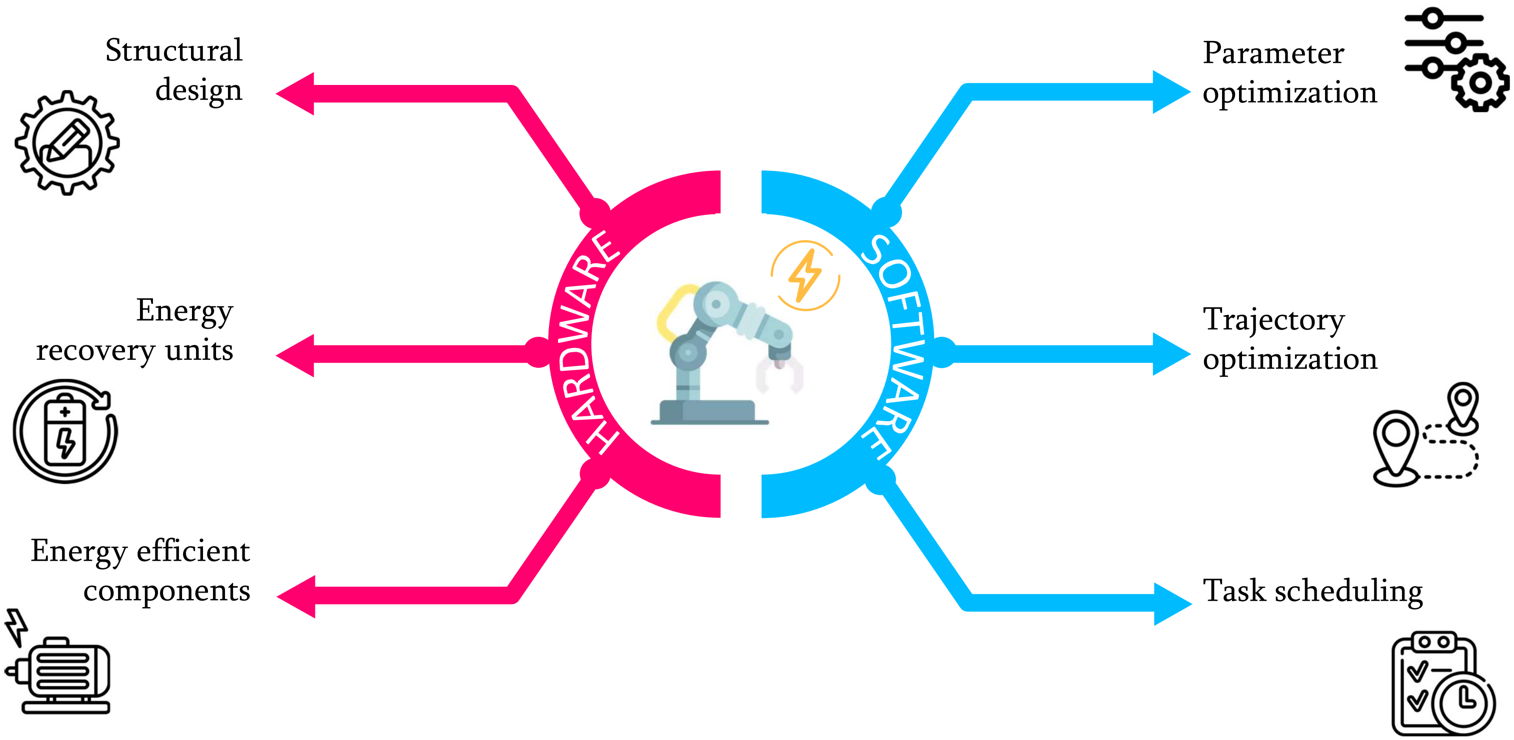
Bukata, L.; Sucha, P.; Hanzalek, Z.; Burget, P. Energy Optimization of Robotic Cells. *IEEE Trans. Ind. Inform.* **2017**, *13*, 92–102.

SWOT

Strengths	Weaknesses
• Software based optimization can significantly reduce energy consumption without altering hardware.	• Performance is highly dependent on accurate models; Artificial intelligence (AI) and machine learning (ML) based methods may require extensive training data.
• Universally effective for wide variety of applications.	• Optimization strategies may vary significantly by task and robot type.
• Online and real-time optimization techniques enable adaptation to varying operational conditions.	• Implementation complexity increases when integrating real-time optimization within existing control systems.
• Can be applied at different levels–motion, task scheduling, and trajectory–offering multi-layered efficiency gains.	• May conflict with other goals such as cycle time or throughput if not well balanced.
Opportunities	**Threats**
• Integration with AI and ML allows adaptive, context-aware optimization.	• Over-reliance on complex algorithms may reduce interpretability and increase system debugging difficulty.
• Scalable to multi-robot cells through task scheduling and robot coordination.	• For large-scale robot systems, computational time or model complexity may become cumbersome.
• Trajectory optimization can take advantage of electromechanical energy recovery (e.g., regenerative braking, DC bus coupling) highlighting the opportunity for hybrid strategies.	• Lack of standardization in optimization methods can hinder adoption across robot types and manufacturers.
• Combining real-time sensor data with optimization models could enable closed-loop energy-aware control.	• Some algorithms do not scale efficiently. As the number of robots, tasks, or decision variables increases, the computational complexity can grow exponentially, making real-time or large-scale implementation impractical

Muru, J.; Rassõlkin, A. A Scoping Review of Energy Consumption in Industrial Robotics. Machines 2025, 13, 542. https://doi.org/10.3390/machines13070542

Energy Consumption Optimization (ECO)



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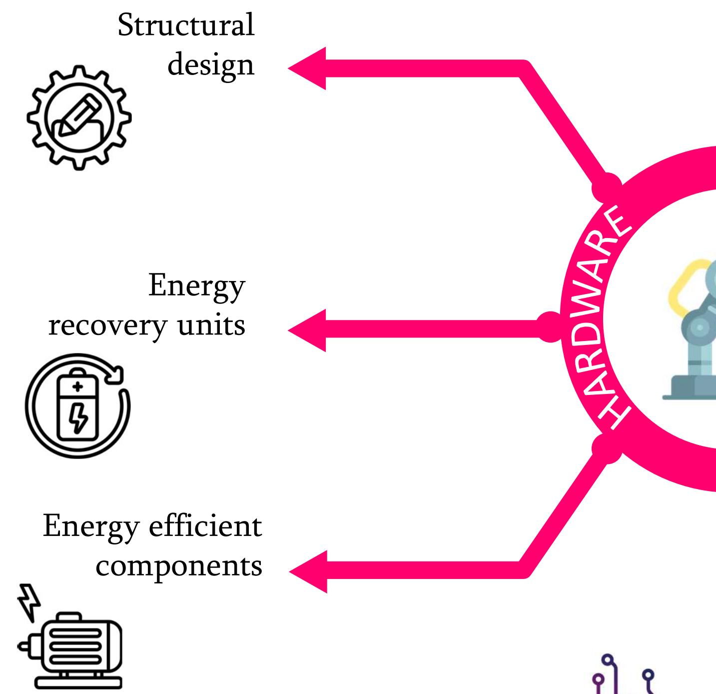
Hardware ECO

- Lightweight components
- Reducing weight
- Reducing inertia

- Kinetic-energy recovery
- Braking recuperation
- DC-bus sharing

- Efficient motors
- Efficient motor drives
- Efficient transmission systems



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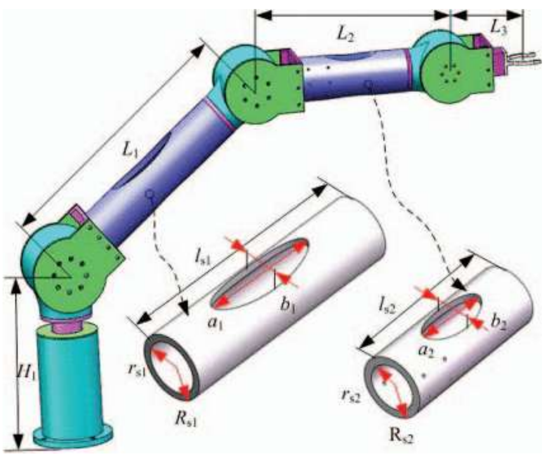
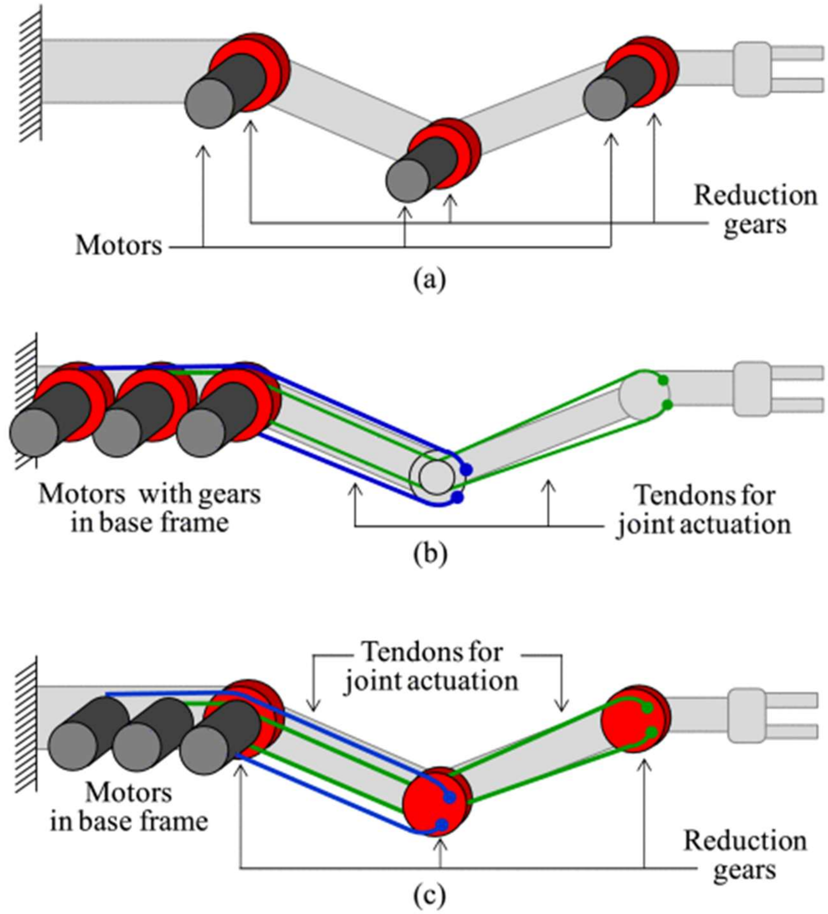
Muru, J.; Rassõlkin, A. A Scoping Review of Energy Consumption in Industrial Robotics. Machines 2025, 13, 542. https://doi.org/10.3390/machines13070542

Structural design

- Structure optimization
- Lightweight components
  - Lower joint torques
- Actuator placement
  - Cable and belt driven systems



Yin, H.; Huang, S.; He, M.; Li, J. An overall structure optimization for a light-weight robotic arm. In Proceedings of the 2016 IEEE 11th Conference on Industrial Electronics and Applications (ICIEA), Hefei, China, 5–7 June 2016; pp. 1765–1770.



Kim, Y.J. Anthropomorphic Low-Inertia High-Stiffness Manipulator for High-Speed Safe Interaction. *IEEE Trans. Robot.* **2017**, *33*, 1358–1374.

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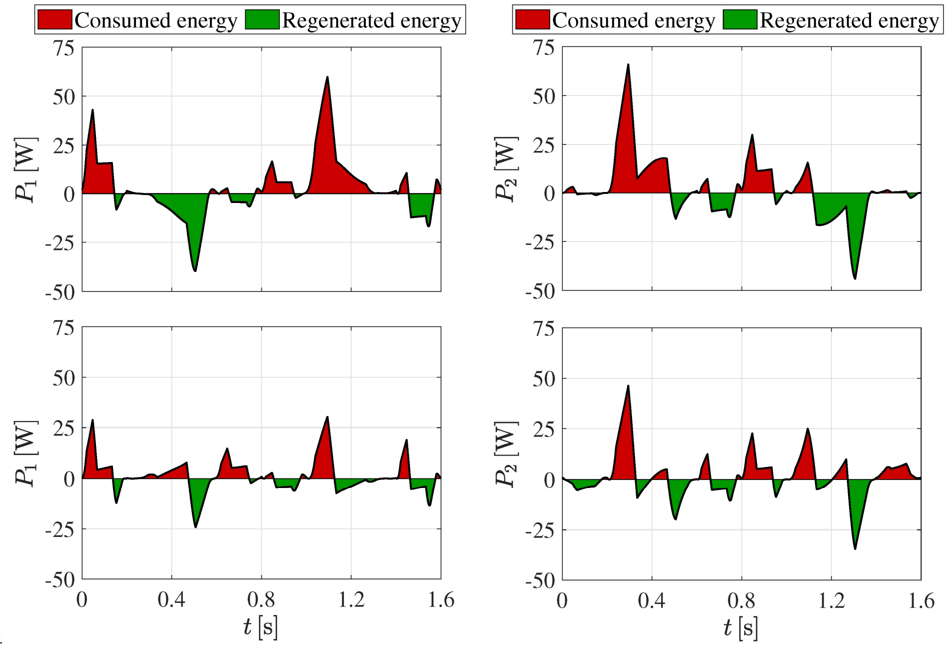
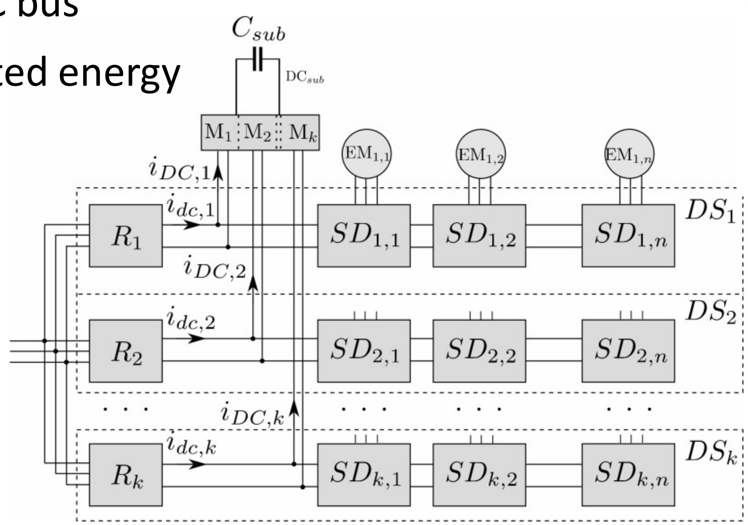
Energy recovery

- Capacitive energy buffering
  - DC-bus capacitors
- Robot to robot energy sharing
  - Shared DC bus
  - Recuperated energy



Palomba, I.; Wehrle, E.; Carabin, G.; Vidoni, R. Minimization of the Energy Consumption in Industrial Robots through Regenerative Drives and Optimally Designed Compliant Elements. *Appl. Sci.* **2020**, *10*, 7475.



Meike, D.; Senfelds, A.; Ribickis, L. Power converter for DC bus sharing to increase the energy efficiency in drive systems. In Proceedings of the IECON 2013—39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 10–13 November 2013; pp. 7199–7204.

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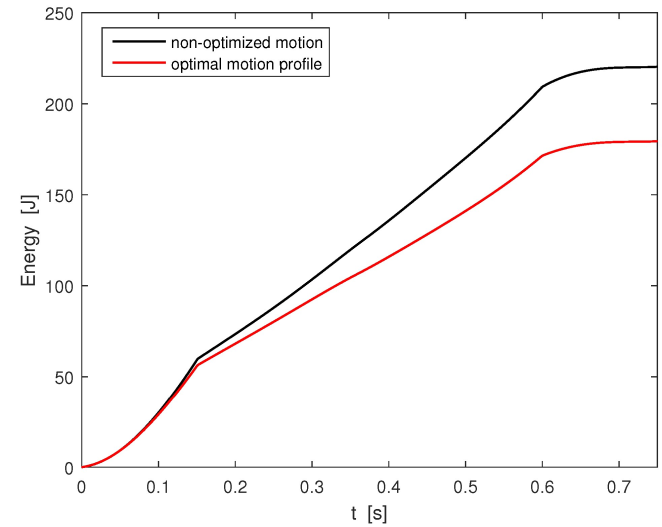
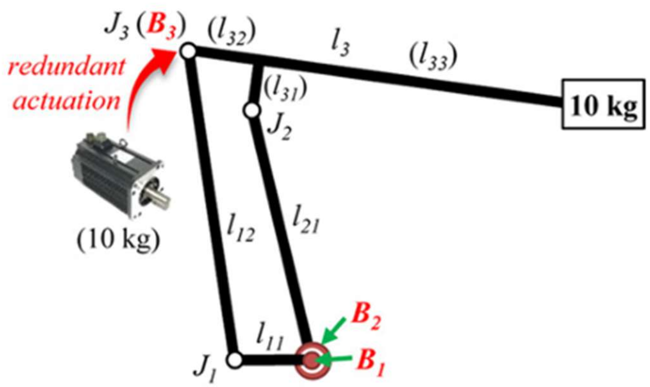
Functional redundancy

- Same tasks – multiple joint configurations
  - Minimal joint torque
- Redundant DOF to reduce peak power
- Mostly relevant for collaborative robots

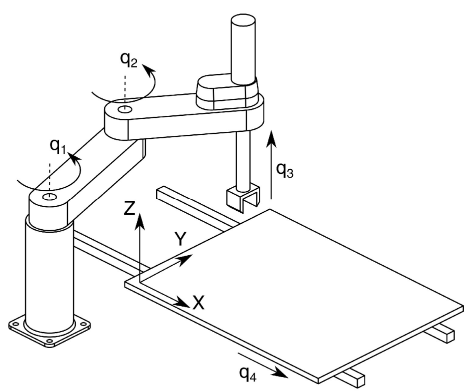


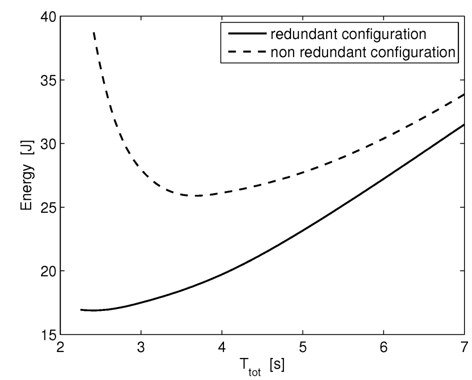
Boscariol, P.; Caracciolo, R.; Richiedei, D.; Trevisani, A. Energy Optimization of Functionally Redundant Robots through Motion Design. *Appl. Sci.* **2020**, *10*, 3022.

- Added links for redundant actuation



Lee, G.; Sul, S.K.; Kim, J. Energy-saving method of parallel mechanism by redundant actuation. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2015**, *2*, 345–351.





Boscariol, P.; Richiedei, D. Trajectory Design for Energy Savings in Redundant Robotic Cells. *Robotics* **2019**, *8*, 15

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SWOT

Strengths	Weaknesses
• Significant reduction in joint torques by relocating actuators to the base	• Increased mechanical complexity in transmission systems.
• Lightweight materials and optimized link design reduce inertia and enable use of smaller motors	• Maintenance and calibration of cable- or belt-driven systems may be more demanding.
• Structural optimization through multi-objective algorithms yields stiffness-mass-efficient designs	• Trade-offs between weight reduction and structural rigidity or load capacity.
• Enables safer and more precise motion due to lower moving mass	• Topology optimization requires high computational resources.
Opportunities	**Threats**
• Potential integration with energy recuperation systems	• Increased design complexity may limit applicability in cost-sensitive or compact environments.
• Applicable to a wide range of robots and payload classes	• Cable or belt fatigue and durability could limit long-term performance.
• Functional redundancy can be leveraged for further energy optimization via smart motion planning	• Dependence on highly specific mechanical configurations may limit modularity or scalability.
	• Structures with optimized topologies often feature open or exposed geometries, which can compromise their suitability for harsh industrial environments by reducing their ingress protection (IP) rating.

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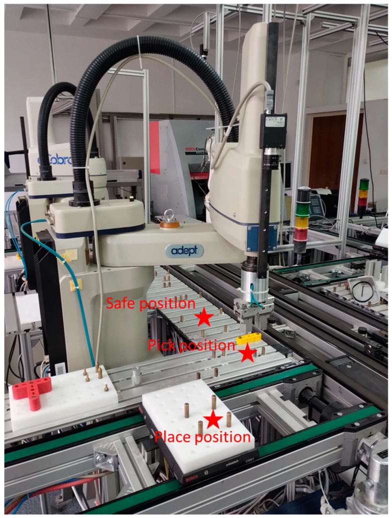
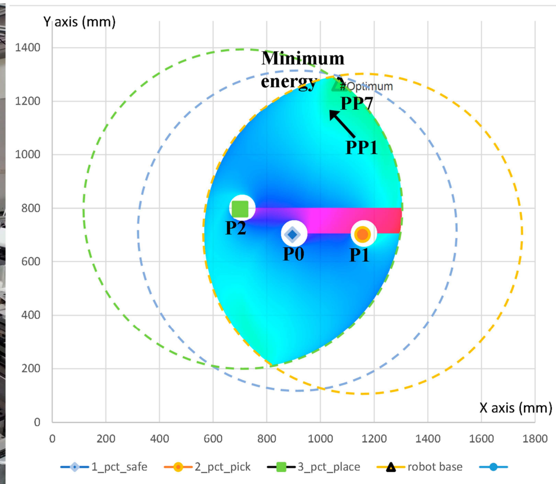
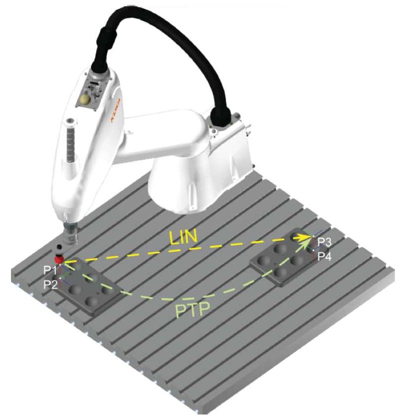
Case examples

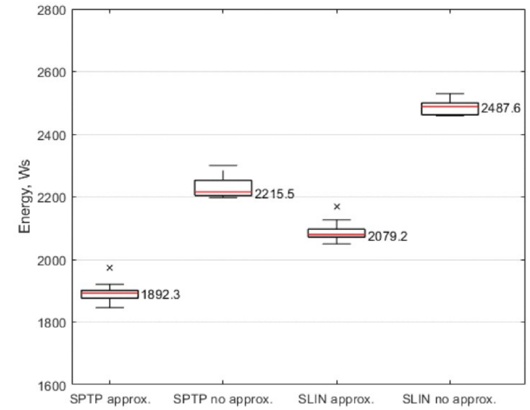




Energy optimal layout design

Răileanu, S.; Borangiu, T.; Lențoiu, I.; Constantinescu, M. Optimizing Energy Consumption of Industrial Robots with Model-Based Layout Design. *Sustainability* **2024**, *16*, 1053.



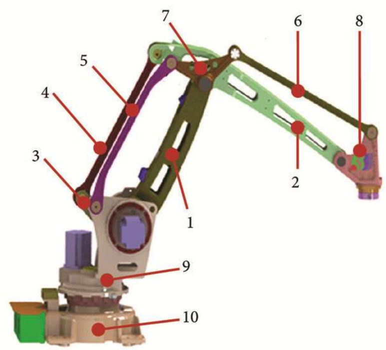


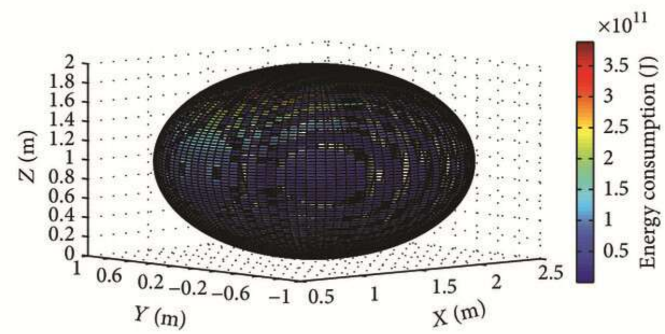
Motion parameters and trajectory design in a pick-and-place application

J. Muru and A. Rassõlkin, "Energy Efficient Motion Parameters for Industrial SCARA Robot In a Pick-and-Place Application," *2025 International Conference on Electrical Drives and Power Electronics (EDPE)*, Dubrovnik, Croatia, 2025, pp. 1-6

Energy consumption vs pick point location in palletizing

Liu, Y.; Liang, L.; Han, H.; Zhang, S. A Method of Energy-Optimal Trajectory Planning for Palletizing Robot. *Math. Probl. Eng.* **2017**, 5862457.





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Conclusion

Energy efficiency means performing the same industrial tasks with less wasted motion, less idle energy and smarter system integration.

- Measure energy use at robot, cell and process level
- Optimize trajectories, motion parameters, scheduling
  - Main takeaway for **robot programmers**
- Select hardware that matches the actual task needs
- Balance energy savings with productivity and quality
- Different methods can be combined

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