

MODAPTO [101091996]: Modular Manufacturing and Distributed Control via Interoperable Digital Twins



9.2.3 Metrics to evaluate robot designs and production line efficiency

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The evaluation of robot designs and production line efficiency through sustainability metrics represents a paradigm shift in manufacturing system assessment. Traditional metrics focused primarily on speed, accuracy, and reliability. Today's comprehensive evaluation framework incorporates environmental impact as a co-equal consideration with operational performance.

Energy consumption metrics form the foundation of sustainability assessment for robotic systems. The MODAPTO framework implements sophisticated energy models that go beyond simple power measurements. These models calculate instantaneous power demand based on the robot's kinematic state, accounting for the energy required to accelerate and decelerate each joint, overcome friction and gravity, and handle payloads. The total energy consumption is calculated by integrating these instantaneous power demands over complete motion cycles. This detailed approach reveals that seemingly minor changes in motion profiles can result in significant energy savings.

The optimization of robot trajectories for energy efficiency demonstrates the practical application of these metrics. Traditional trajectory planning focused on minimizing cycle time, often resulting in aggressive acceleration and deceleration profiles that consume excessive energy. The sustainability-aware optimization algorithms in the virtual commissioning environment can find alternative trajectories that reduce energy consumption by 10-30% while maintaining acceptable cycle times. These optimizations consider factors such as the synchronization of multi-axis movements to minimize peak power demand and the use of gravity-assisted motions where possible.

Carbon footprint metrics extend the analysis beyond direct energy consumption. The carbon intensity of robot operations depends not only on how much energy is consumed

Resource efficiency metrics evaluate how effectively robots and utilize materials and consumables. In welding applications, for example, the metrics might include wire consumption per weld, shielding gas usage, and the percentage of welds requiring rework. In assembly operations, metrics could track the precision of adhesive dispensing or the waste generated from packaging materials. The virtual environment allows these metrics to be optimized through simulation, testing different process parameters to minimize waste while maintaining quality.

Overall Equipment Effectiveness (OEE) has been expanded in the MODAPTO framework to include sustainability dimensions. Traditional OEE considers availability, performance, and quality. The sustainability-enhanced OEE adds energy efficiency as a fourth dimension, creating a more comprehensive metric that balances productivity with environmental impact. This expanded metric helps

identify situations where small sacrifices in traditional OEE components can yield significant sustainability improvements.

Life cycle assessment (LCA) metrics provide a holistic view of robot and sustainability.

Comparative metrics enable benchmarking and continuous improvement. The virtual commissioning environment can maintain libraries of performance data from different robot models, allowing engineers to quickly compare options for new applications. These comparisons go beyond simple datasheet specifications to include real-world performance under specific application conditions. Real-time optimization metrics support dynamic adjustment of production systems for sustainability. These metrics evaluate the current state of the production system and identify immediate opportunities for improvement. For example, if certain equipment is operating below capacity, the system might suggest consolidating operations to allow some equipment to be powered down. During periods of high renewable energy availability, the system might suggest accelerating production to take advantage of cleaner power.

The integration of artificial intelligence and machine learning enhances the sophistication of these metrics. AI algorithms can identify complex patterns in the relationship between operational parameters and sustainability performance. They can predict the long-term impact of design decisions on sustainability metrics and suggest non-obvious optimizations. For example, machine learning might reveal that slightly reducing robot speed during certain operations not only saves energy but also reduces wear and extends maintenance intervals, providing compound sustainability benefits.

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