Joint environmental and economic assessment of cutting tool replacement policies in Ti6Al4V milling under uncertain condition estimate

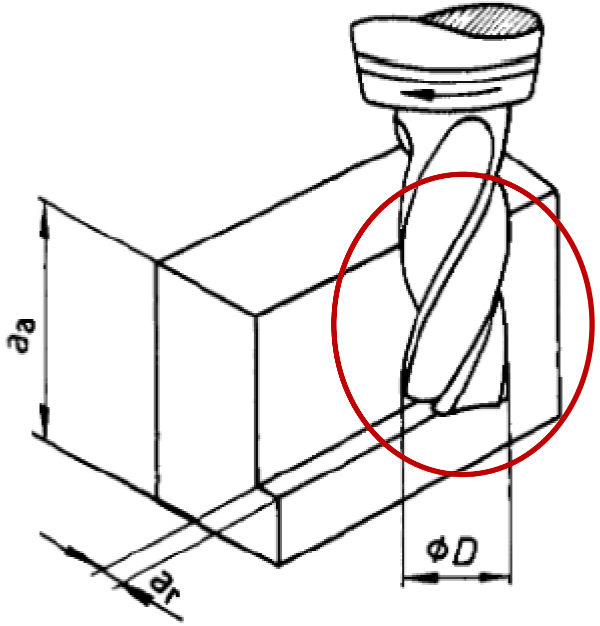
L. Colantonio[1], G. Moroncini[1], O. Sénéchal[2], P. Dehombreux[1], F. Ducobu[1] & **L. Equeter**[1]

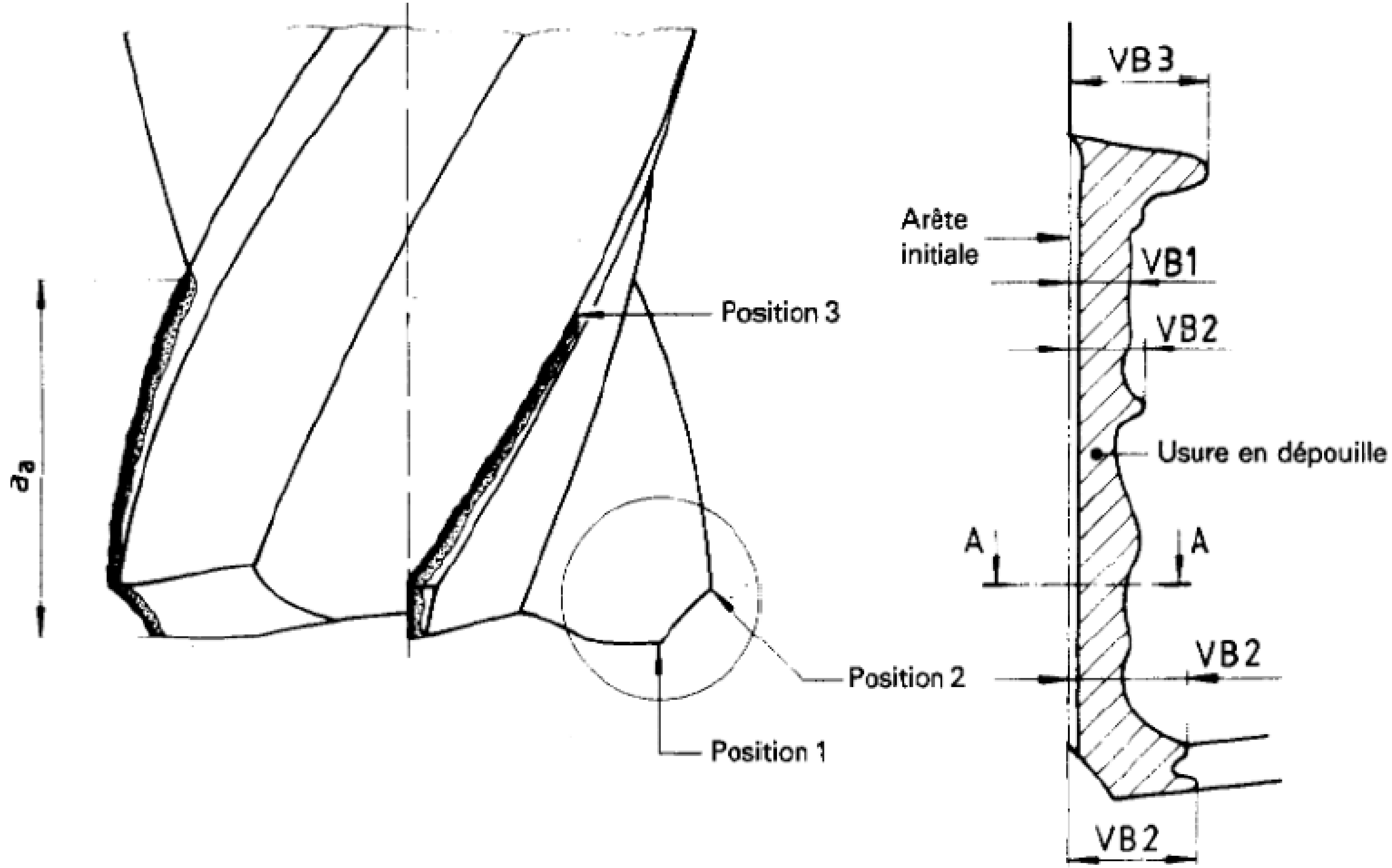
Lucas.EQUETER@umons.ac.be

[1] Université de Mons, Machine Design and Production Engineering, Mons, Belgium

[2] Université Polytechnique Hauts-de-France, CNRS UMR 8201, LAMIH, Valenciennes, France

Milling tool degradation and end-of-life: ISO 8688-2:1989 and reality





Tool life criterion: VB = 300 µm

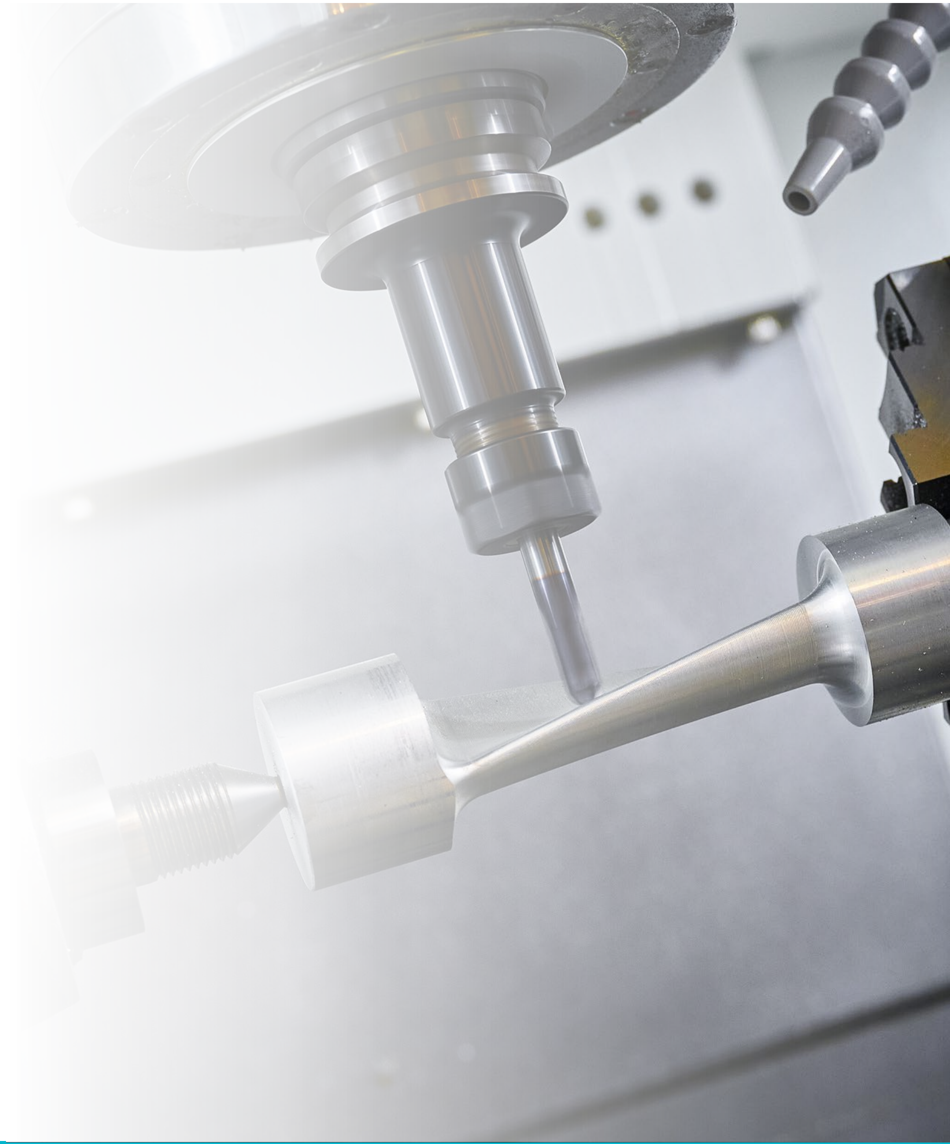
ISO 8688-2:1989

Milling tool degradation and end-of-life: ISO 8688-2:1989 and reality

Timely tool replacement is usually a cost optimum

- Tool replacement optimization → 30% cost reduction
- Wide range of available condition monitoring variables
- RUL estimate from statistical models or AI
- Uncertainty on RUL can be estimated

- Optimization through:
  - Cutting parameters
  - Tool choice



Colantonio et al. (2021), Colantonio et al. (2024), Ding & He (2011), Liu et al. (2018), Siddhpura & Paurobally (2013)

Limited efforts toward environmental optimization

- Underrepresented problem in the literature
- Assessments on the machining process and cutting tool production

- Current approaches similar to cost optimization: optimization through
  - Cutting parameters
  - Tool choice

Elnourani et al. (2024), Shi et al. (2021), Kshitij et al. (2022), Fairoz & Shokrani (2025), Shokrani et al. (2024), Sun et al. (2020), Pimenov et al. (2022)

The questions of tool replacement

Industrial need

- Quality (roughness, dimensions, etc.)
- Productivity
- Environmental assessment
- Etc.

Available strategies

- Tool selection
- Cutting parameters fine-tuning
- Conditional maintenance
- Predictive maintenance

First optimized for cost
then evaluated for economic, social, and environmental impacts

No existing joint assessment of economic and environmental impacts

Iqbal et al. (2022), De Souza et al. (2022), Campatelli & Scippa (2016)

Joint economic and environmental assessment in simulations of Ti6Al4V milling

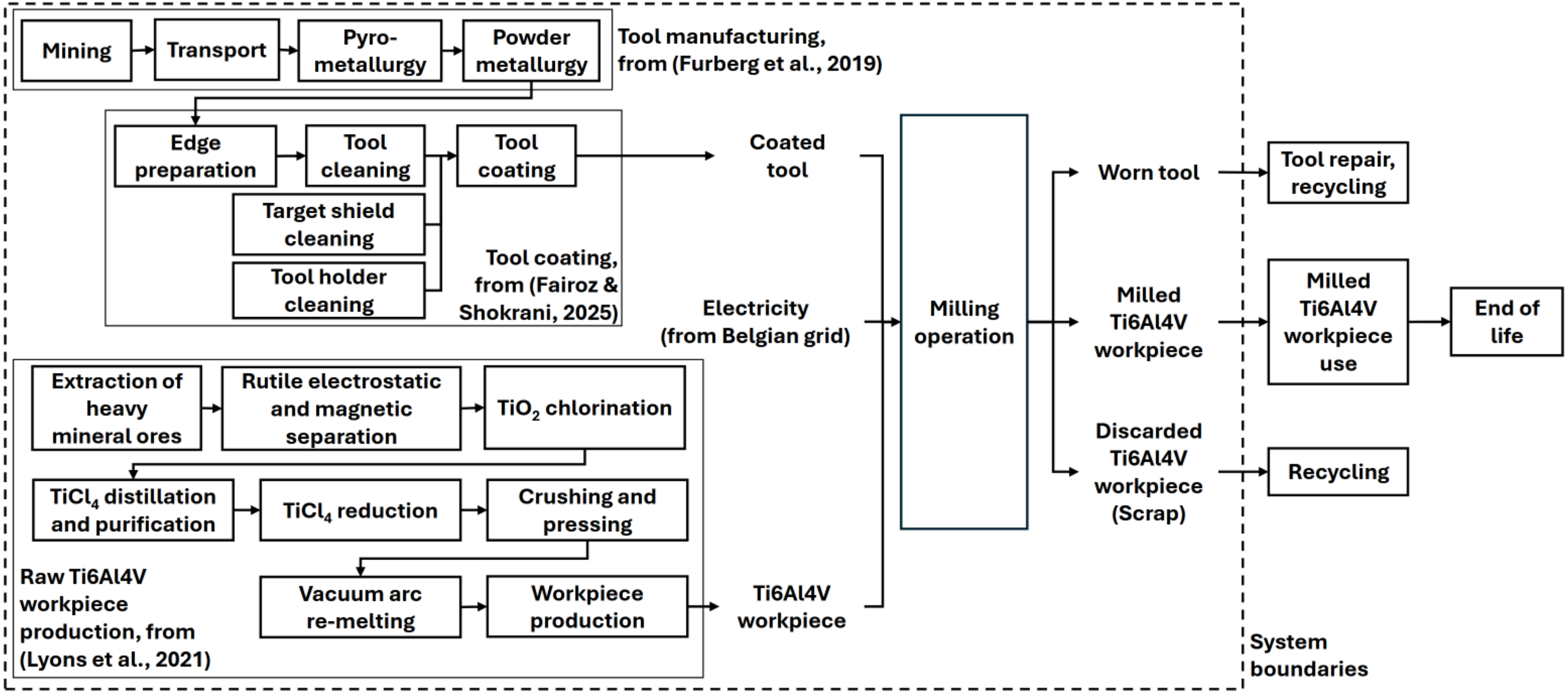
This contribution presents:

- A comparison of strategies for tool replacement

- Through a simulation including:
  - Cutting tool end of life and scrap production
  - Cutting tool degradation estimates
  - The machine tool energy consumption
  - The production of the workpiece

Including costs and CO_2-eq emissions

Joint economic and environmental assessment in simulations of Ti6Al4V milling



Functional unit: 1 good produced part

Furberg et al. (2019), Fairoz & Shokrani (2025), Lyons et al. (2021), Electricity Maps (2025)

Joint economic and environmental assessment in simulations of Ti6Al4V milling

Hypotheses:

- Two-shifts system (16 h/day), 7 days/week
- Location: Belgium

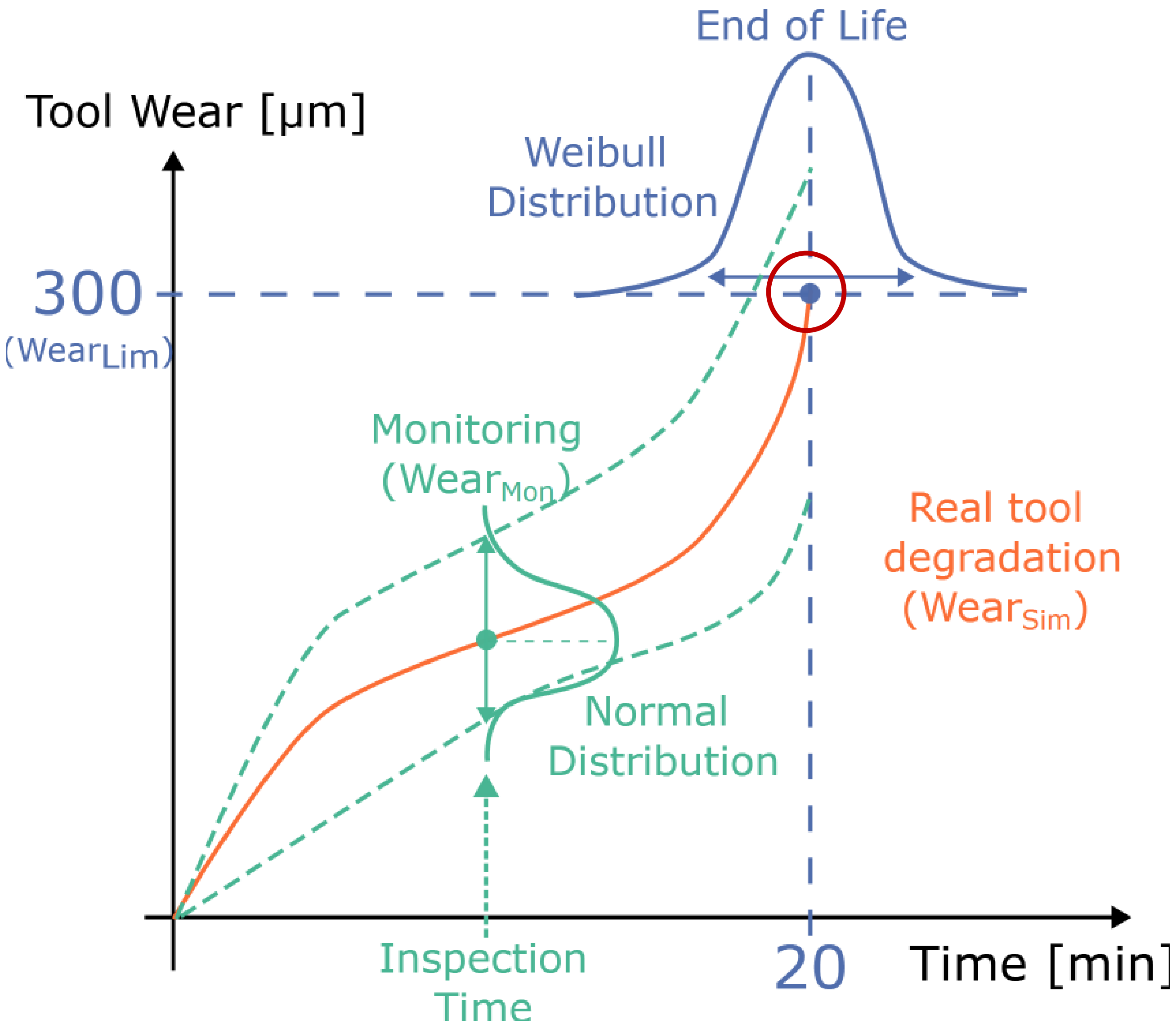
Cutting tool		Workpiece		Machine	
Diameter	5 mm	Raw mass	410 g	Mean electrical consumption for 20 workpieces (1 hour of machining)	15.5 kWh
Number of teeth	4	Useful Mass	320 g		
Coating	TiAlN/TiN (PVD)	Production Time	3 min		
Coated surface	300 mm²				
Mass	15 g				
Cost	40 EUR	Cost	8.20 EUR	Cost	0.15 EUR/kWh
CO_2	234 kg CO_2-eq	CO_2	15 kg CO_2-eq	CO_2	0.2 kg CO_2-eq/kWh

15 g of sintered tungsten carbide ⟶ 0.255 kg CO_2-eq

\+ 300 mm² of coating (TiAlN/TiN) through PVD ⟶ 234 kg CO_2-eq

Hoffmann Group (n.d.), Furberg et al. (2019), Fairoz & Shokrani (2025), Triebe et al. (2018), Electricity Maps (2025), Dahmus & Gutowski (2004), Fratila (2013)

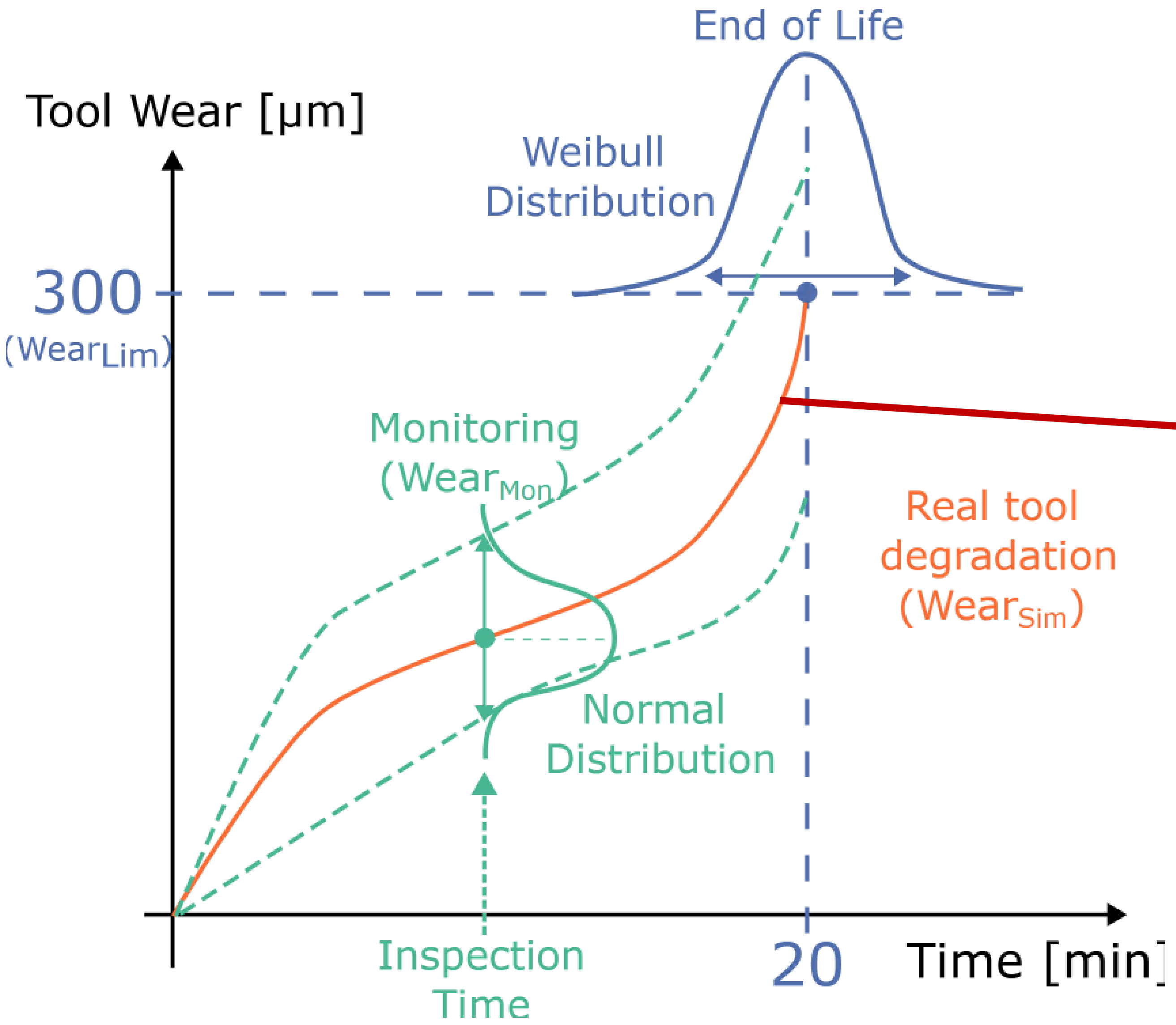
Degradation modeling



1. Generate a hitting time: Weibull distribution
   - β = 7
   - η = 21.38 min

Aramesh et al. (2016), Nystad et al. (2012)

Degradation modeling



1. Generate a hitting time: Weibull distribution
   - $\beta = 7$
   - $\eta = 21.38$ min

2. Generate the corresponding Degradation curve:

$$W = c \cdot (\sinh(a \cdot b) + \sinh(a \cdot (t - b)))$$

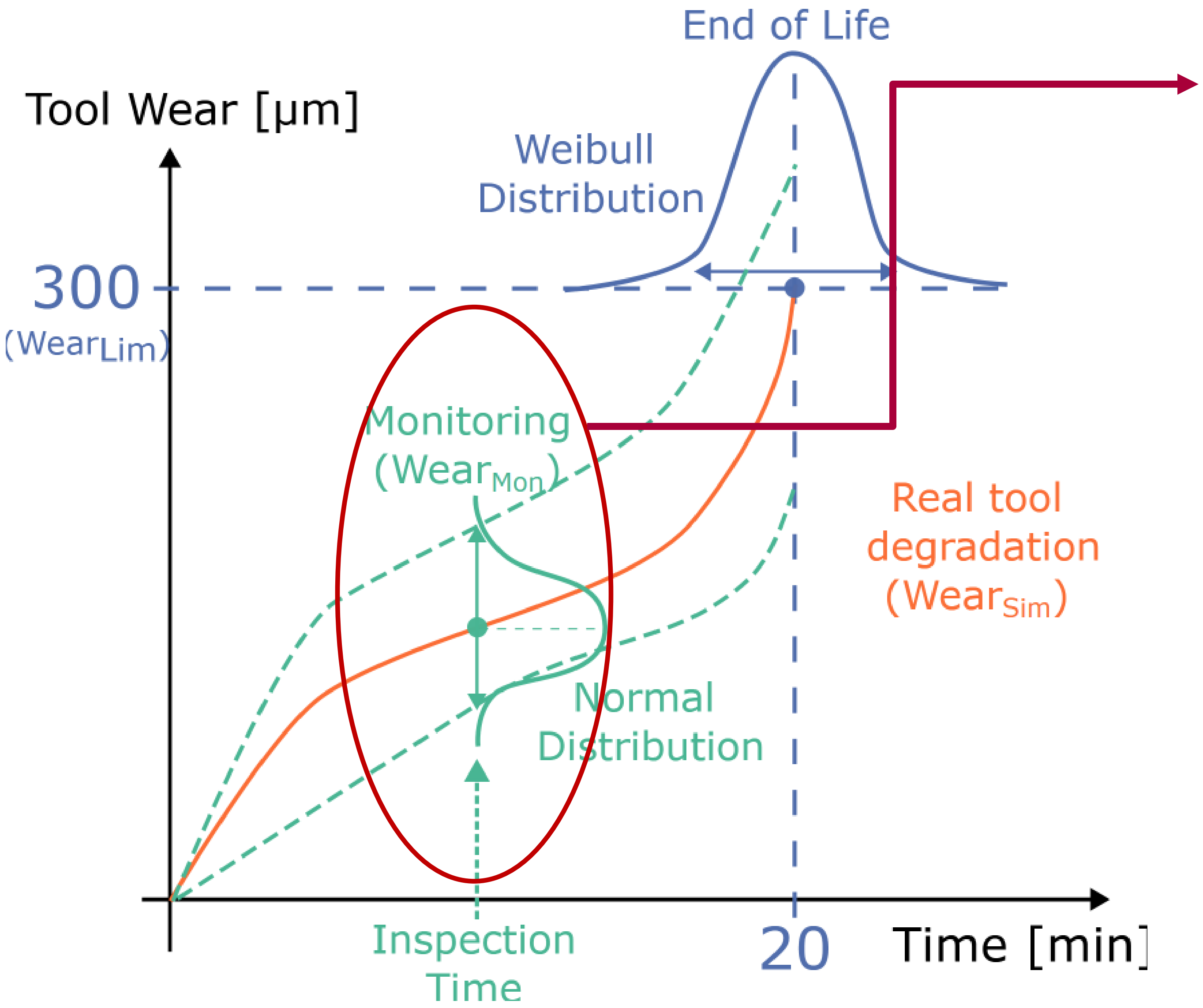
$a \in [0.2, 0.5]$ → from random uniform distributions

$b \in [5,10]$ → from random uniform distributions

$c = f(\mathrm{t_{fail}}, \mathrm{a}, \mathrm{b})$

Aramesh et al. (2016), Nystad et al. (2012)

Degradation monitoring



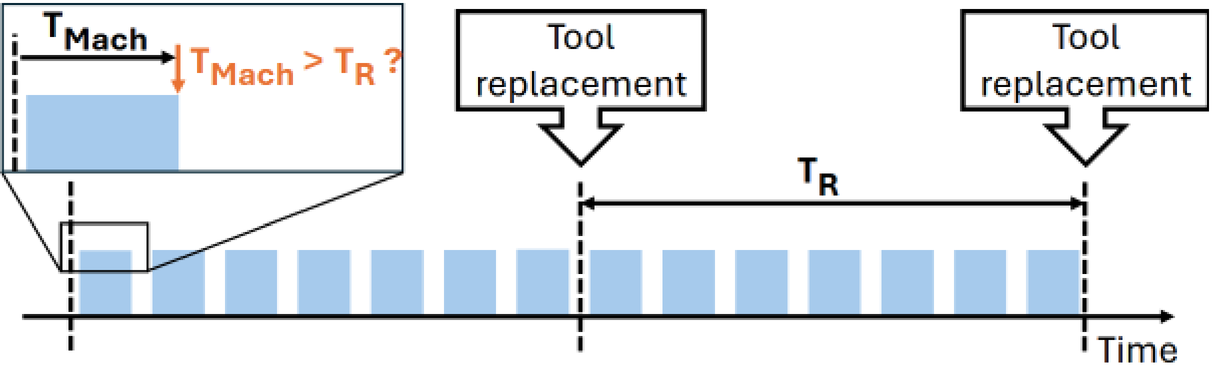
In scenarios with monitoring:

- On each inspection, Mean Average Percentage Error (MAPE) of 15 %
- Normal distribution around the simulated value

Colantonio et al. (2024)

Scenarios

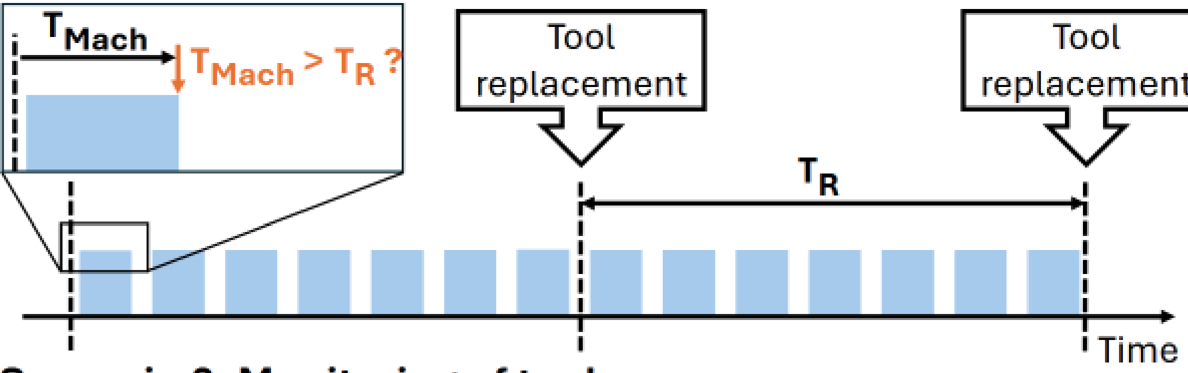
Scenario 1: Tool replacement after T_R minutes of machining



Legend

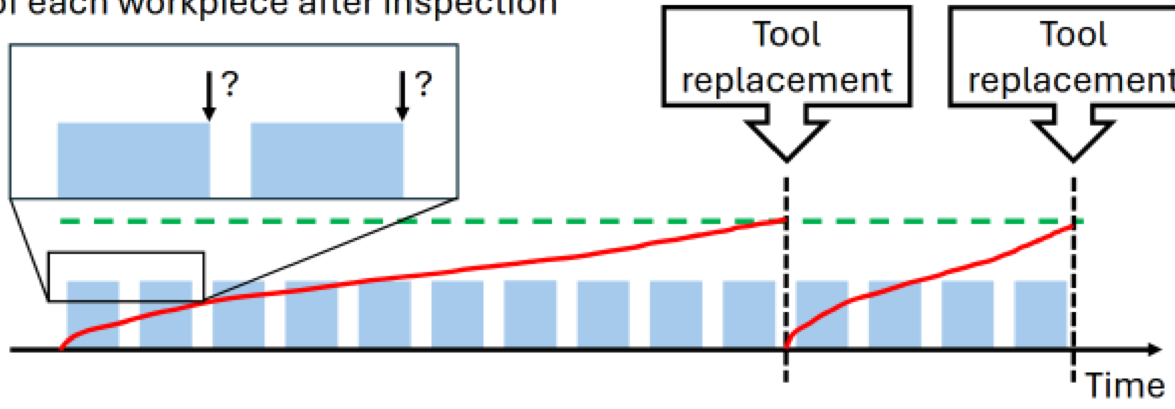
Scenarios

Scenario 1: Tool replacement after T_R minutes of machining



Scenario 2: Monitoring of tool wear

Tool replacement only admitted at the end of the machining operation of each workpiece after inspection



Legend

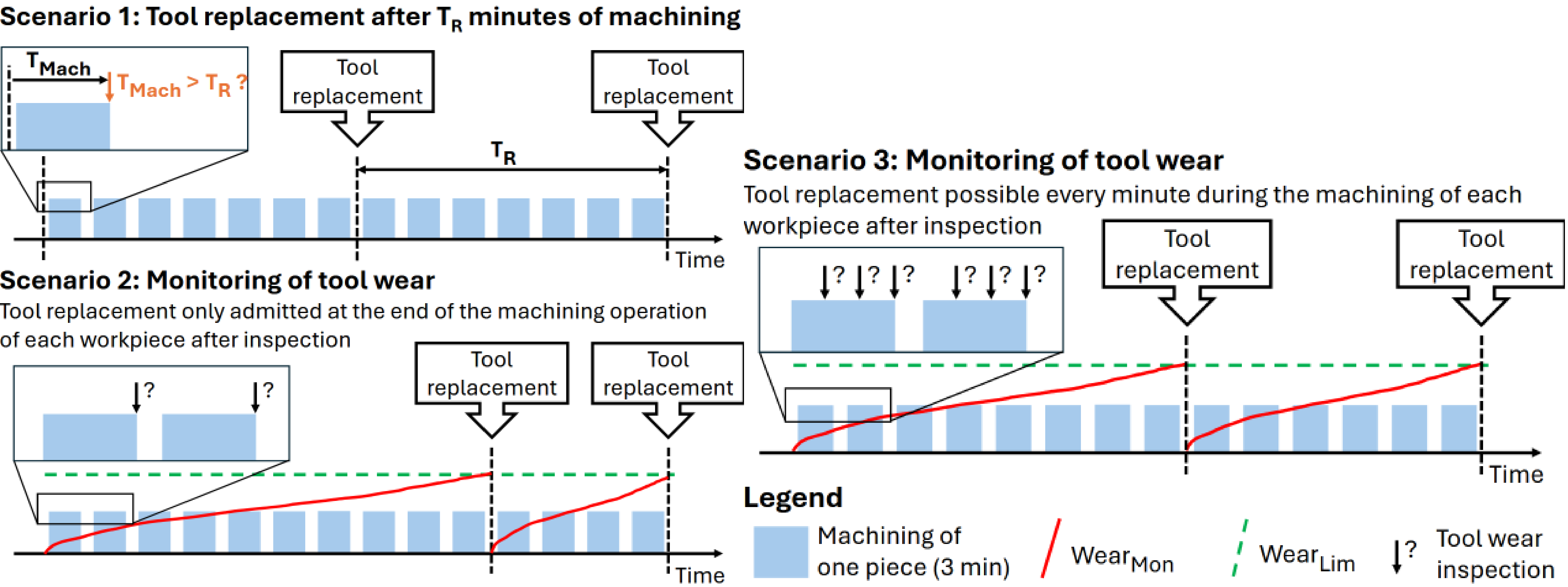
Machining of one piece (3 min)

$Wear_{Mon}$

$Wear_{Lim}$

? Tool wear inspection

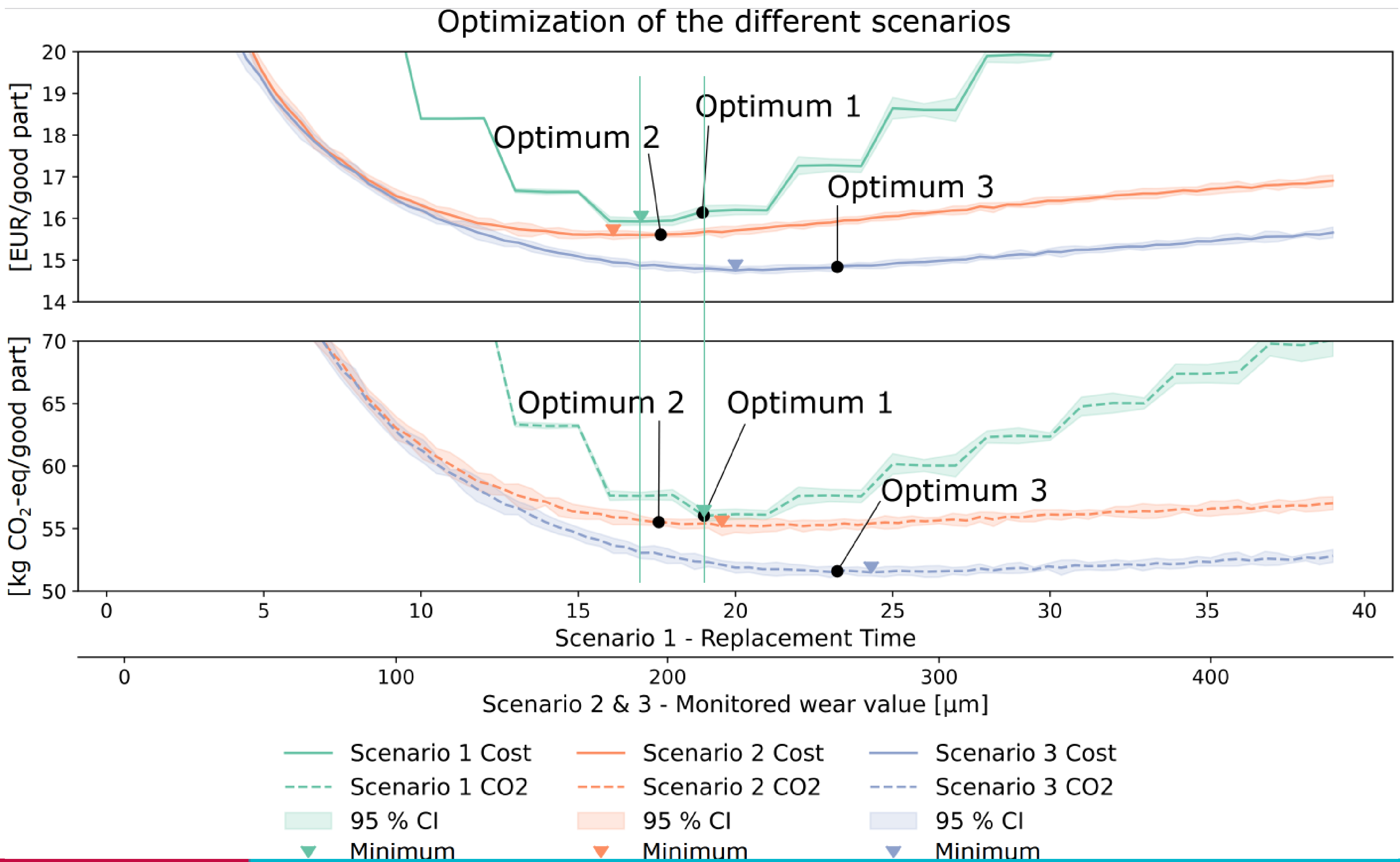
Scenarios



Independent optimization of each scenario parameter:

- Scenario 1: tool replacement periodicity T_R
- Scenarios 2 and 3: wear estimate threshold for replacement $Wear_{Lim}$

Results


Optimization of the different scenarios
[EUR/good part]
20
19
18
17
16
15
14
Optimum 2
Optimum 1
Optimum 3
[kg CO_2-eq/good part]
70
65
60
55
50
Optimum 2
Optimum 1
Optimum 3
0
5
10
15
20
25
30
35
40
Scenario 1 - Replacement Time
0
100
200
300
400
Scenario 2 & 3 - Monitored wear value [µm]
Scenario 1 Cost
Scenario 1 CO2
95 % CI
Minimum
Scenario 2 Cost
Scenario 2 CO2
95 % CI
Minimum
Scenario 3 Cost
Scenario 3 CO2
95 % CI
Minimum

Results

	Scenario 1	Scenario 2	Scenario 3
Number of good workpieces	8310.6 ± 30.7	8880.7 ± 17.3	9194.7 ± 17.5
Number of scrap	1289.4 ± 30.7	719.8 ± 17.19	405.3 ± 17.5
Number of tools	1372 ± 0.0	1479.2 ± 5.5	1408.3 ± 6.52
Total Cost [1000 EUR]	134.6 ± 0.0	138.9 ± 0.2	136.1 ± 0.26
Total CO_2 [1000 kg CO_2-eq]	466.6 ± 0.0	491.7 ± 1.3	475 ± 1.529
Cost/good part [EUR]	16.20 ± 0.06 (100 %)	15.64 ± 0.04 (96.54 %)	14.80 ± 0.04 (91.35 %)
kg CO_2-eq/good part [kg CO_2-eq]	56.15 ± 0.21 (100 %)	55.3 ± 0.20 (98.48 %)	51.6 ± 0.20 (91.89 %)

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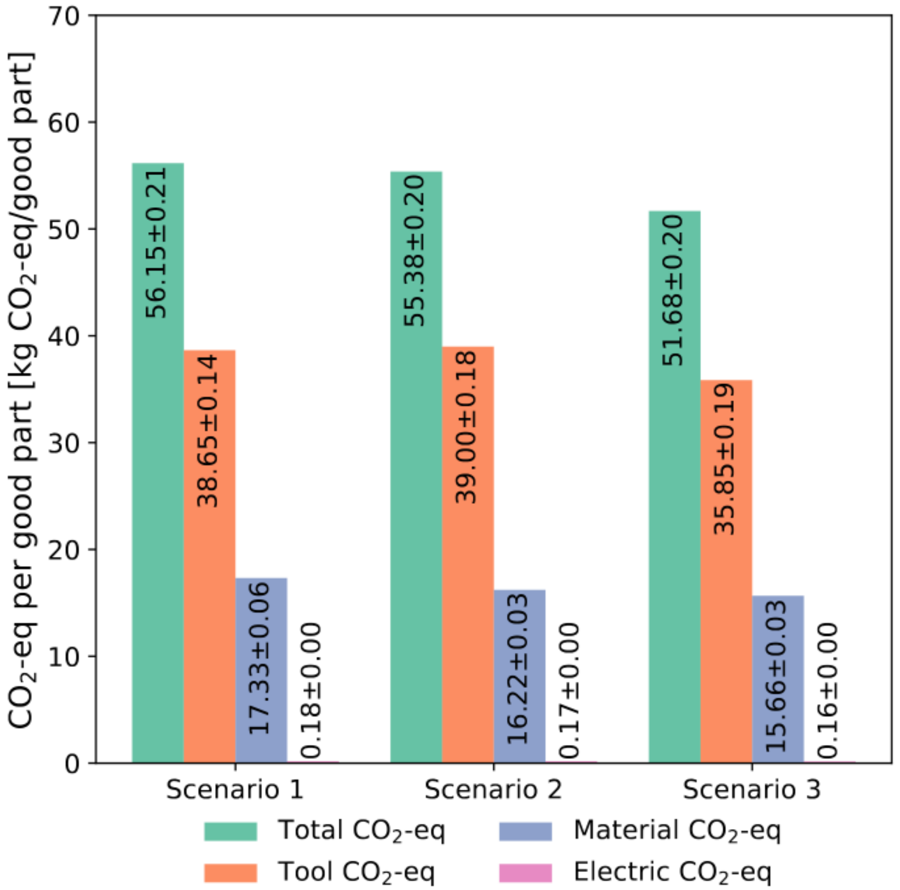

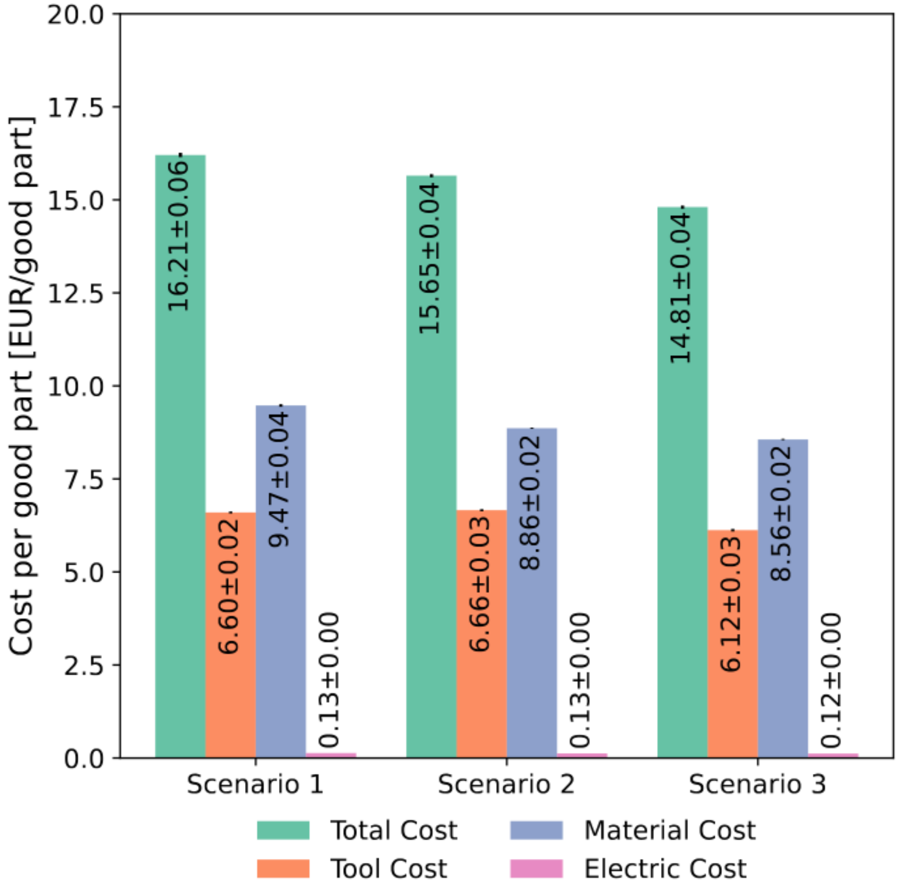

Conclusions

- Current industrial strategies (scenario 1) less effective than monitoring
- 3.5 % economic gain and 1.5 % environmental impact reduction thanks to monitoring
- 8.7 % economic gain and 8.1 % environmental impact reduction if machining can be interrupted thanks to monitoring

- Possible to jointly evaluate economic and environmental impacts
- Tools account for 70 % of the environmental impact

Perspectives

- Integrate the machine, the monitoring system
- Tool recycling, resharpening, recoating, uncoated tools assessment
- Lubrication, cutting parameters, etc.

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