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Recent Developments in Grinding Machines

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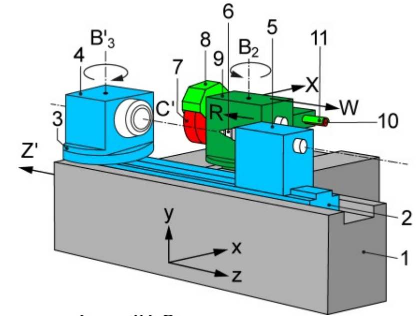
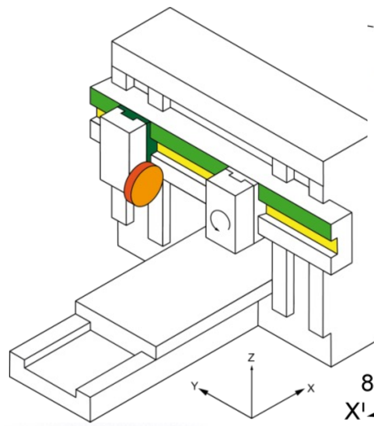
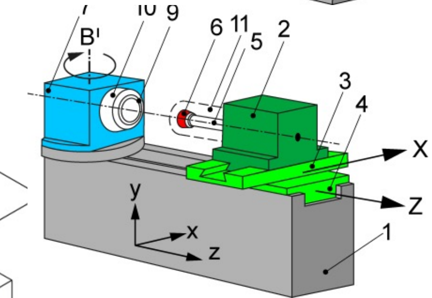
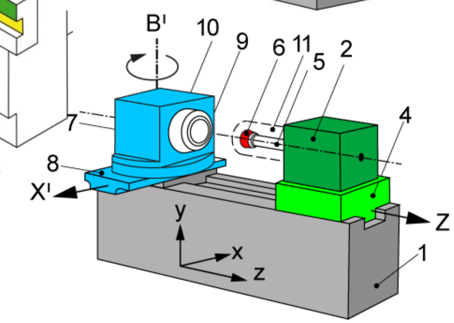
Contents

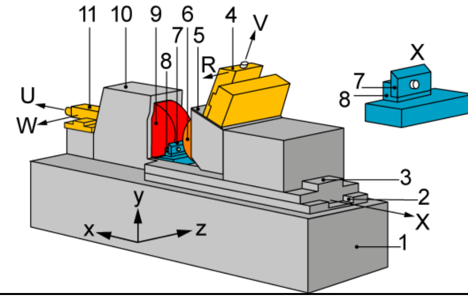
- 1. Introduction to grinding machines
- 2. Trends in development of abrasive processes
- 3. Market driven requirements
- 4. Implications on grinding machines
- 5. Trends in auxiliary devices
- 6. Special machine developments
- 7. Simulation, control and expert systems
- 8. Conclusion and open issues

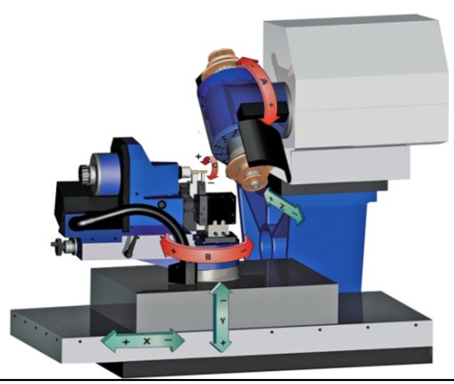


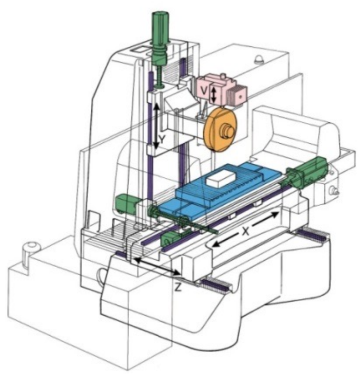


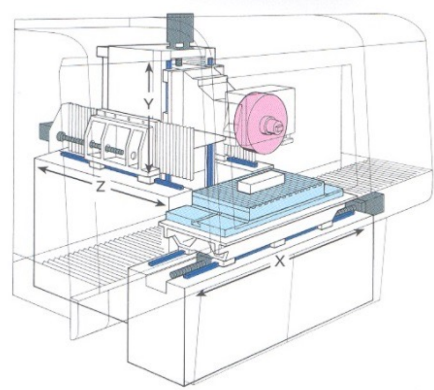












Technology position in the value chain

Semi-finished — Hot forming → **Intermediate** — Soft machining → **Finishing** — **Grinding** → **Fine finishing** — Polishing

Effort
Know-how

For each process

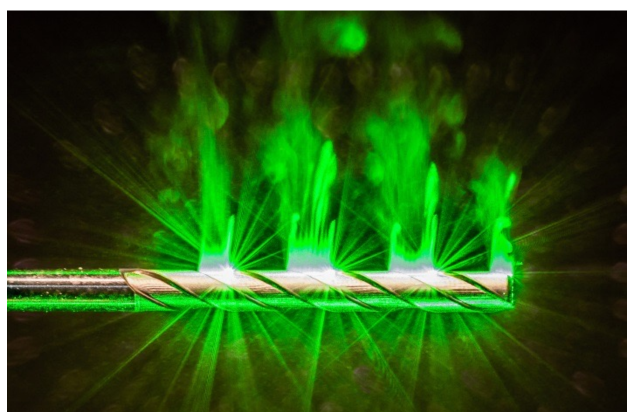
Increase
Robustness
Process speed

Improvement
Accuracy
Surfaces

Degree of completion →

Semi-hot forming → High-performance grinding

Process competition:
- Laser ablation
- Hard machining with geometrically defined cutting edges

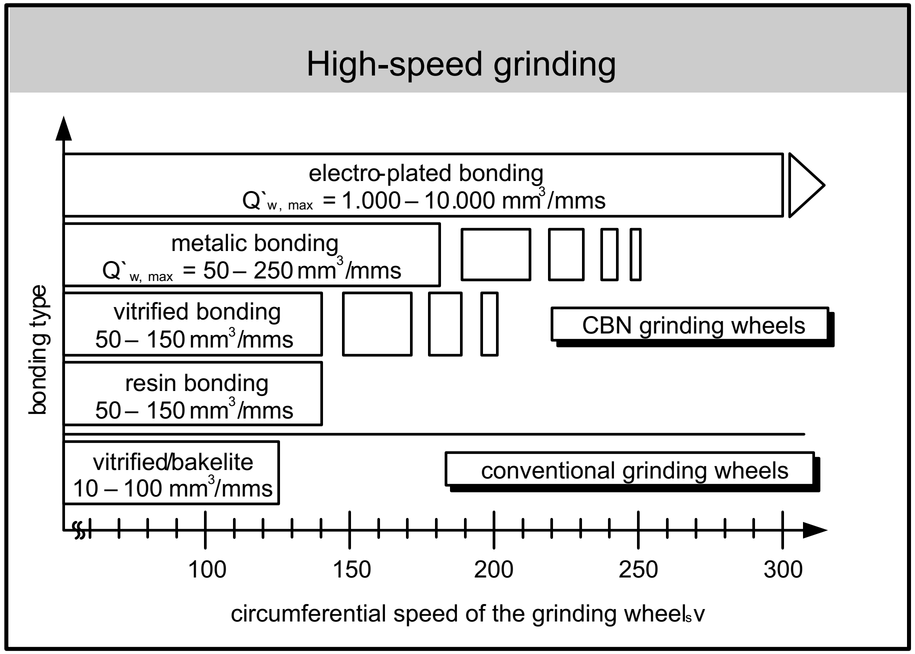


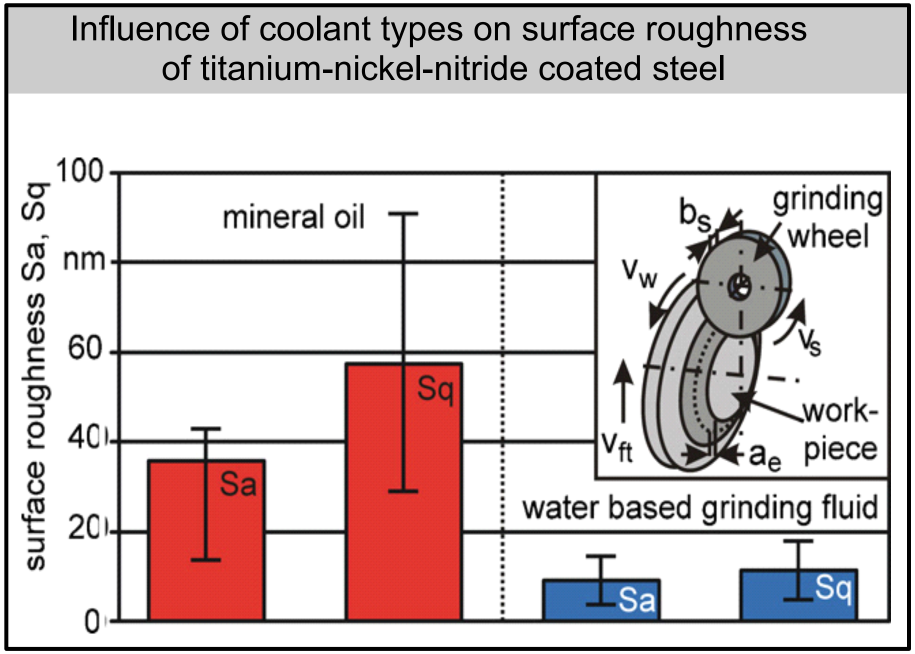
Peculiarities of grinding machines

- High cutting speed ranges: 30 to 300 m/s
- Normal forces significantly higher than the tangential forces
- Grinding machines need massive protections against wheel failure
- CNC driven dressing devices to generate the tool geometry
- Extreme precision of axes, rotational accuracy of spindles
- Balancing device to reduce centrifugal forces
- Large heat generated ➔ cooling dominates energy consumption
- Grinding machines with oil as coolant require a fire protection
- Contact-sensor based on acoustic emission (AE)
- High quality enabler ➔ part measuring device for iterative correction
- Abrasive swarf ➔ requirements for sealing-off machine parts
- High costs

Trends in development of grinding processes

- Structured abrasive layer technology and grain orientation
- Modified grinding wheel hub designs
- High-speed-grinding (HSG)
- Hybrid & multi-task grinding technologies
- Temperature-controlled grinding processes
- Importance of coolant supply and coolant type

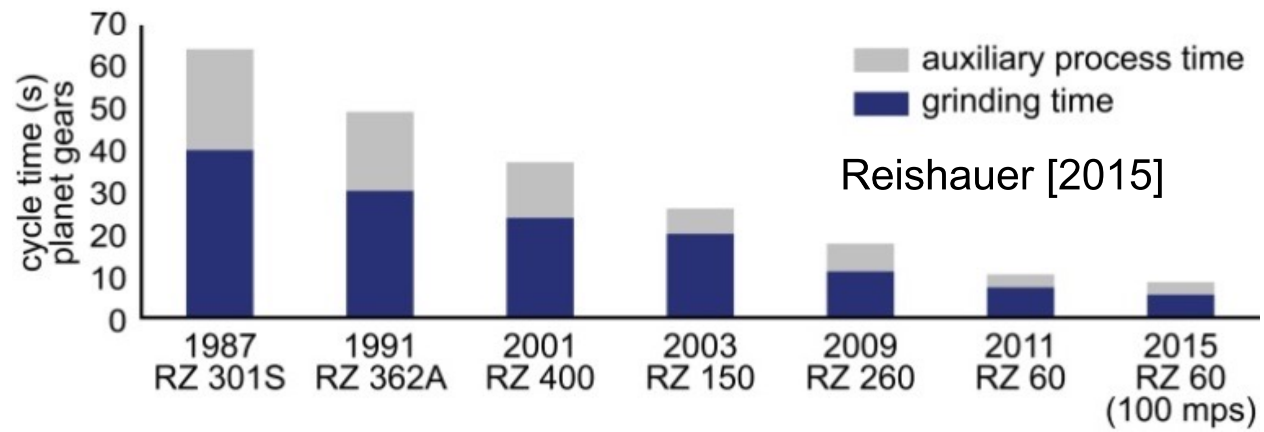


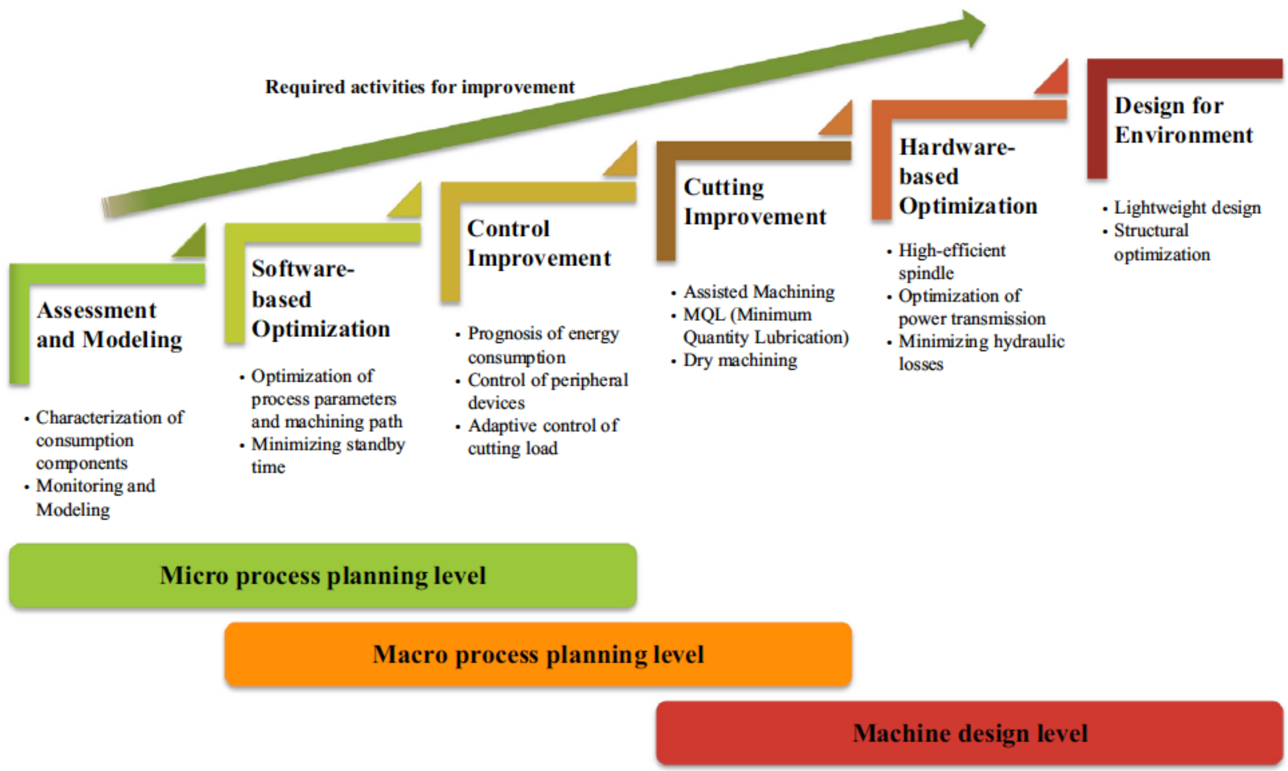


Grimme [2010]

Market-driven requirements

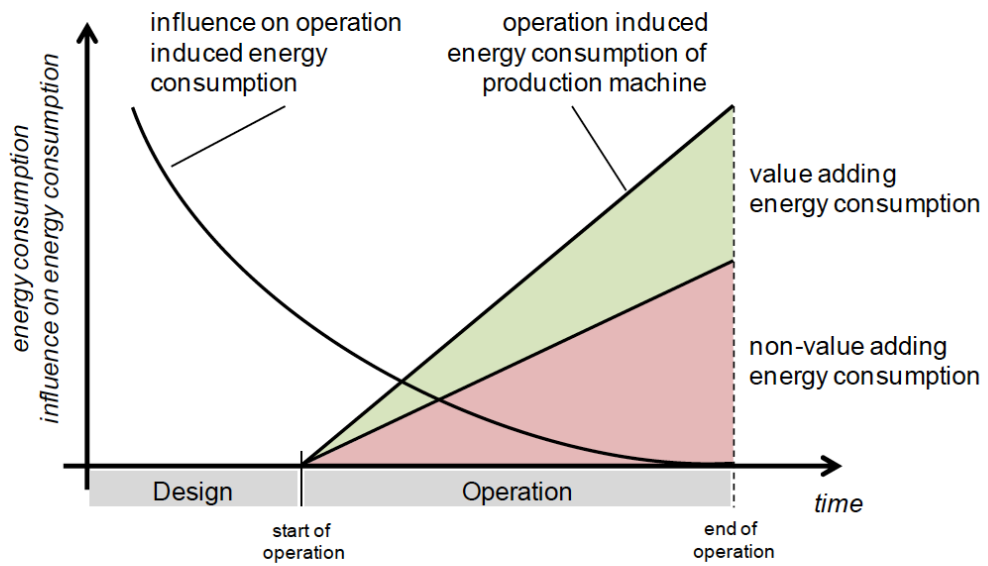
- Productivity
- Accuracy
- TCO
- Resource and energy efficiency
- Footprint
- Safety and ergonomic impact
- Maintenance requirements
- Industry 4.0

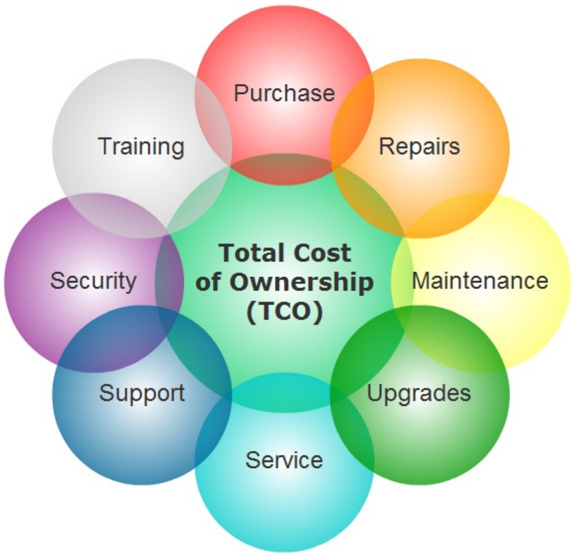




Total cost of ownership (TCO)

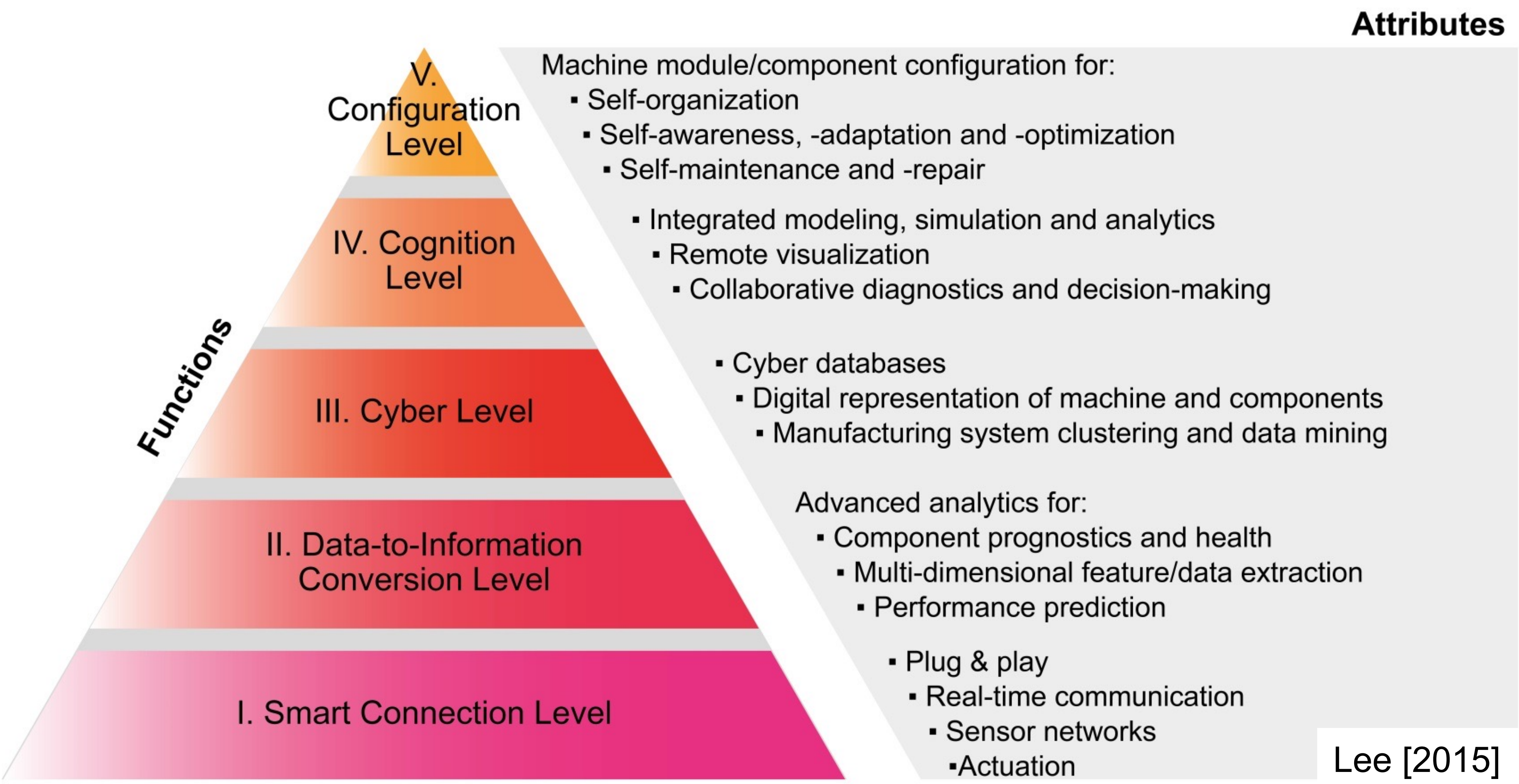
- Machine-tool acquisition and depreciation, services and support (e.g. maintenance, training), operating expenses (e.g. tooling costs for grinding and dressing), the cost of machine downtime & productivity losses.
- The cost of **energy consumption** can be incorporated into to specific operation's data, such as the **OEE**. The machine-tool builder has significant leverage to effect the TCO in terms of energy and resource efficiency in the machine design phase.
- New **business models**? Material-removal rate as a service? "Result-oriented" services focuses on a specific manufacturing result.





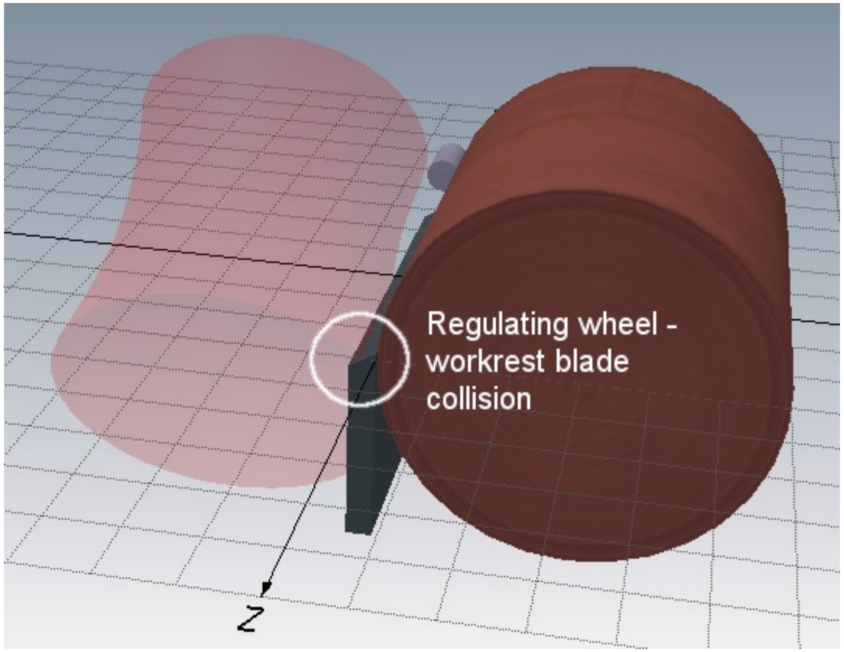
Industry 4.0

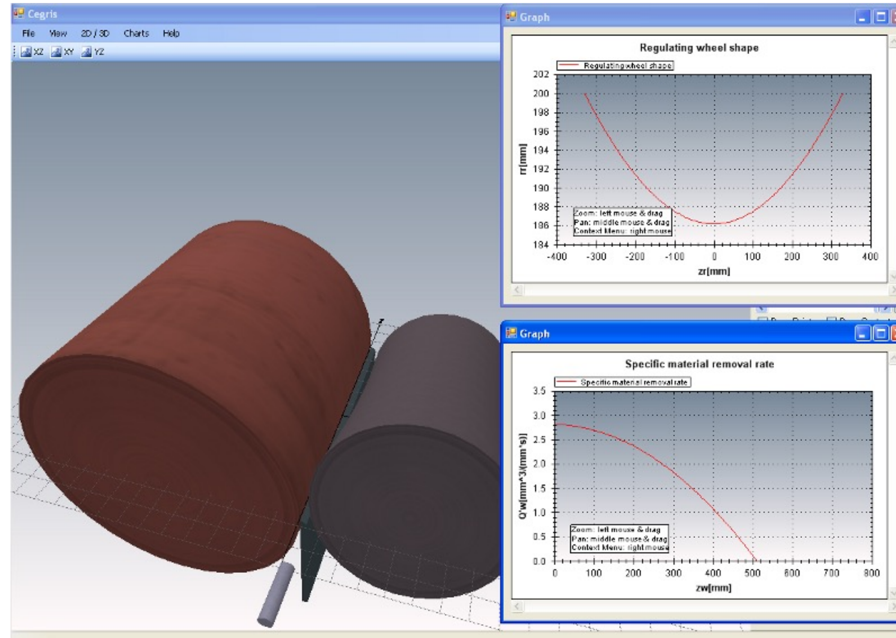
- (1) **Big data**, (2) **advanced analytics**, (3) new systems of **human-machine interaction**, and (4) utilization of **cyber-physical systems** (CPS) for interconnecting digital (virtual) resources with the physical assets.

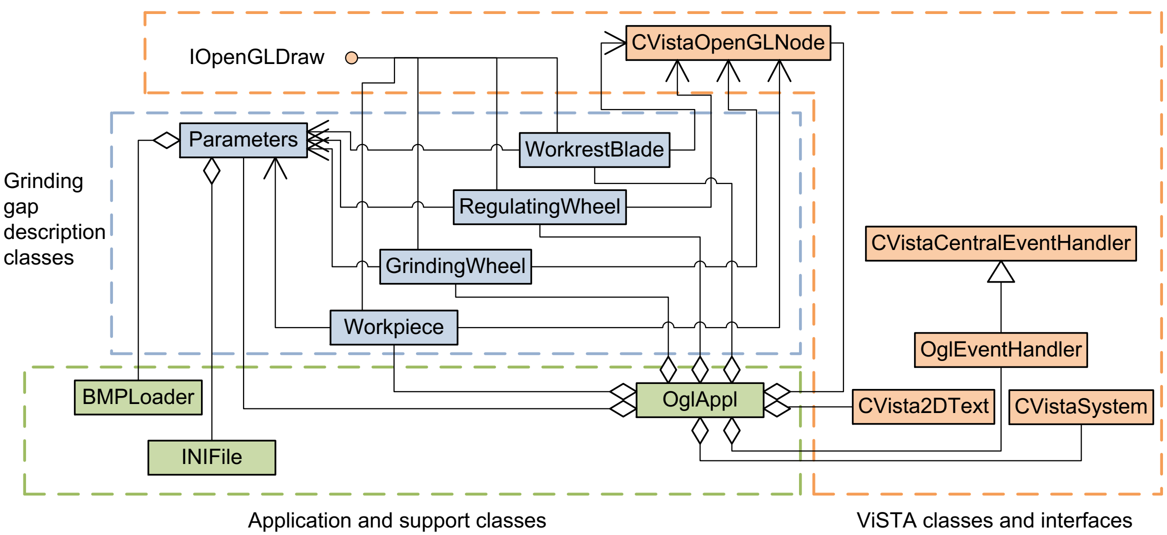


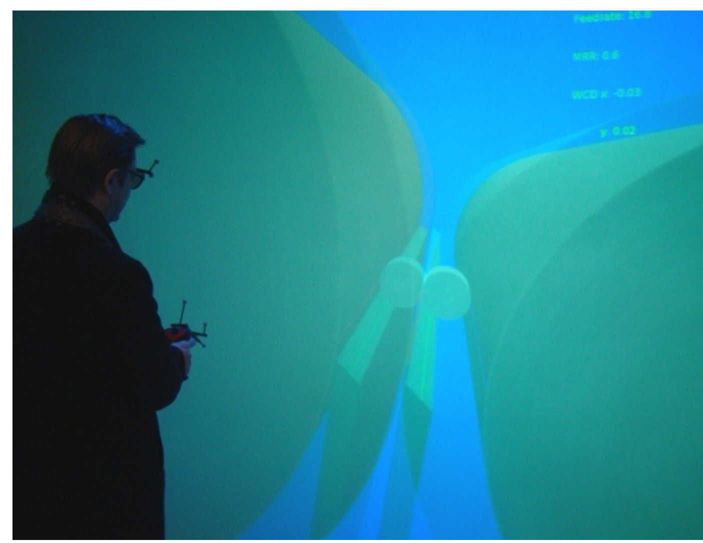
Lee [2015]

Virtual reality



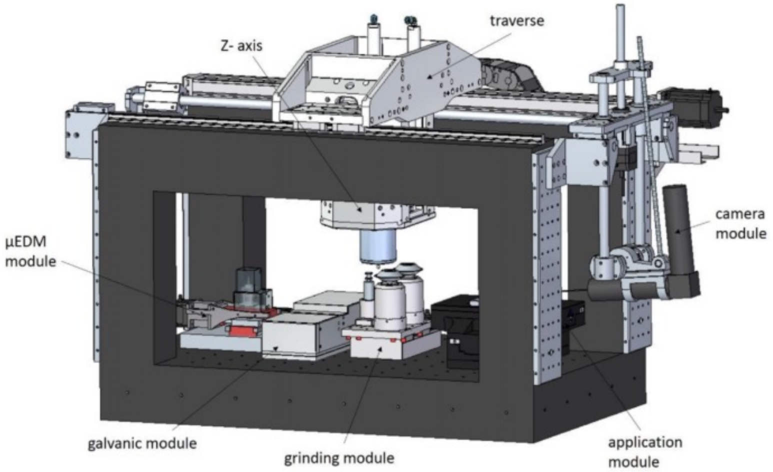




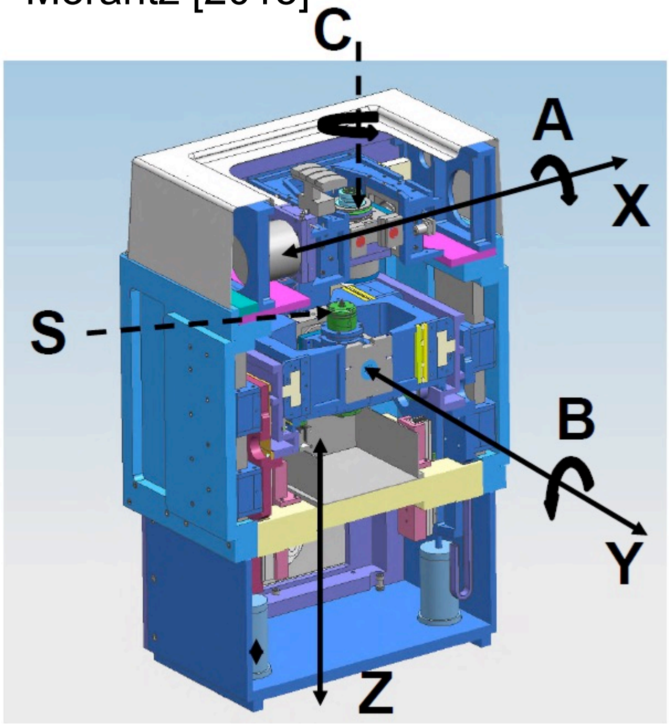


Principles of accuracy

- Error budgeting in design phase
- A closed structural loop indicates high stability and the likely use of symmetry to achieve a robust design
- Abbé’s and Bryan’s measurement principles
- Minimizing of thermally-sensitive and mechanical cantilevers and offsets
- Minimizing thermal spatial and timely gradients by design and thermal control
- Use of thermo- and load-symmetric designs
- Hydrostatic bearings and guideways
- Use of materials with low coefficient of thermal expansion
- Use of feed-back systems with high accuracy and linearity
- On-machine tool generation / rework of tools

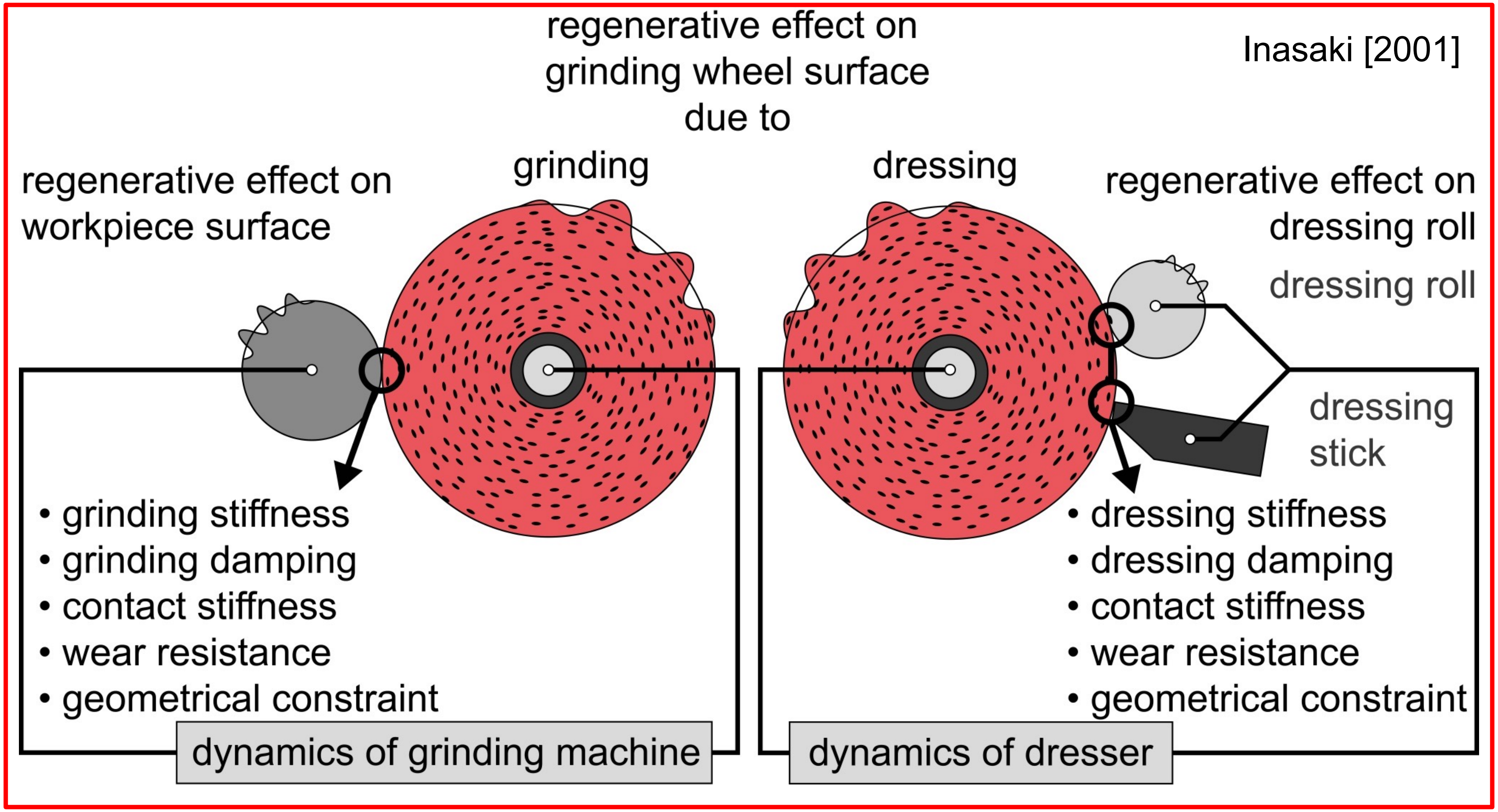


Aurich [2014]
Morantz [2015]



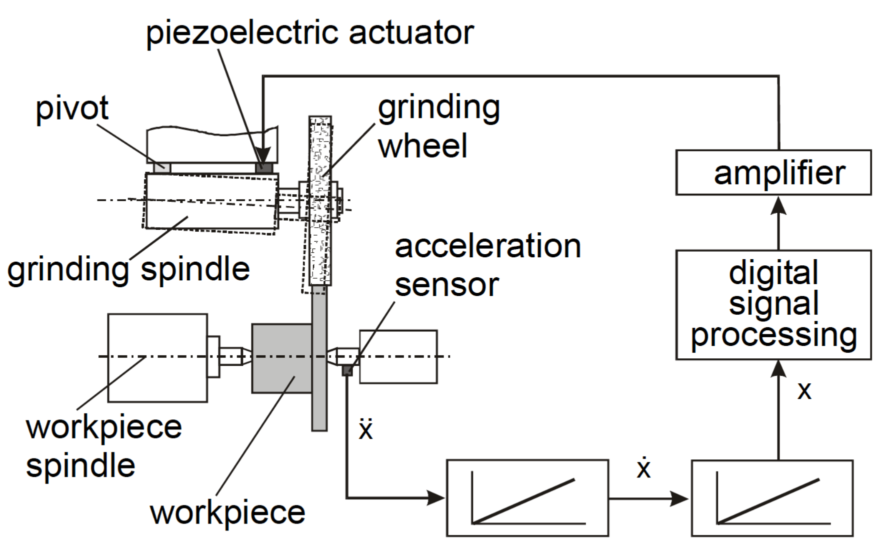
Chatter (self-excited vibrations)

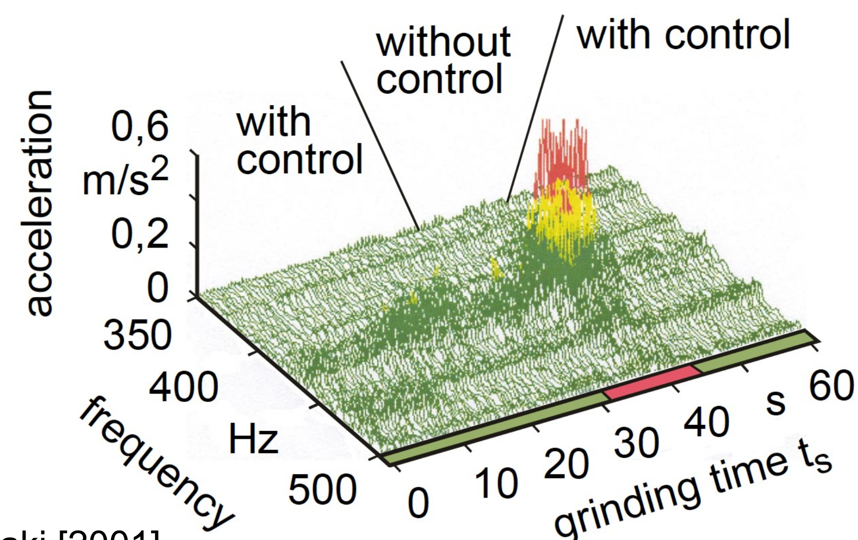
- Regenerative effects ➔ workpiece and grinding wheel surfaces
- Chatter suppression systems ➔ monitoring and control modules



Chatter mitigation

- Continuous-variable-feed-rate (CVFR)
- Continuous-workpiece-speed-variation (CWSV)
- Grinding-wheel speed variation
- Modification of components to increase stiffness and/or damping in the in the design phase (structural damping)
- Passive damping
- Active damping ➔ integrated monitoring and mitigation systems



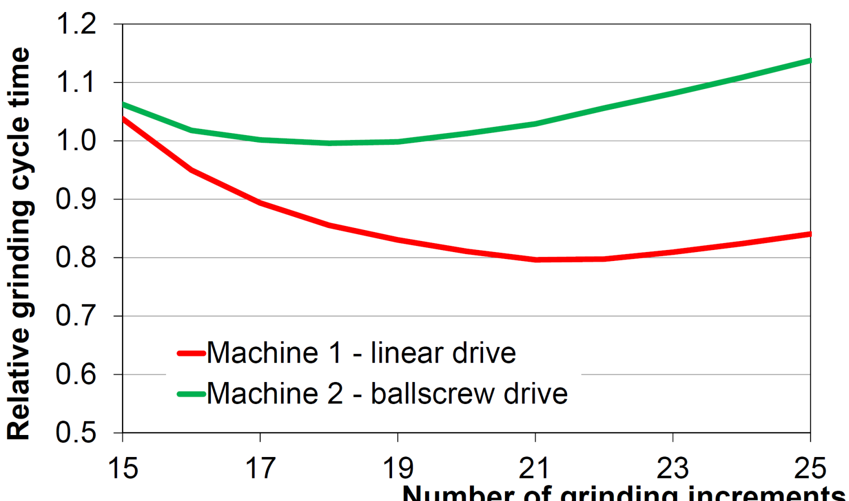


Inasaki [2001]

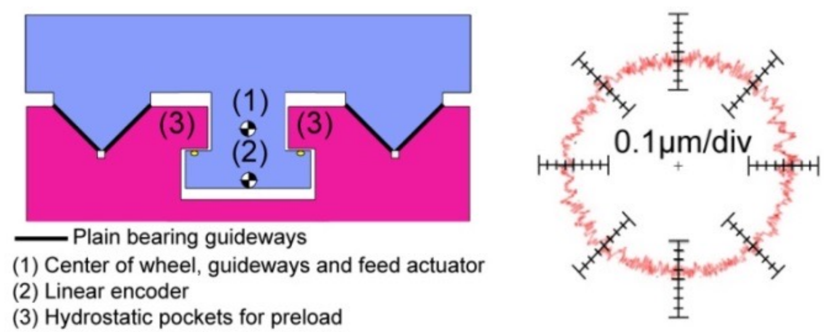
Drive systems and guideways

Studer [2017]

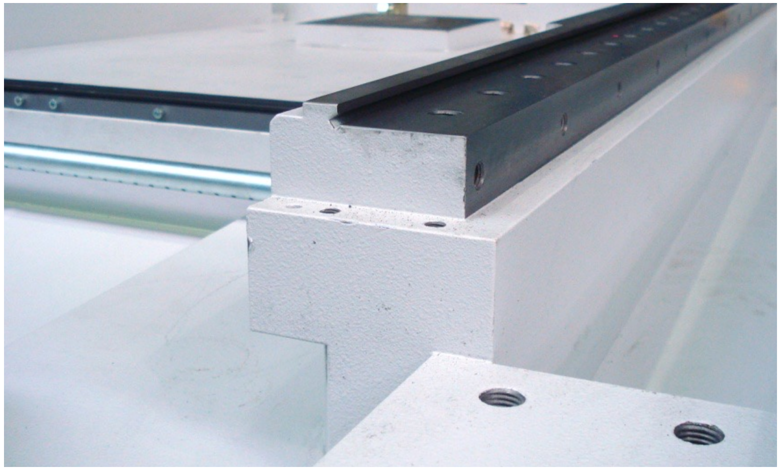
- Focus on realizing precise movements with low friction and high damping – most damping in machines comes from drives and guideways
- Role of velocity, acceleration and jerk to realize necessary grinding kinematics
- Linear motors – no backlash, increased dynamic stiffness and in combination with hydrostatic guideways low friction and no wear



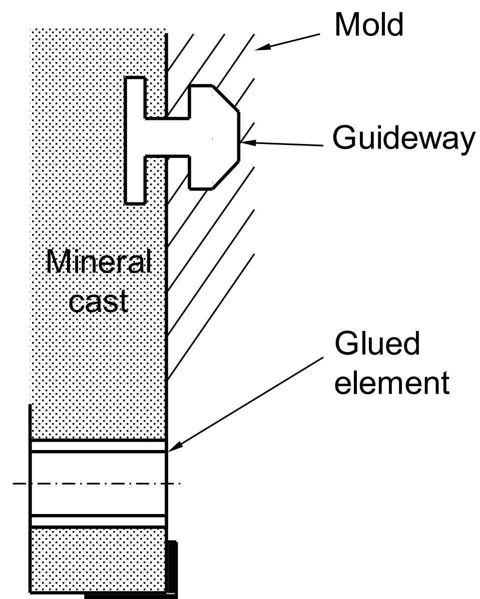
Hashimoto [2012]



Grinding machine base made of mineral cast

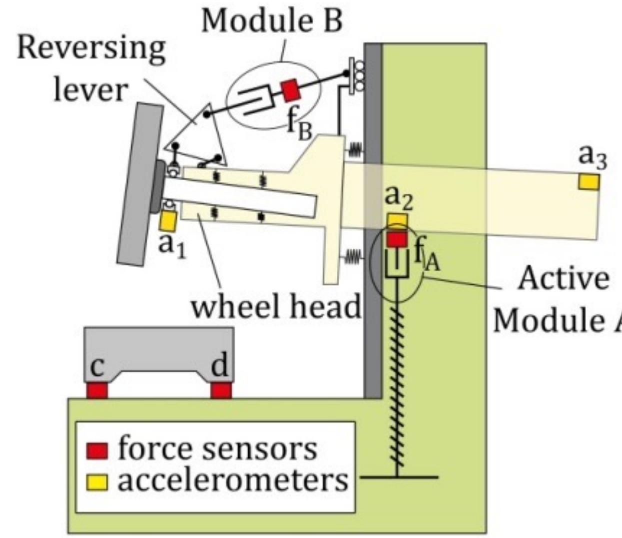


- Consisting of natural hard stone of various sizes, mixed with a bonding agent
- Other terms used are “Epoxy Granite”, “Polymer Concrete”, “Reaction Resin Concrete”.
- Very high damping!

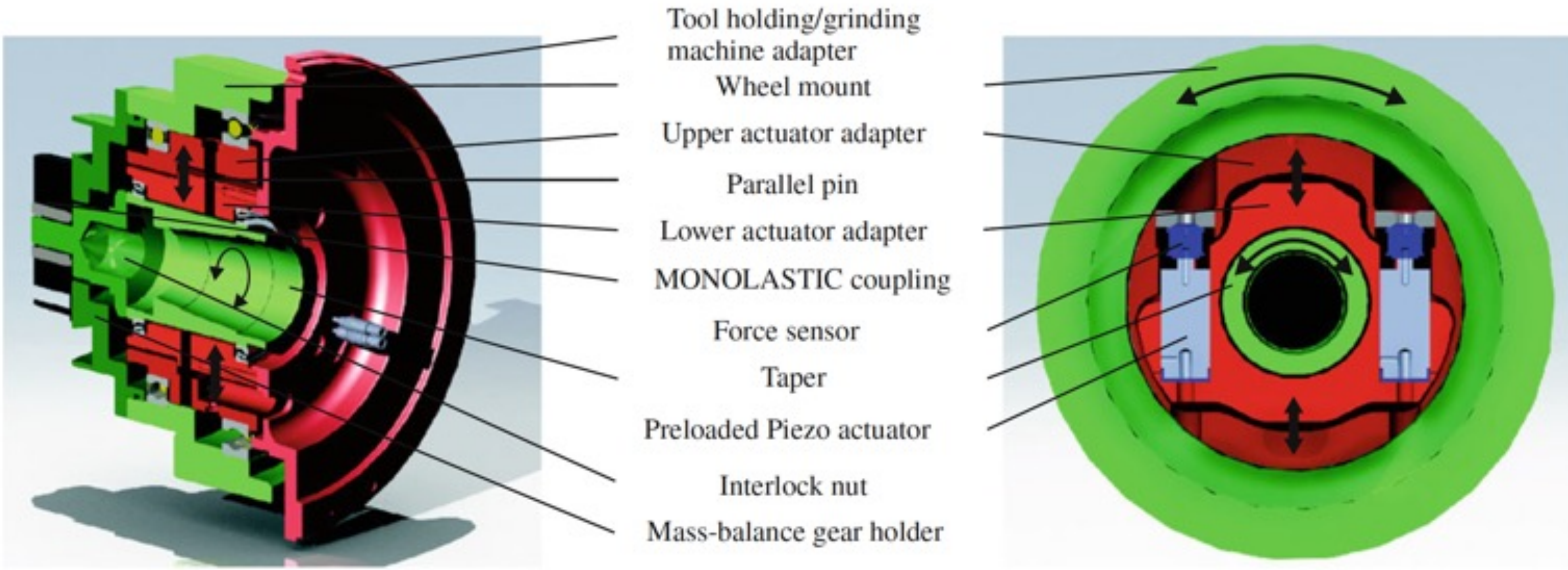


Adaptive and mechatronic systems

- Integration of sensors, intelligence and actuators without weakening the machine structure
- Adaptive hydrostatic bearings for compensation
- Active damping, tool holders, workpiece fixtures
- Adaptive spindle for chatter mitigation
- Adaptive workrest blade for centerless grinding
- Adaptive dressing
- Adaptive fluid supply

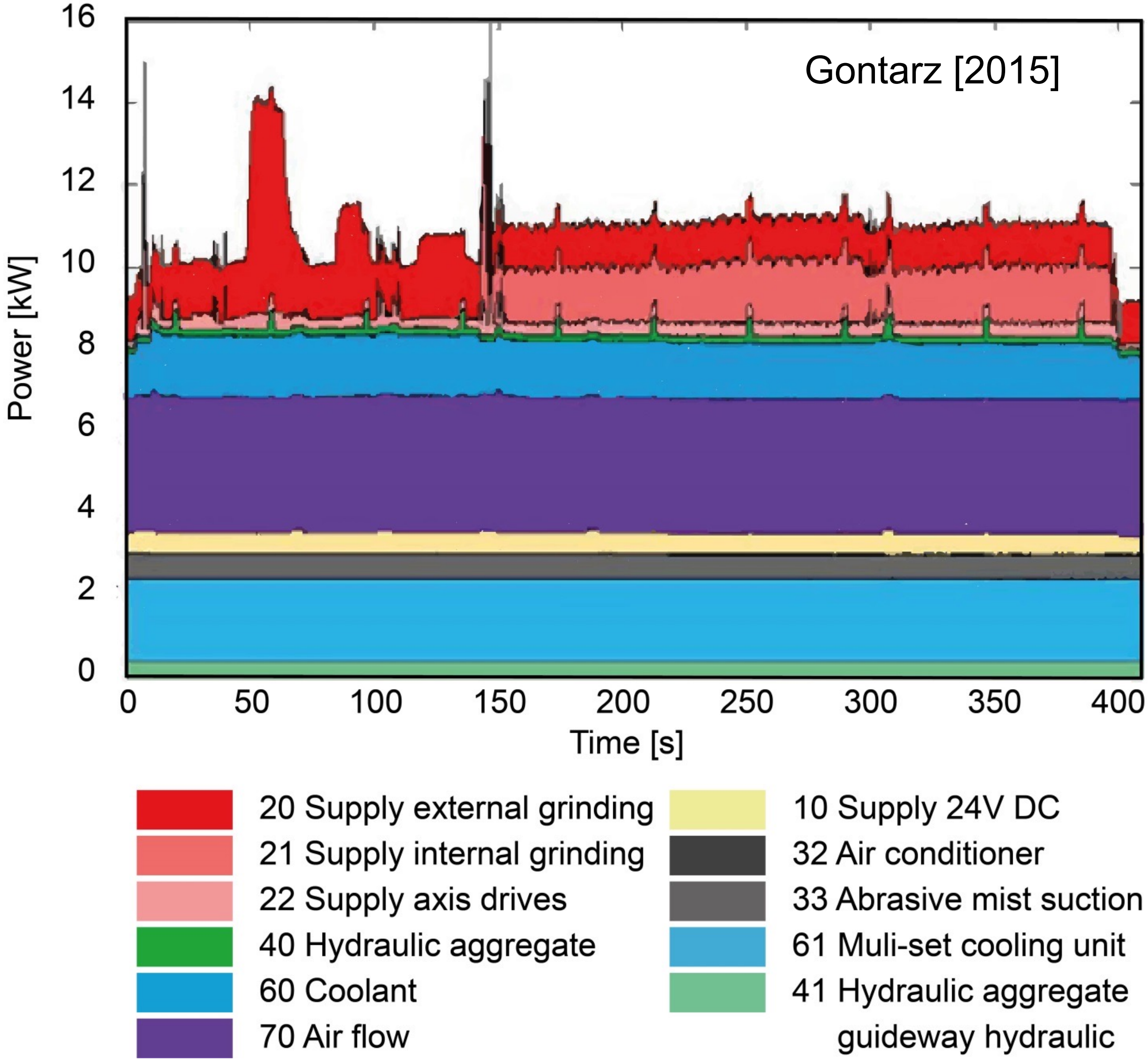


Boldering [2012]



Simnofske [2009]

Power profile and energy efficiency



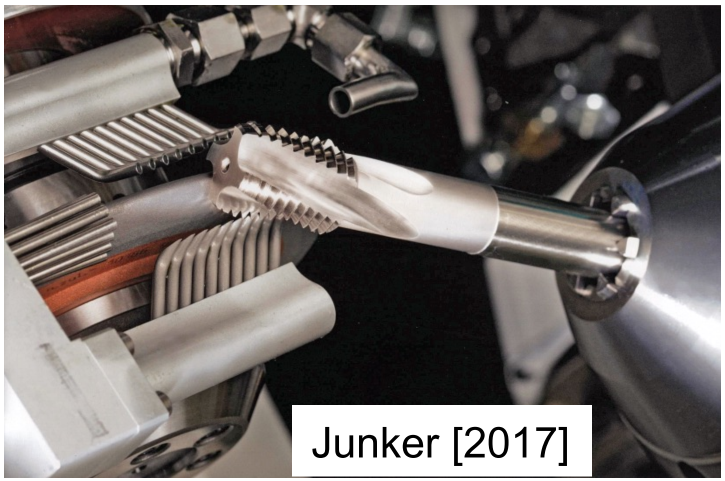
1st type efficiency: machine tool configuration

2nd type efficiency: standby management

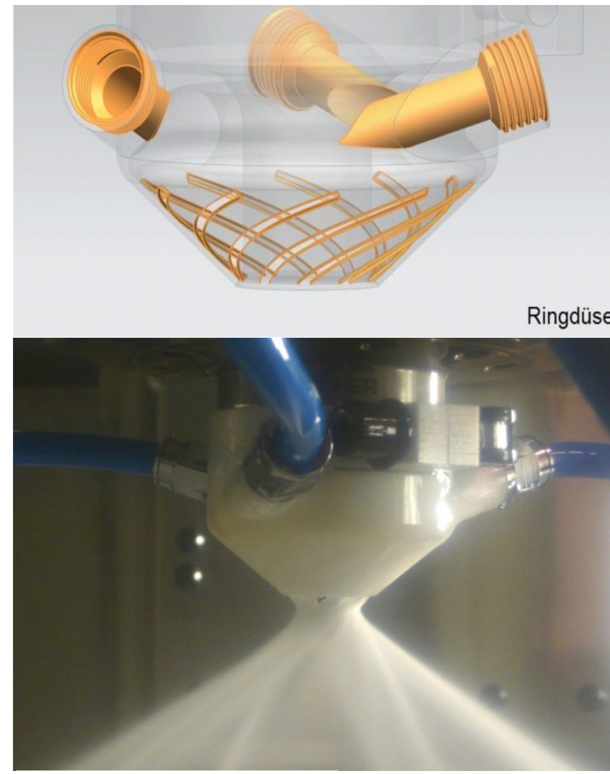
3rd type efficiency: process design

Coolant supply

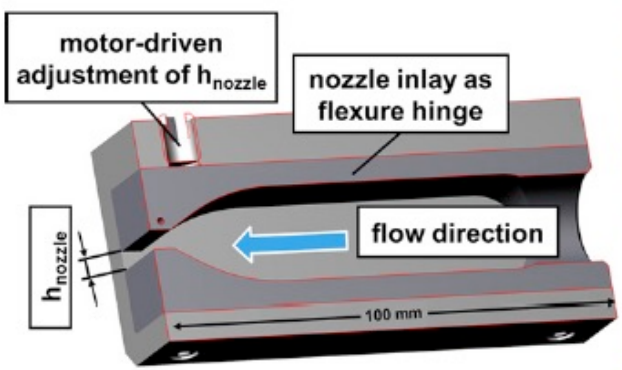
- Significant amount of coolant to counteract the grinding burn
- The circumferential wheel speed is very high
- Due to wear and dressing the grinding wheel changes geometry
- Dedicated systems, adaptive systems, closed loop controls

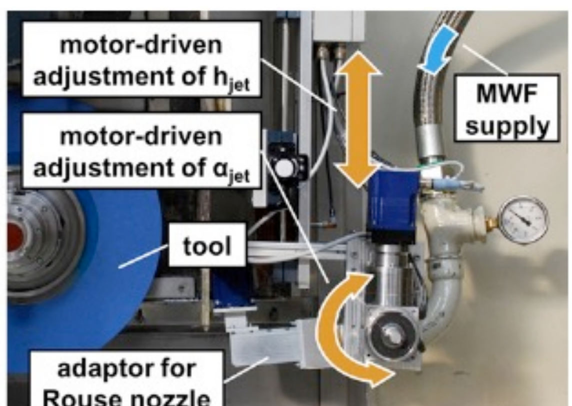


Junker [2017]



Jochum [2012]

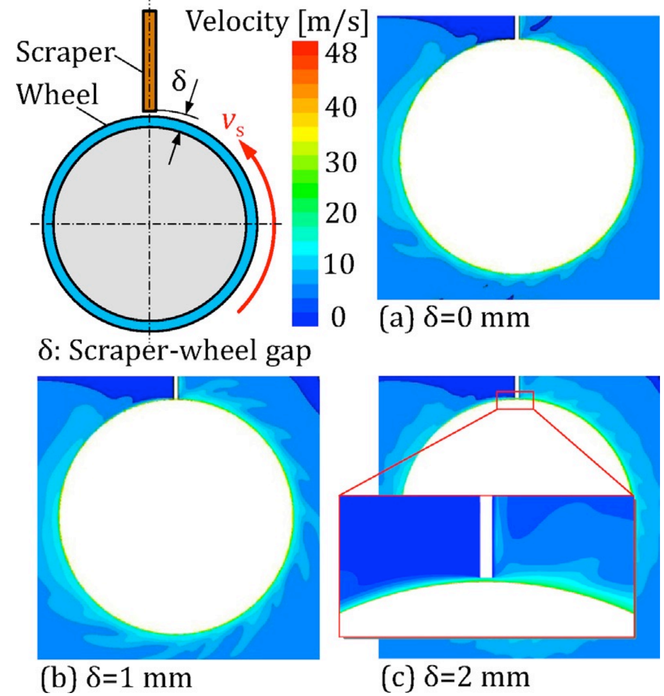




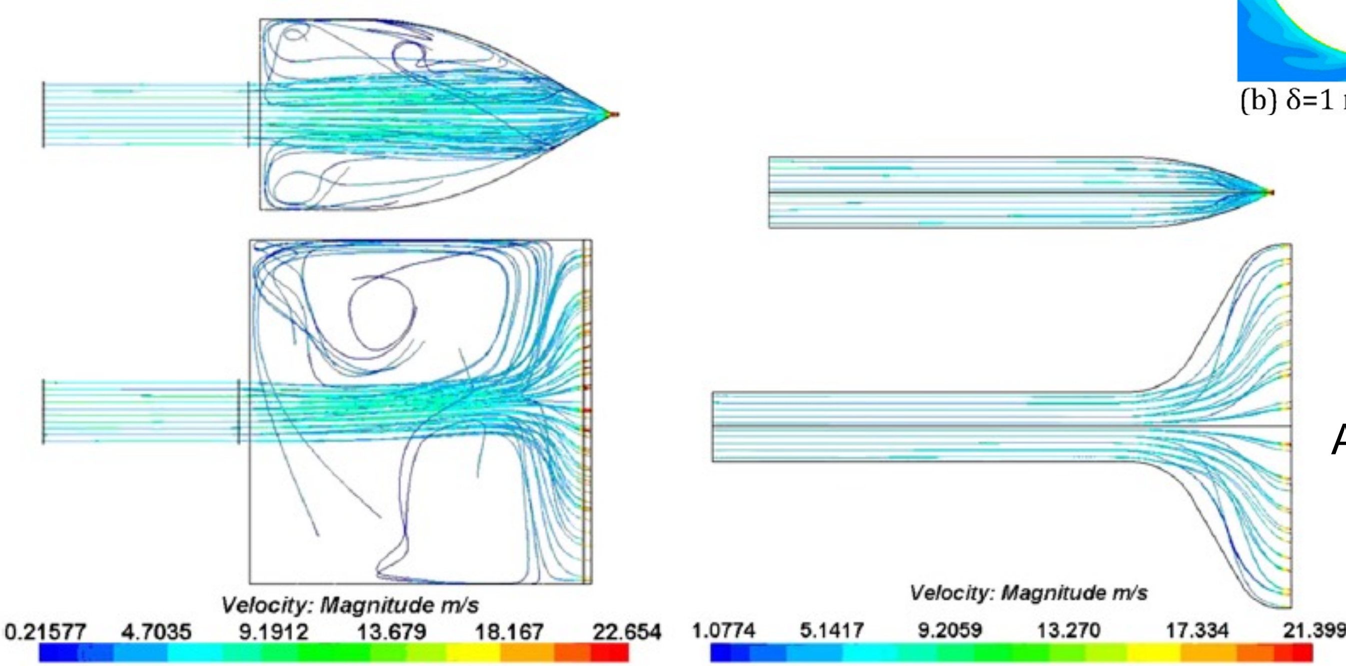
Heinzel [2015]

Coolant supply – CFD optimization

- Understanding multiphase and boundary conditions
- Prediction of cooling behavior
- Optimizing the flow around the grinding wheel
- Optimizing nozzle designs



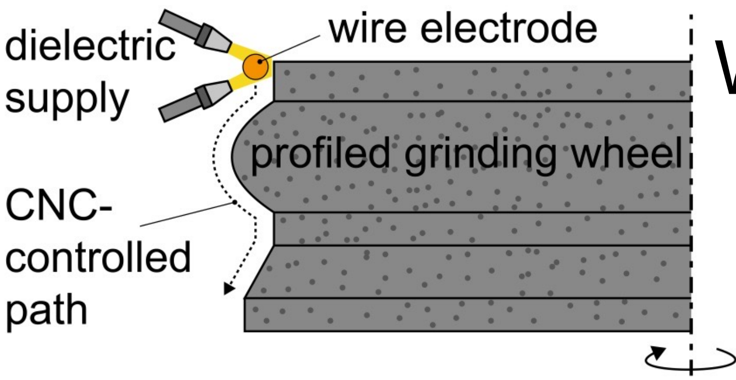
Hosokawa [2016]



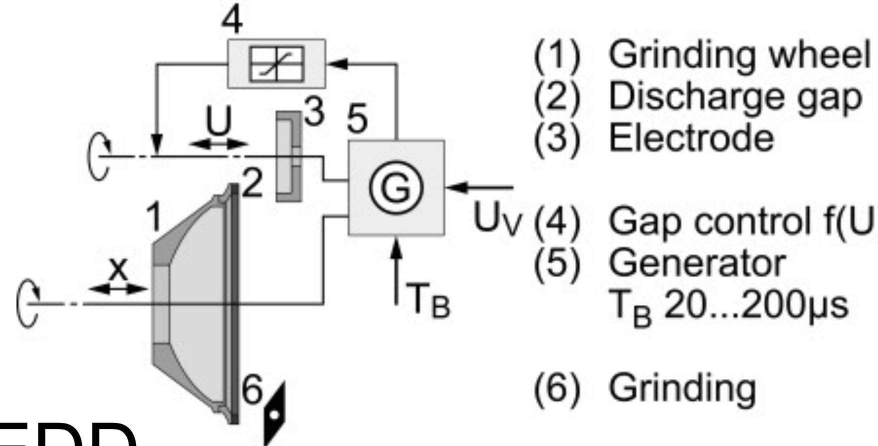
Alberdi [2011]

Wheel conditioning

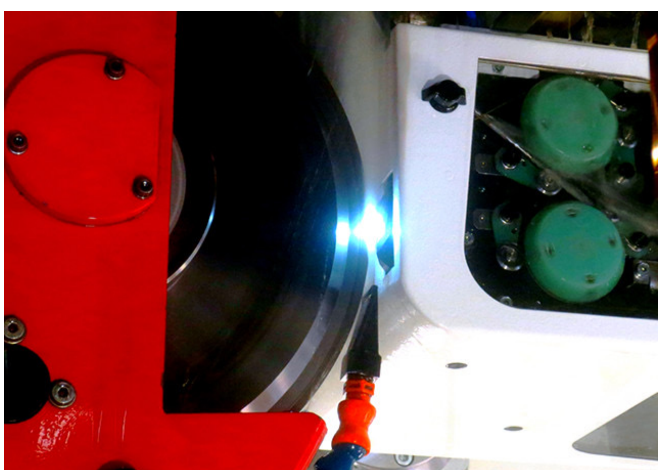
- Profiling, sharpening, cleaning, (structuring)
- Non-mechanical dressing processes developed, but mechanical dressing prevails in the industry
- Industrial breakthrough for xEDD



WEDD

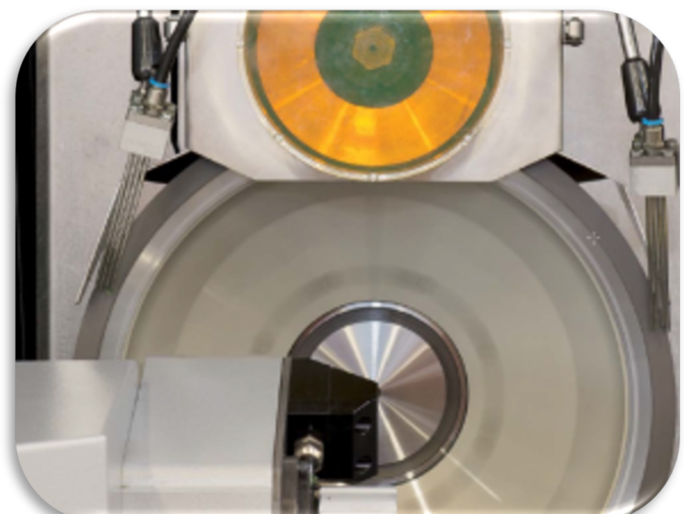


SEDD



Klotz
Studer [2016]

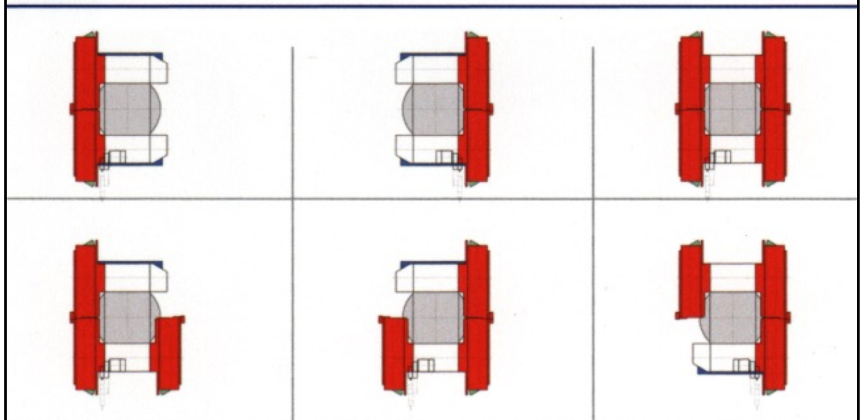
Scholze
Agathon [2016]

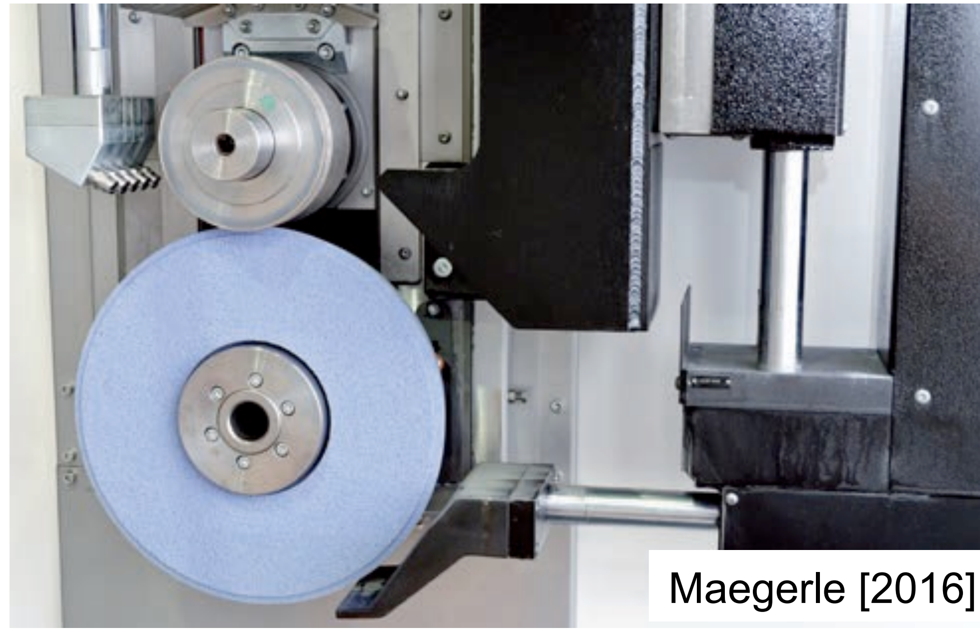


Tool exchange and clamping

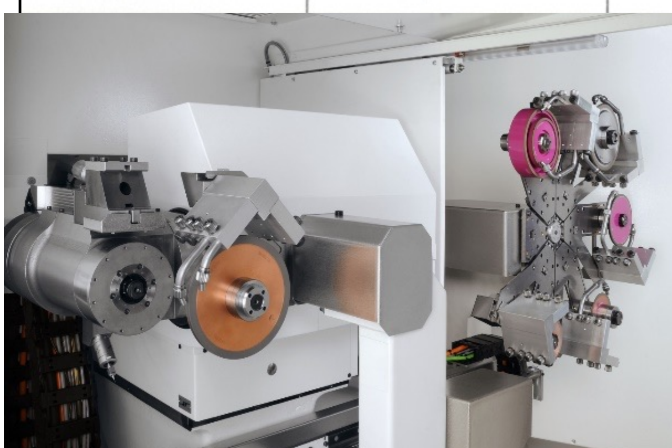
- Extreme requirements for balancing and runout ➔ reproducibility
- Dedicated fluid supply
- Dressing requirements

Standard solution: B-axis

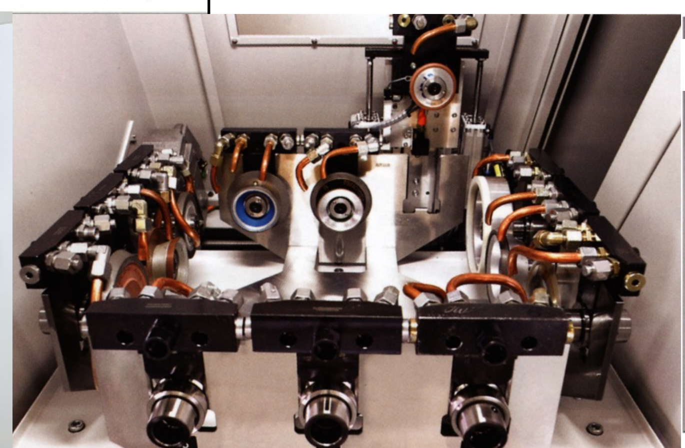




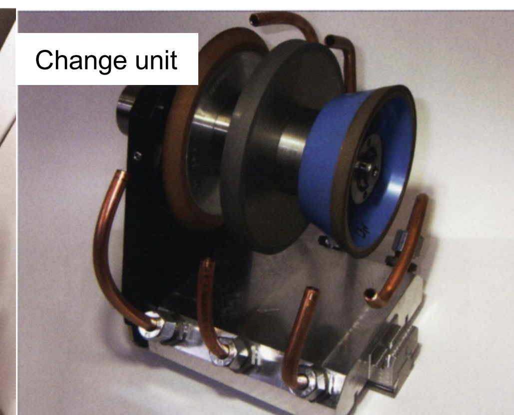
Maegerle [2016]



Rollomatik [2014]



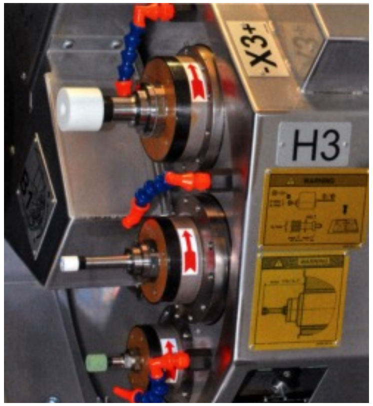
Alfred Schütte [2016]



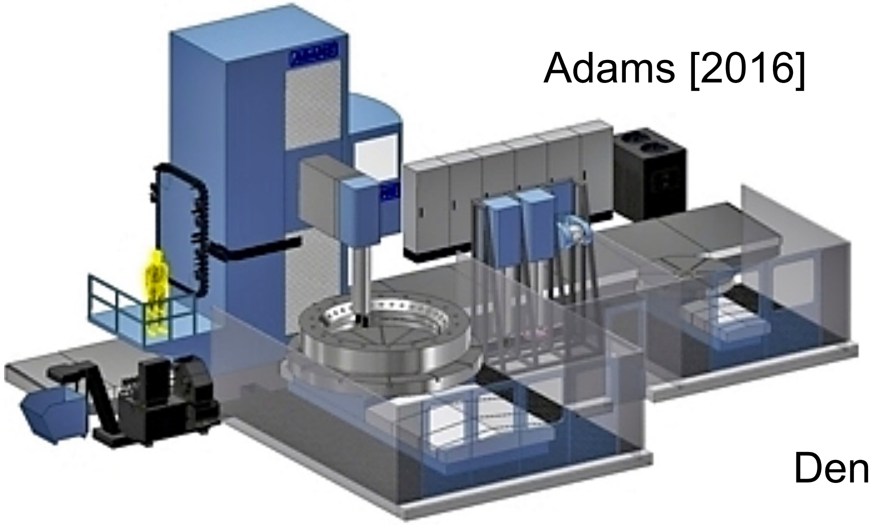
Schneeberger [2016]

Special machine developments

- Combined machines: grinding combined with: cutting with defined cutting edges, LDMD, EDM
  ➔ specialized process chain on one machine
  ➔ accuracy by avoiding re-clamping

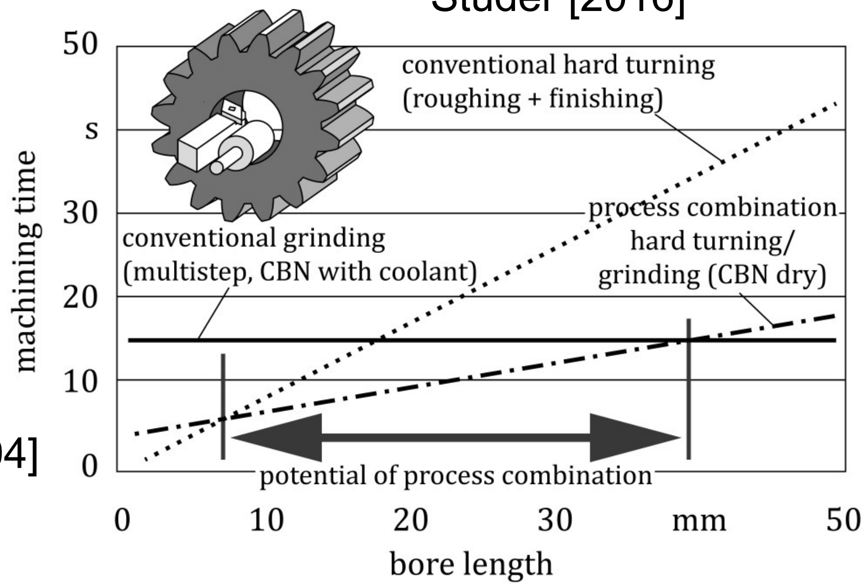


Studer [2016]

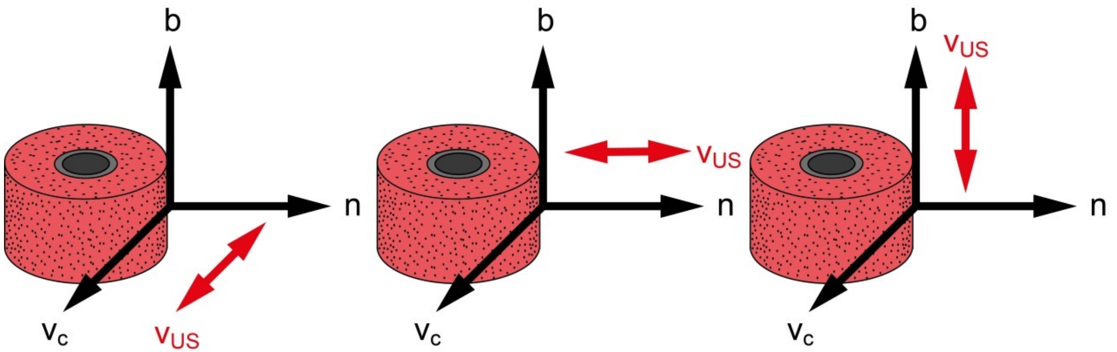


Adams [2016]

Denkena [2004]

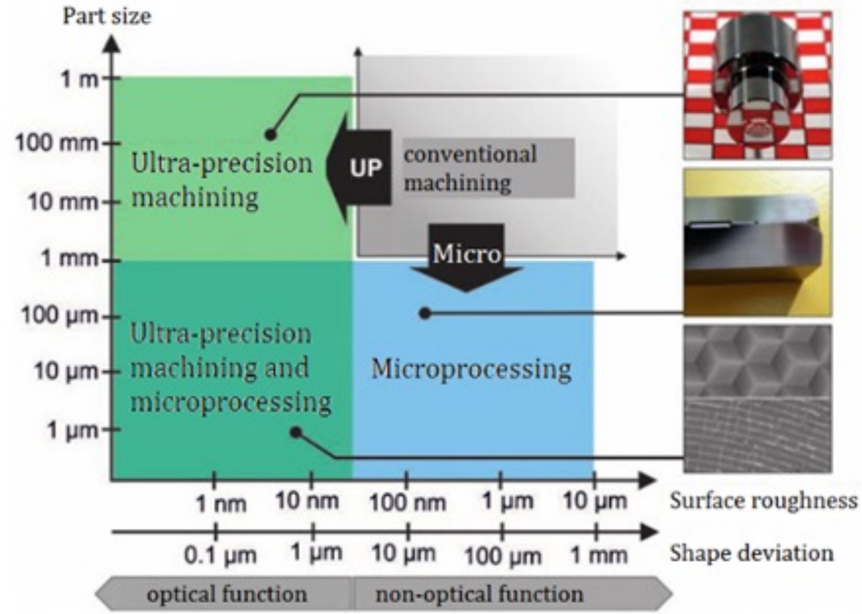


- Hybrid machines industrially available US assistance in different types up to 70 kHz

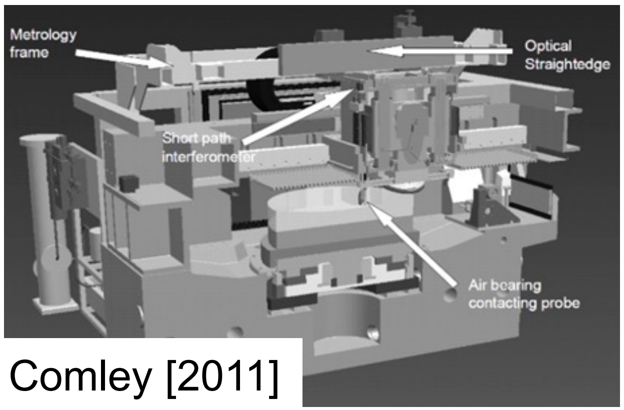


Special machine developments

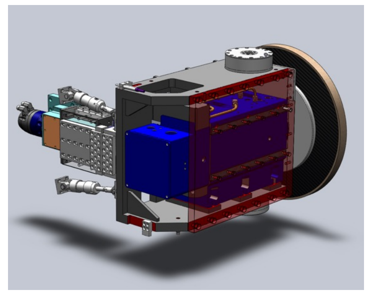
- Ultraprecision machines
- Ultra-large machines
- Micro grinder
- Compact and desktop machines

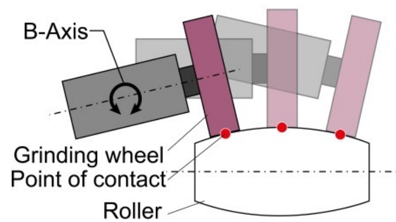


Brinksmeier [2013]

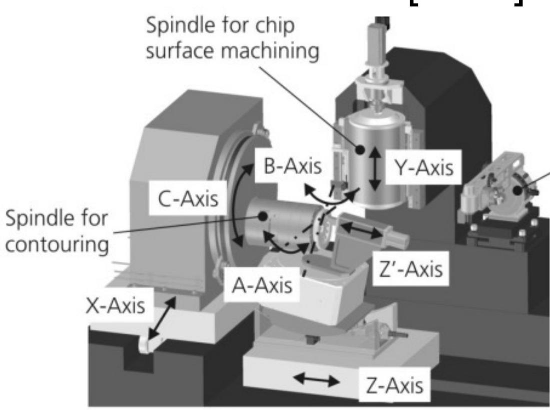


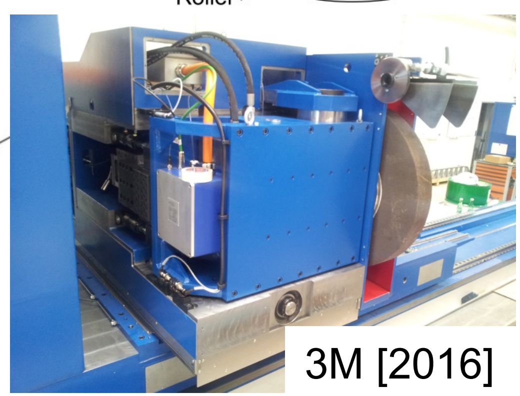
Comley [2011]



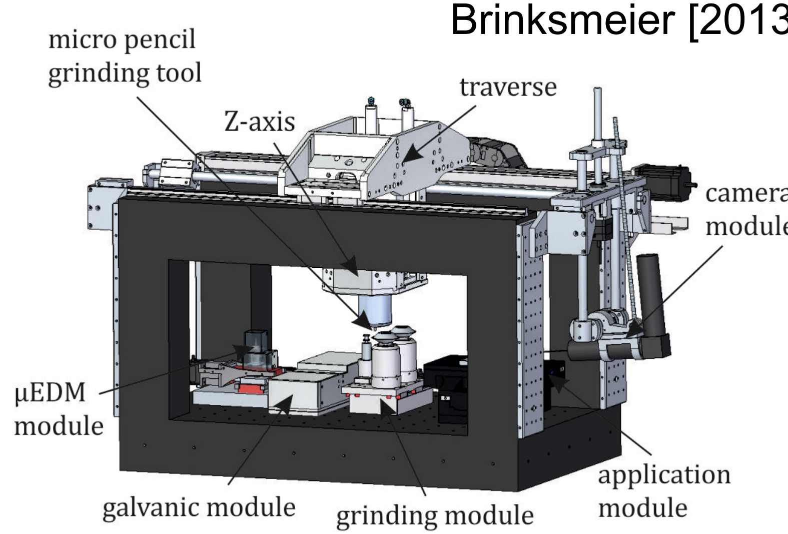


Brecher [2009]





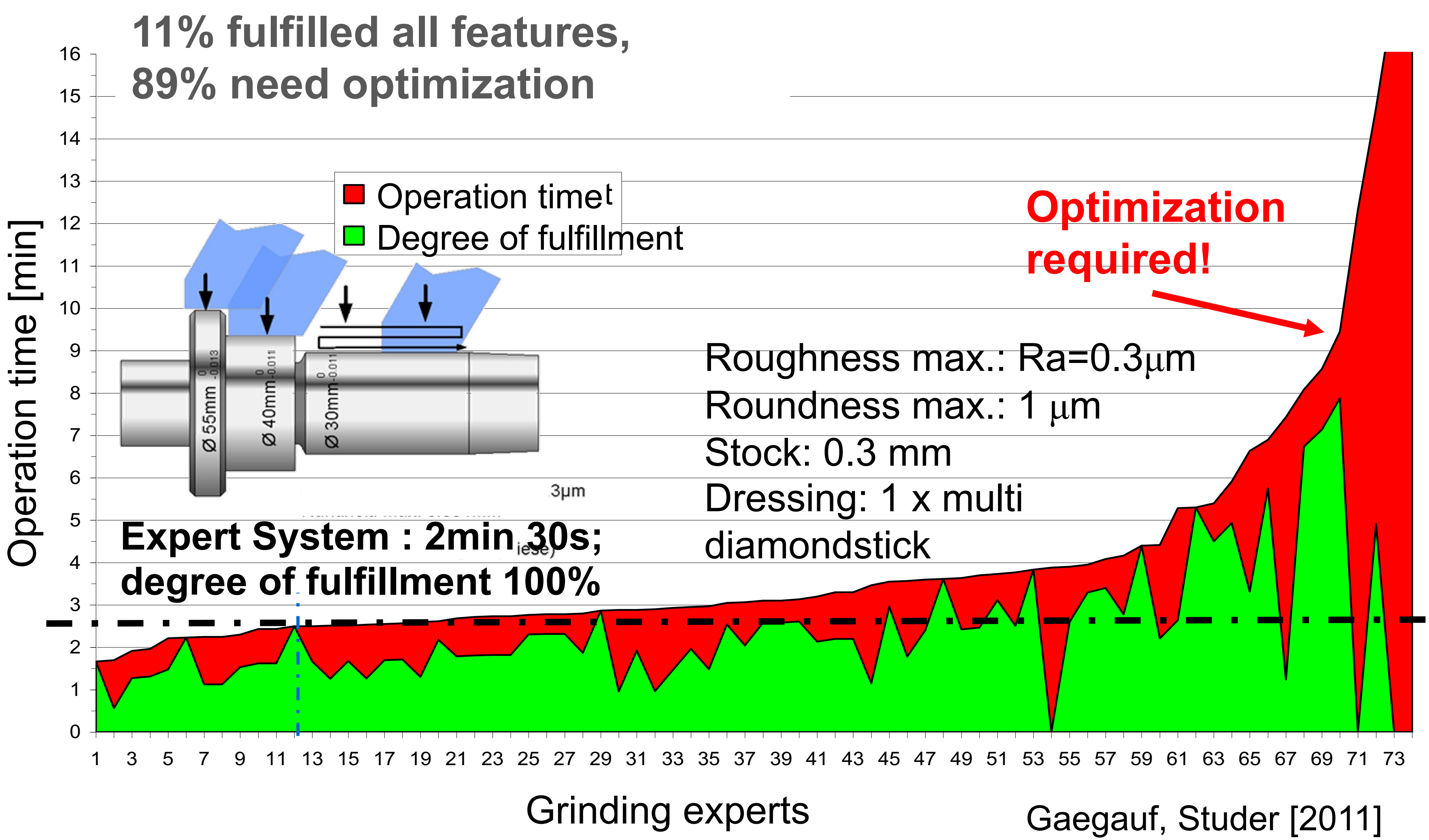
3M [2016]



Walk, Aurich [2014]

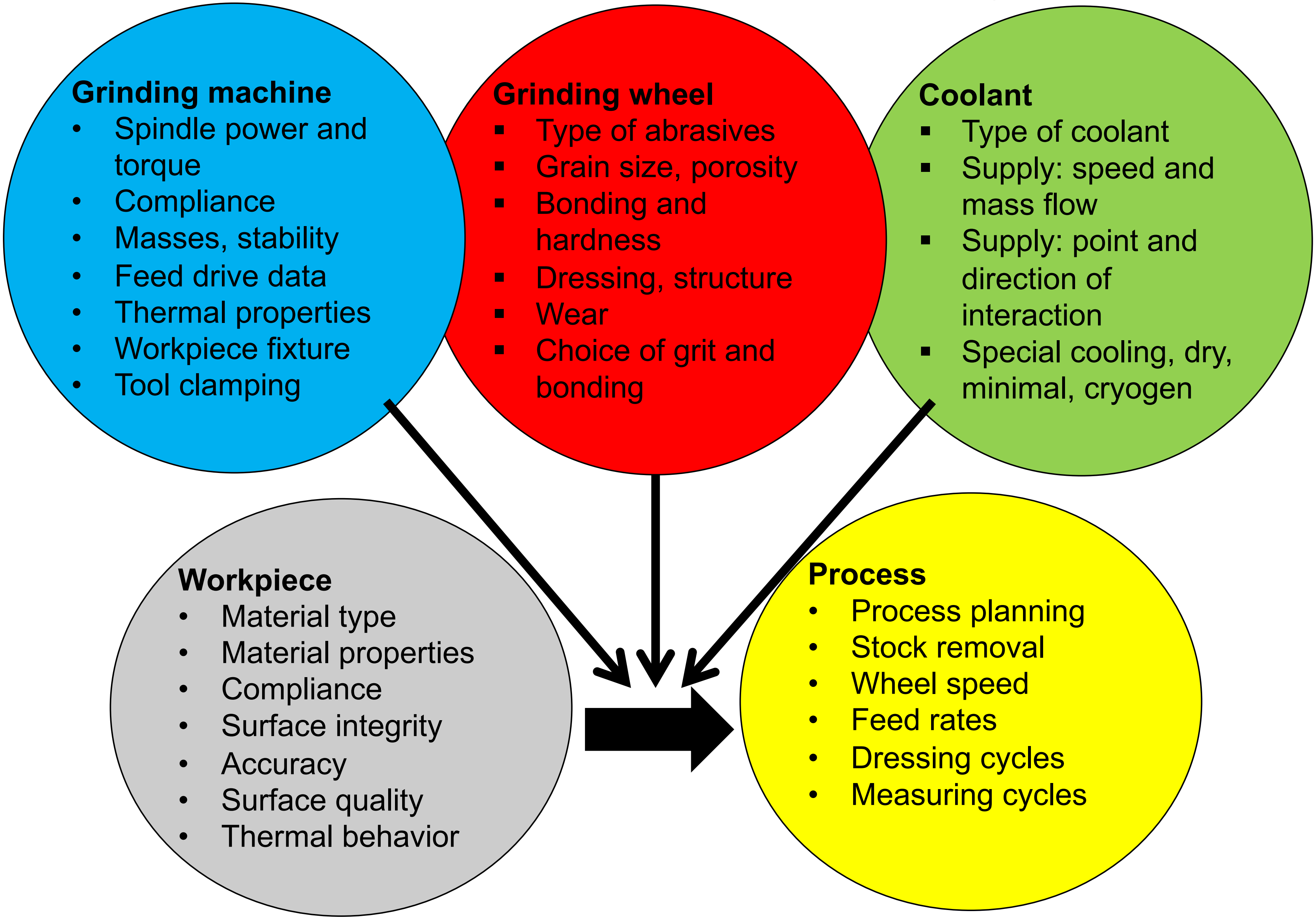
Value of operator support systems

Grinding today strongly depends on experience

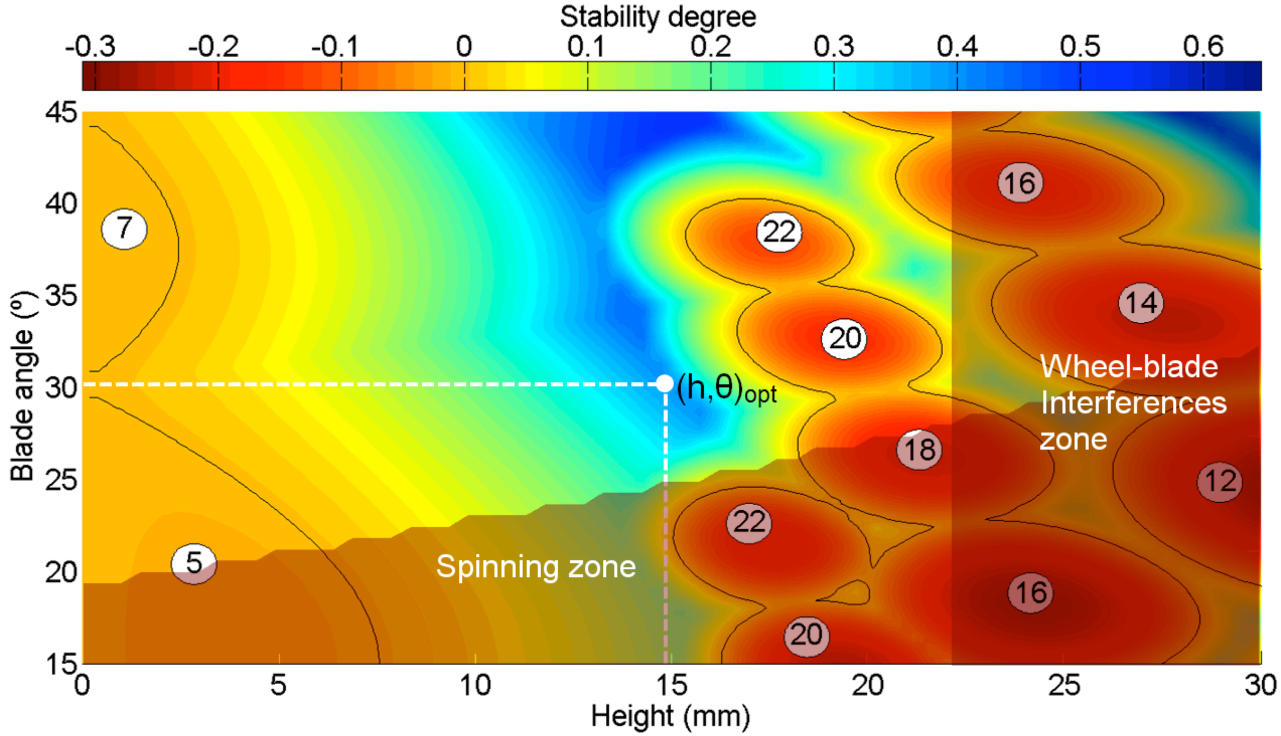


Gaegauf, Studer [2011]

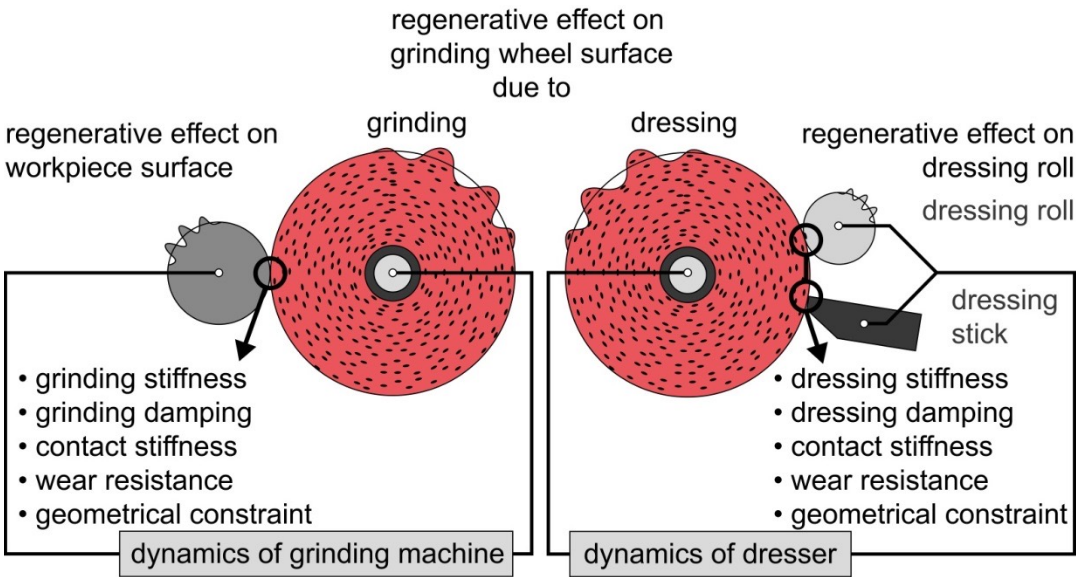
Requirements for operator support systems



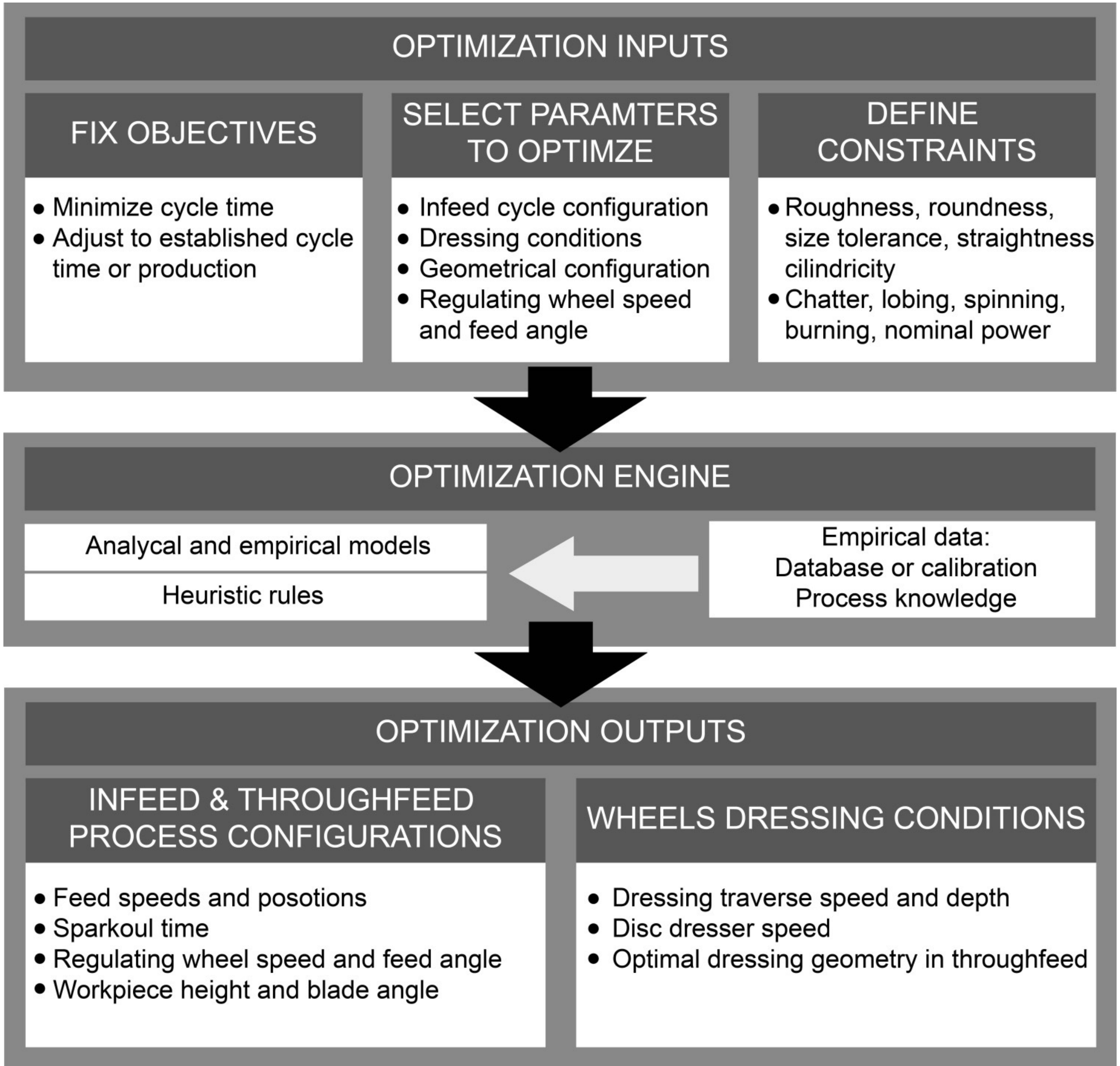
Stability lobes



Barrenetxea [2014]



Realization of operator support system

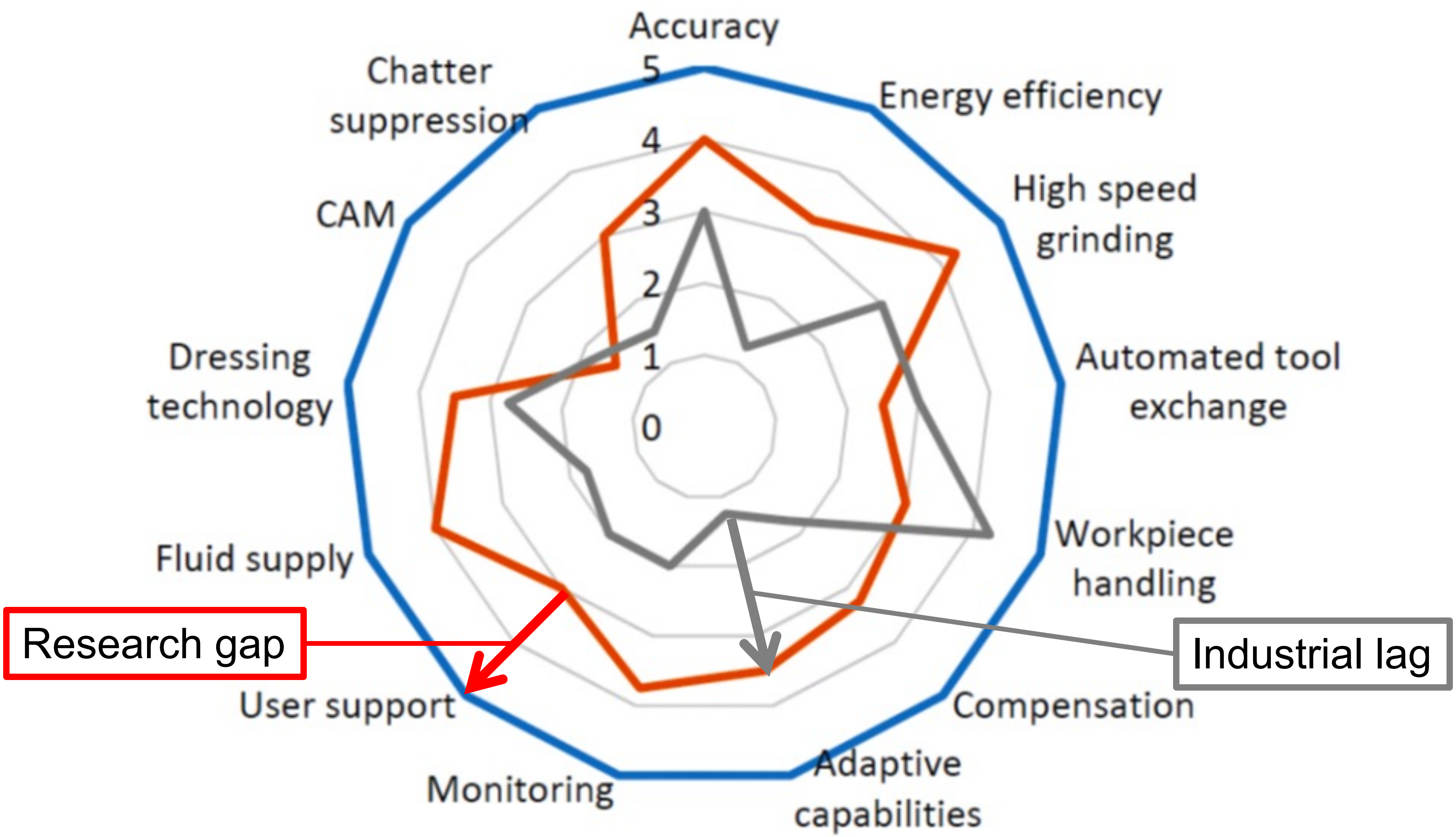


Barrenetxea [2011]

Main game changing technologies in machines

- Tool changers with sufficient accuracy so that re-conditioning or rebalancing after tool change is no more necessary
- Expert systems or simulation based support systems for operators that drastically reduce the setup times
- Energy- and resource-efficient grinding machines
- Scientific, model-based machine design and construction
- Model-based compensation of erroneous motions like dynamic and thermal drift
- Enhanced and adaptive coolant supply
- Self learning, self-adapting machines equipped with sensors, actuators and model-based artificial intelligence
- Interconnectivity

State of research vs. industrial maturity



Recent Developments in Grinding Machines

Thank you for your kind attention!