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Scaling solar cell production efficiently with MES

Ensuring quality & cost-effectiveness

pv magazine webinars

PV trends and their impact

Source: VDMA, ITRPV 2025[1]

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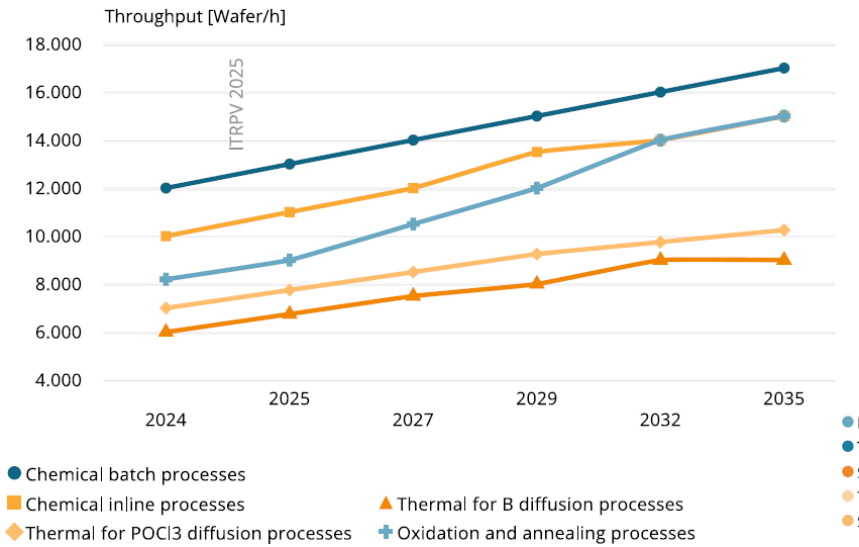
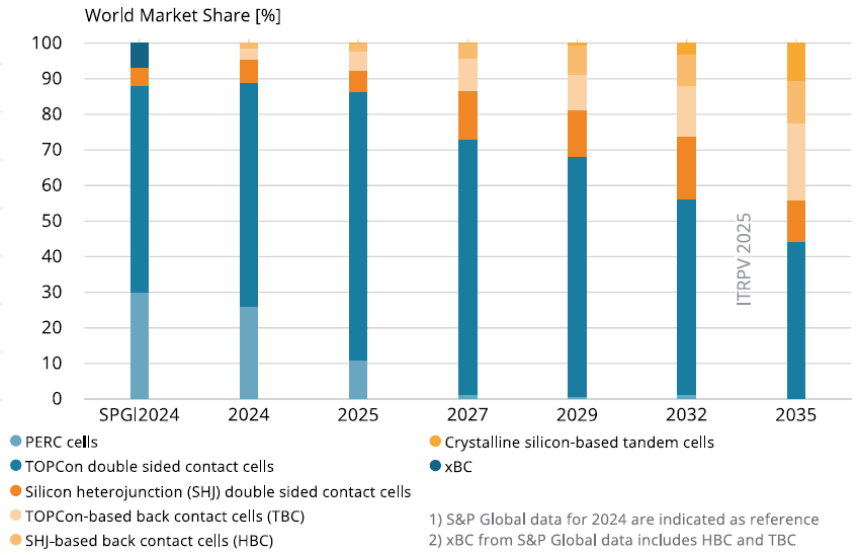
- More efficient machines with higher throughput and automation
- Change to cell technologies with higher complexity
- Trend towards single wafer tracking

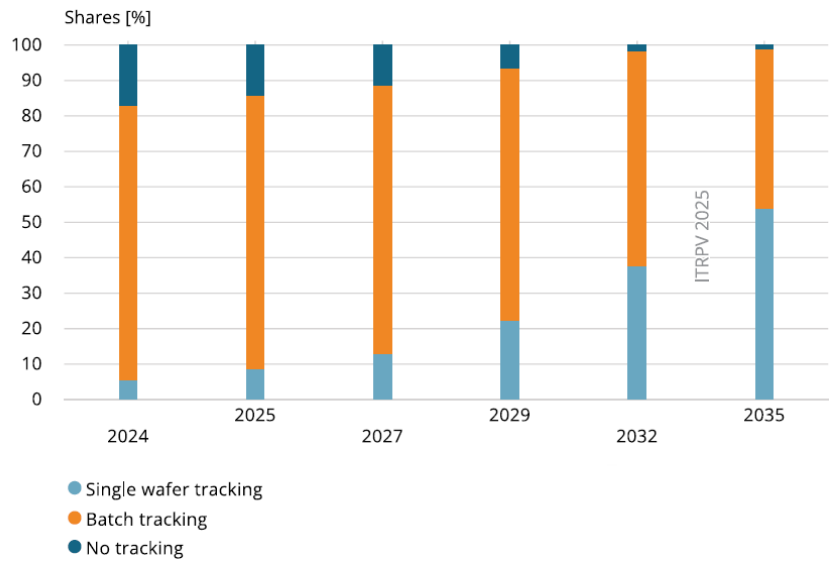
Cell production tool throughputs



Cell technologies



Trends in tracking methods



[1] https://www.vdma.org/international-technology-roadmap-photovoltaic

Now it's your turn

How would you rate the digital maturity of your planned production?

- Level 0: Pre-digital
- Level 1: Connected Fab (basic data flows and centralized server)
- Level 2: Transparent Fab (monitor effectively processes and make informed decisions)
- Level 3: Assisted Fab (suggest optimization strategies and troubleshoot measures)
- Level 4: Autonomous fabs (make real-time decisions and adjust machine parameters)

Agenda

1 Introduction of ISC Konstanz and its services

2 (New) challenges in process optimization

3 Manual tracking methods and their limitations

4 Introduction of Kontron AIS and FabEagle®MES

5 Benefits of MES and single wafer tracking

6 Recent Examples

1

Introduction of ISC Konstanz and its services

ISC Konstanz & services offered

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- Nonprofit association based in Germany, founded in 2005
- Team of 65 employees from 20 different nations
- Services:
  - **Research and development**, on c-Si solar cells, modules and energy systems
  - Training and education, material testing, prove-of-concept, pilot production
  - **Technology transfer** and consulting

ISC's roadmap for the next generation silicon solar cells

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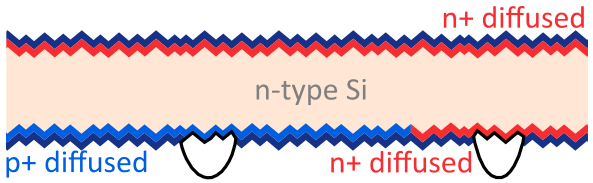
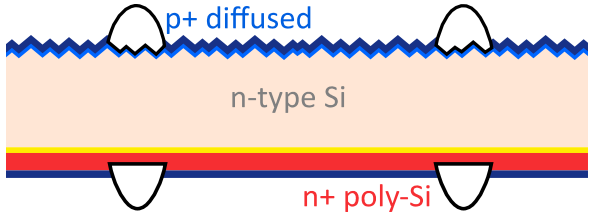


ZEBRA (IBC)

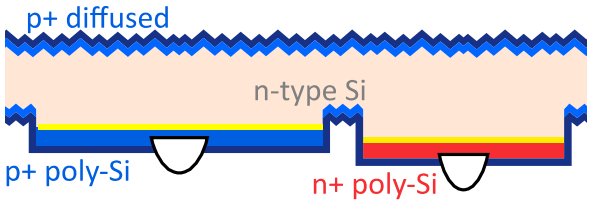
- In production
- 24.5%+ guaranteed
- High bifaciality



TOPCon

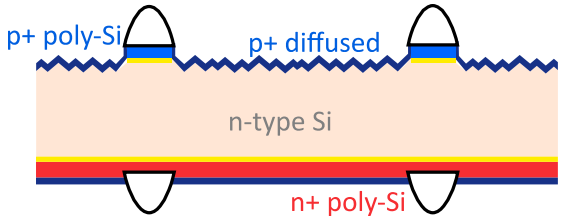
- In Production
- 24.5%+ guaranteed

Upgrade



polyZEBRA[1]

- 25.5%+ expected
- Can be pilotized in ZEBRA or TOPCon factory
- IP secured [EP4195299A1]



SELFI[2]

- 25.0%+ expected
- Easy upgrade for TOPCon
- IP secured [EP3982421A1]

[1] Linke, Jonathan, et al. " Fully passivating contact IBC solar cells using laser processing." Proc. 8th World Conf. Photovolt. Energy Convers. 2022

[2] Hoß, Jan, et al. "Selective p+ Poly-Si Fingers for TOPCon Front Contact Passivation." EUPVSEC 2024, 1CV.2.10

Manufacturing excellence

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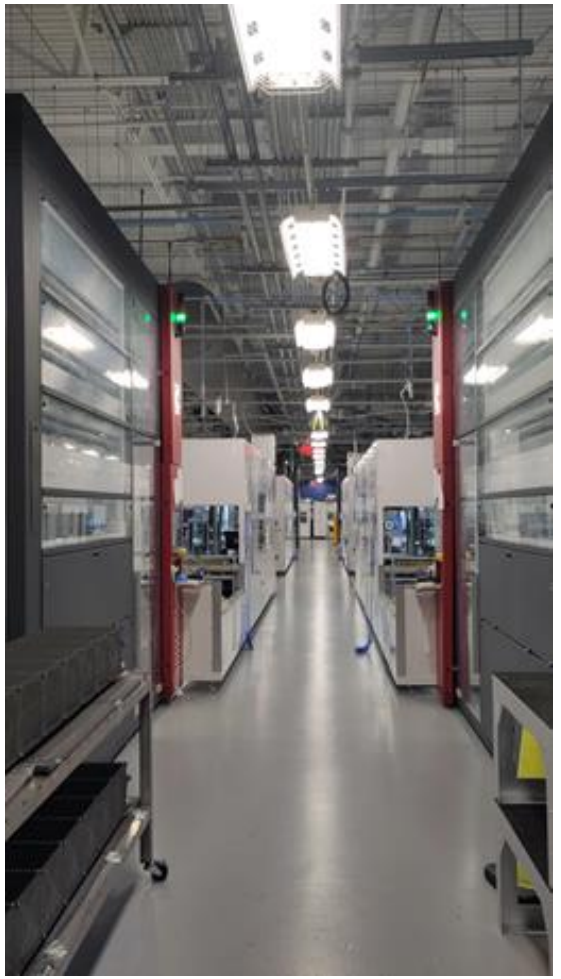
- Services provided by ISC:
  - **Technology transfer** (licensing of advanced solar cell processes)
  - **Ramp-up** support
  - **Optimization** of production lines
  - General **consulting** for manufacturing
  - Dashboards, DOE, clean room protocols …



References factory ramp-up

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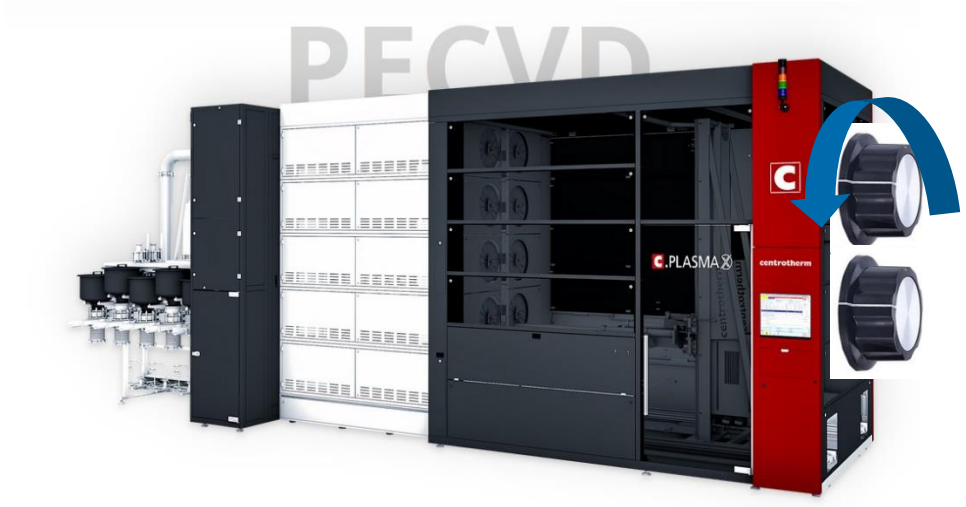
- ISC Konstanz has **more than 15 years of experience** in development and industrialization of solar cell concepts with focus on n-type

- Successful process transfers and ramp-up projects
  - 2015, MegaCell, **Italy** ➡ n-PERT process transfer
  - 2017, Adani, **India** ➡ n-PERT process transfer
  - 2018, **Asian** customer ➡ n-PERT converted to TOPCon
  - 2020, SPIC, **China** ➡ IBC process transfer
  - 2021, Valoe Solar, **Lithuania** ➡ IBC process transfer
  - 2023, **Indian** customer ➡ PERC process consulting
  - 2024, **Indian** customer ➡ TOPCon process consulting
  - 2025, SUNIVA, **USA** ➡ PERC process consulting
  - 2025, **Indian** customer ➡ TOPCon process consulting

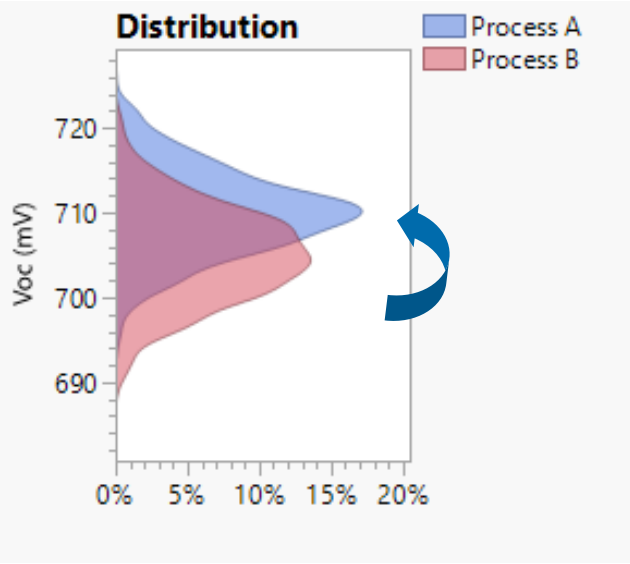
DOE based process optimization

(Design of experiment-based process optimization)



Correlation to

(requires tracking)



DOE: Turning of knobs and observation of its effect on process results

In reality: many knobs (input variables) and many process results (output parameters) require an educated turning of knobs, the use of **statistical data analysis** and **physical models** for interpretation of results

2

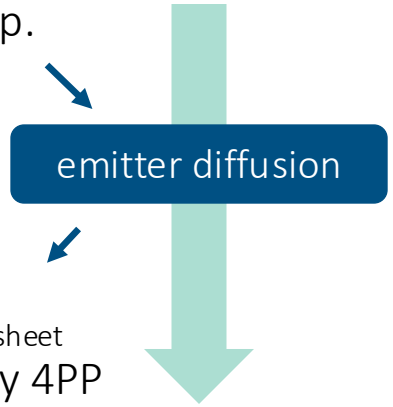
(New) challenges in process optimization

Challenge 1: Long feedback loops

Parameters may not be directly accessible
Measurement for SPC may not be feasible

R_{sheet}

Variation Temp.



Variation in R_{sheet} measurable by 4PP

TOPCon process with PECVD

Minority carrier lifetime (MCLT)

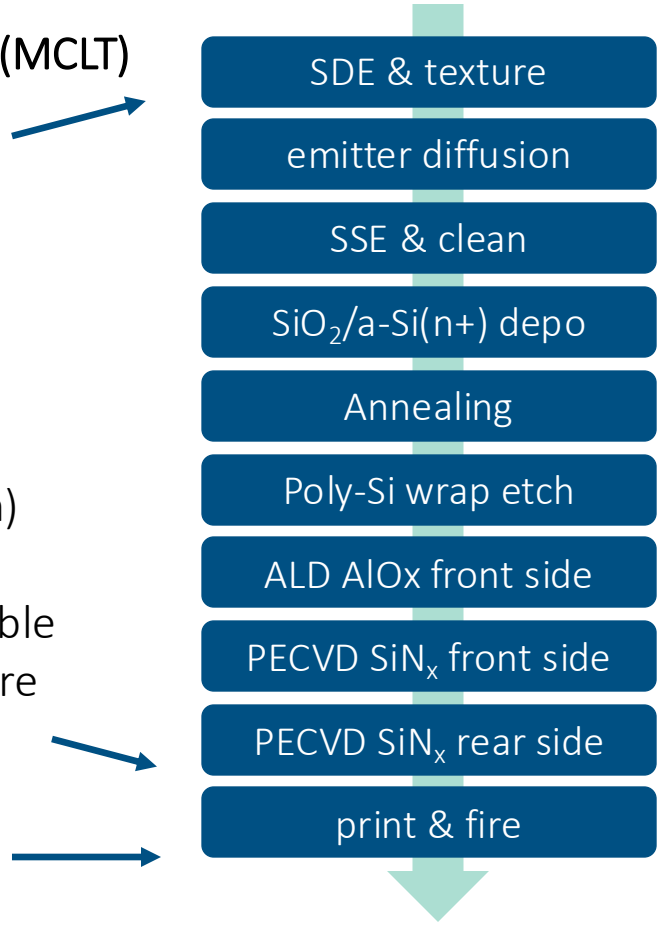
Contamination

(Gettering)

(Emitter Passivation)

Low MCLT measurable for the first time here

Or in final IV test



Challenge 2: More sophisticated cell structures

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PERC (w/o SE)

- SDE & texture
- emitter diffusion
- SSE & clean
- AlOx/SiNx RS
- Laser LCOE
- PECVD SiN_x
- print & fire

7-8 step

TOPCon

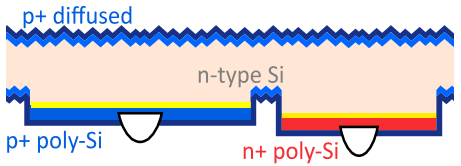
- SDE & texture
- emitter diffusion
- SSE & clean
- SiO_2/a-Si(n+)
- Annealing
- Poly-Si wrap etch
- ALD AlOx
- PECVD SiN_x FS
- PECVD SiN_x RS
- print & fire

10 steps

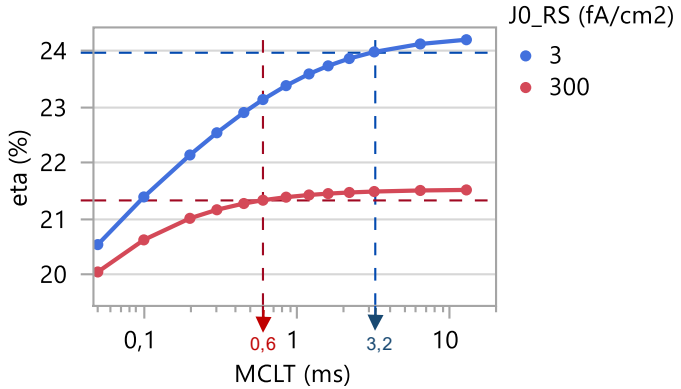
PolyZEBRA

- SDE
- SiO_2/a-Si(n+)
- SiNx
- Laser Ablation
- Alk. etching
- SiO_2/a-Si(n+)
- B-Diffusion
- HF-Clean
- Laser Doping
- Texture
- B-Diff
- Wet Clean
- PECVD AlOx/SiN_x
- PECVD AlOx/SiN_x
- print & fire

15 steps



Cross section polyZEBRA



Simulation of efficiency of TOPCon cell for different surface recombination

- More sophisticated cell structure → longer process sequence
- Higher efficiency, cells get more sensitive, e.g., higher MCLT level required

Challenge 3: Bigger fabs, higher throughput

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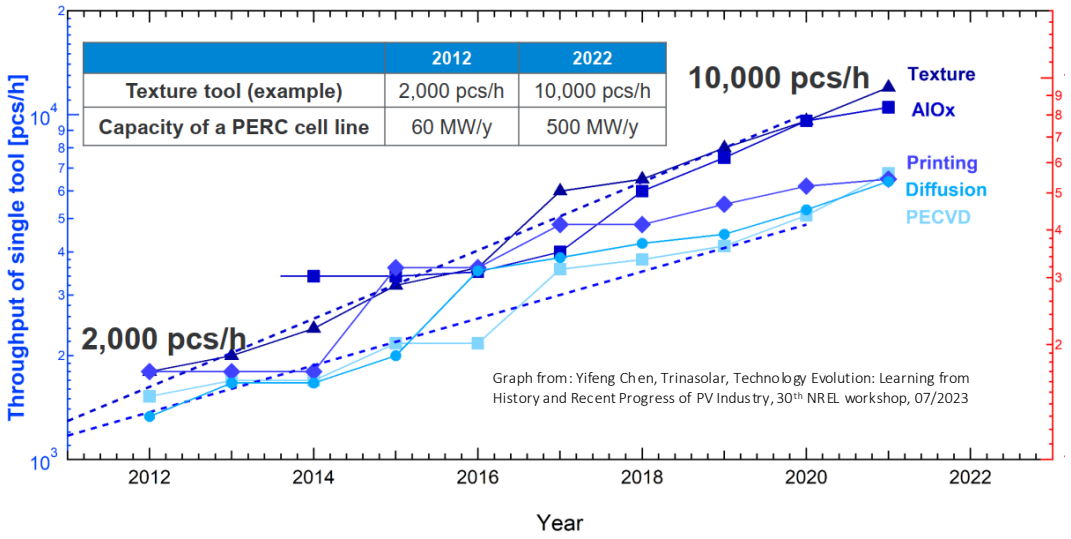
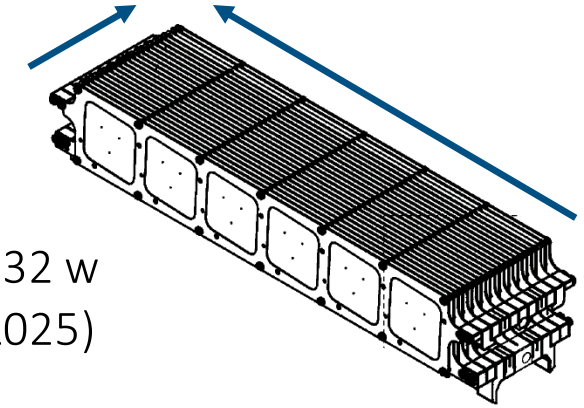
- Factories get bigger
  - Many parallel tools, served according to availability
  - Throughputs and batch sizes not matched, e.g., diffusion 2640 w, wet 600 w, PECVD 632 w
- Single tools get bigger and faster
  - Batch size increased to a degree that homogeneity becomes a problem
  - Speed > 1 w/s difficult to track for the human eye



Example
PECVD boat size



144 w -> 312 w -> 632 w
(2005) (2012) (2025)

Challenge 4: Throughput optimized tools

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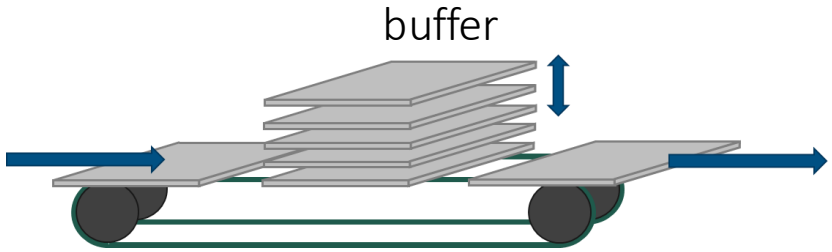
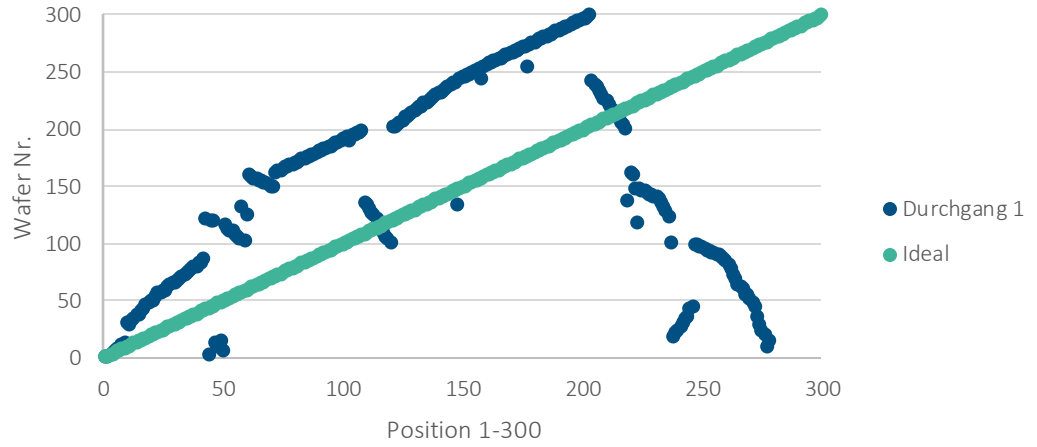
- Tools are not optimized for tracking but for maximum capacity:
  - Buffers (first in – last out) are used to reduce interruption of wafer flow
  - Unloading and loading of carrier in parallel lanes
- Complex mixing patterns

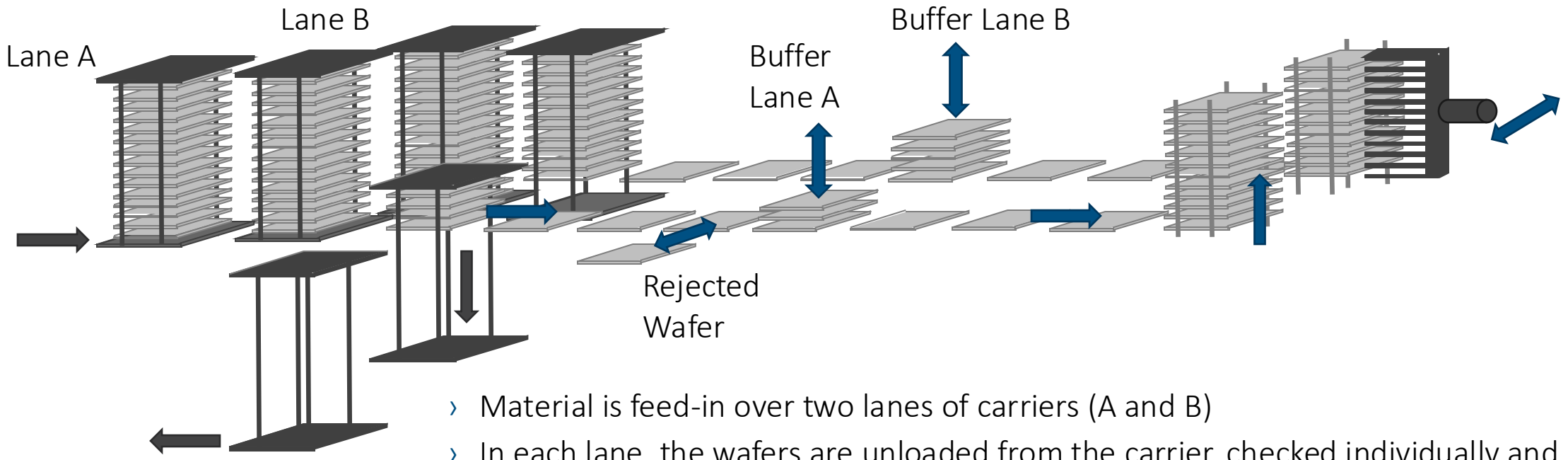




Example: Material flow in 3-stage printing line with buffers, only 300 wafers are manufactured

Challenge 4: Throughput optimized tools

Example loading unit PECVD



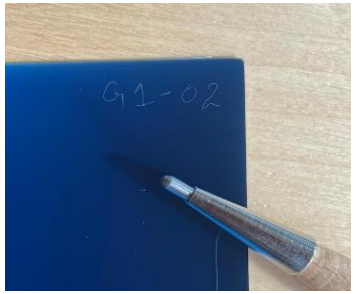
- Material is feed-in over two lanes of carriers (A and B)
- In each lane, the wafers are unloaded from the carrier, checked individually and rejected in case of cracks, buffered, and then finally stacked in a loading unit
- Depending on which loading unit is ready first, the gripper takes a package of 32 wafers from it and places it in the next row of pockets in the boat
- Unloading works in a comparable way also via two lanes
- Result: wafers from one carrier are distributed in packages across four carriers

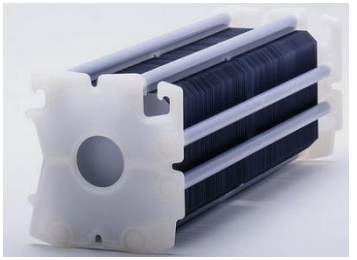
3

Manual tracking methods and their limitations

Manual tracking methods and their limitations

Method	Pro	Disadvantage
Wafers marking (diamond pen or laser)	Reliable information	› Extremely time consuming › Difficult to track and sort back
Carrier-wise tracking (100 - 500 w per group)	Several split groups possible	› Difficult to avoid mixing › Substantial effort for tracking, i.e., manual operation of loadings › Discontinuous production might influence process outcome
Trolley-wise tracking (1000 – 10k w per group)	Higher chance to get (mostly) correct information	› Only few variations can be tested › Substantial effort for tracking › Failed groups are large





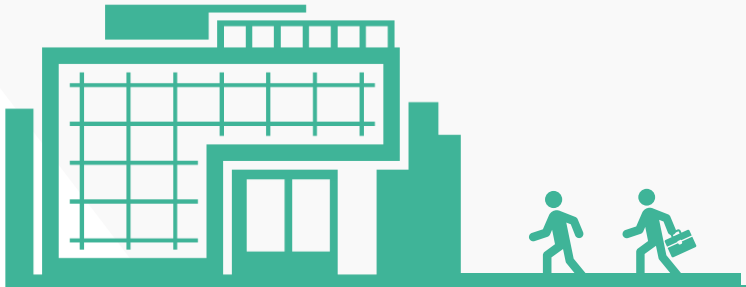
› With an experienced team and skilled operators, all variants are possible, but none of them is fun!

4

Introduction of Kontron AIS and FabEagle®MES

Portrait

Provider
for industrial
software



35
years of experience

> 250
employees

28 mio.
€ turnover

8
Products

- EquipmentCloud®
- KontronGrid
- ToolCommander®
- FabLink®
- FabEagle®Connect
- FabEagle®Monitoring
- FabEagle®MES
- FabEagle®LC

> 200
customers
in 2024

45
countries

Kontron AIS – PV customers

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FabEagle®MES

Crystallization Growing Wafering	Thin film production	Silicon based cell manufacturing	PV module manufacturing	Solar receiver production
10 x	14 x	52 x	23 x	2 x

MES functions that are needed today

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Increased Transparency

- Online Process Visualization
- Production Visualization
- Trends and Reporting
- Logbook / Machine Log

Traceability

- Material and Carrier Tracking & Interlock
- Inspection and Rework
- Quality Data Acquisition
- Long-term Archiving

Production Control

- Production Orders
- Workflows
- Maintenance Management
- Online-SPC
- Event Management

MES functions that are needed today

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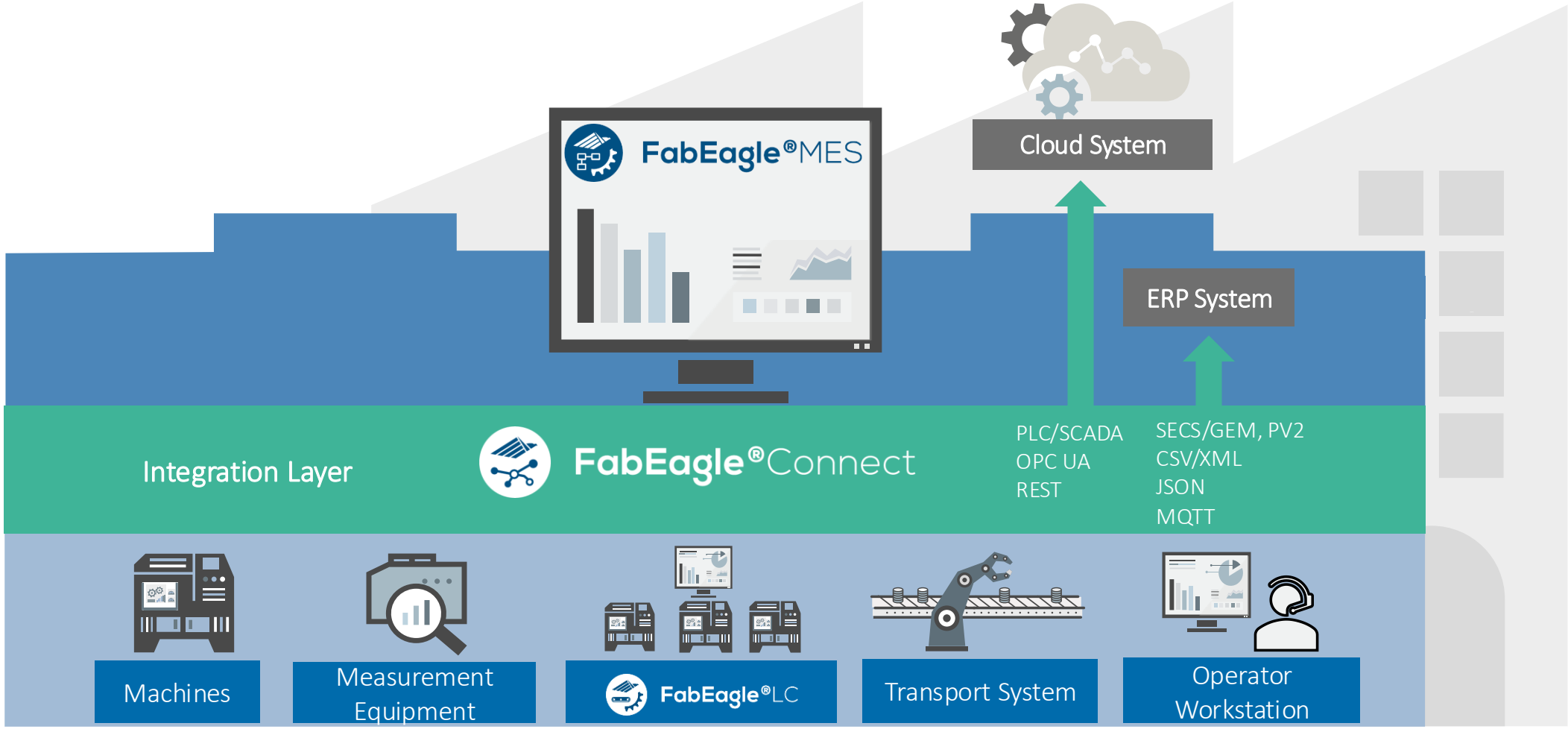

MES functions that are needed today

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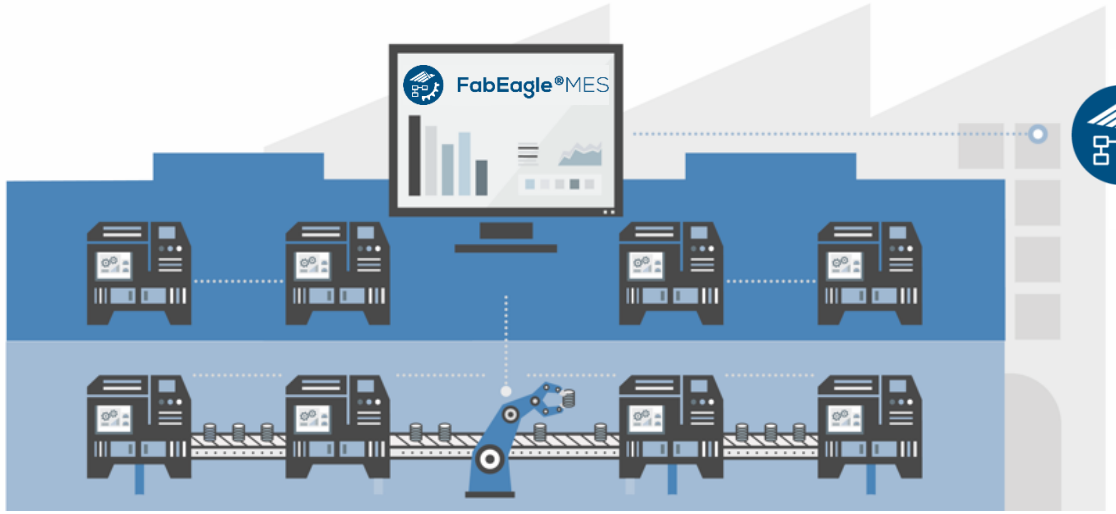
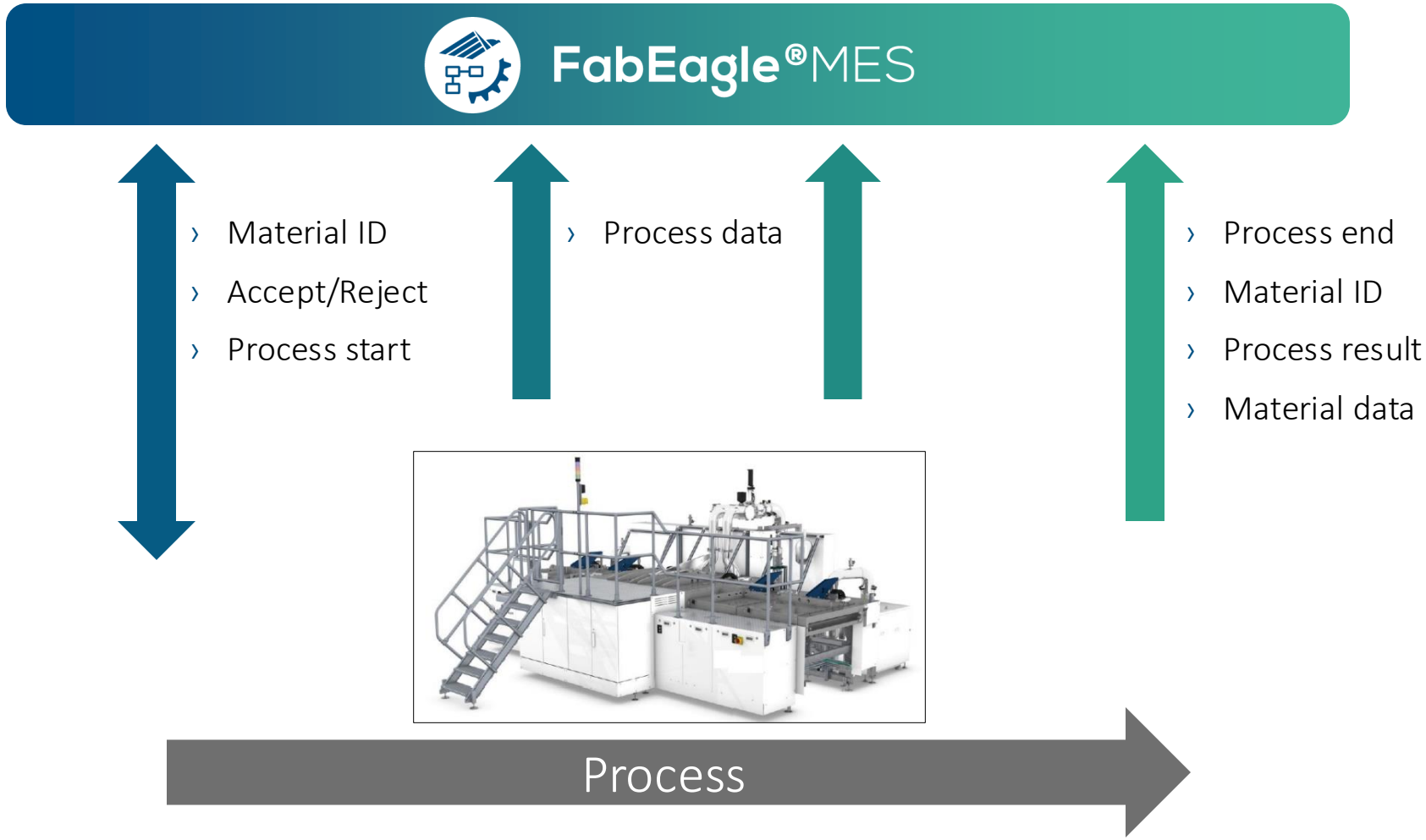
- Production Visualization
- Order Management
- Work Plans
- Recipe Management
- Production Control
- Material Tracking
- Machine Data Acquisition
- Process Data Acquisition
- Reporting & Online SPC
- Long-term Data Archive
- Operator Workstation
- User Management



FabEagle®MES

Communication MES – Equipment



5

Benefits of MES and single wafer tracking

Sample setup of a PV cell production line

Complexity of cell tracking across process steps

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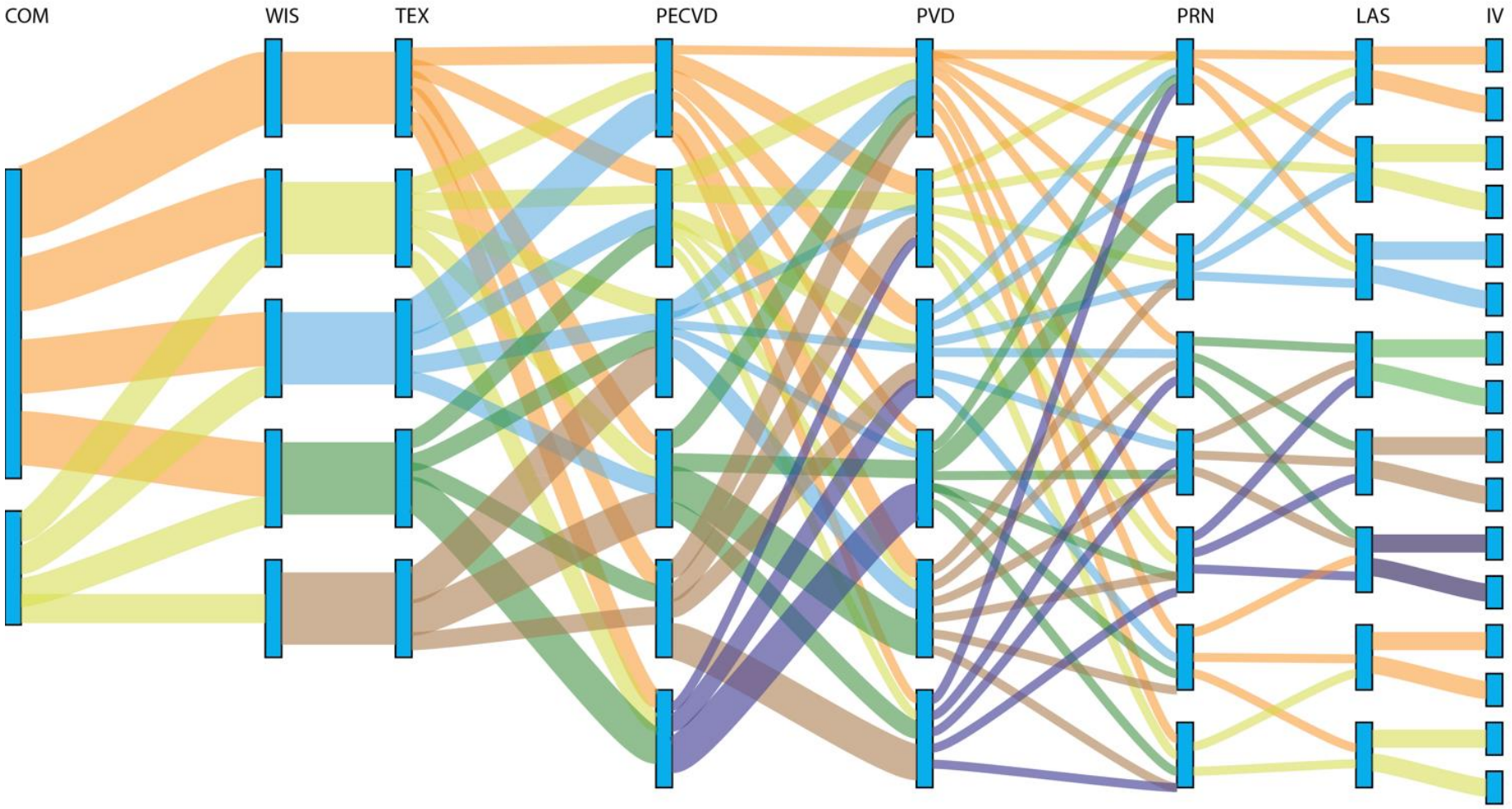

Benefits of single wafer tracking

Tracking and solar cell efficiency

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› Increase efficiency by using virtual wafer tracking in solar cell manufacturing
› Reduce efficiency deviations

Benefits of single wafer tracking

Samples of application

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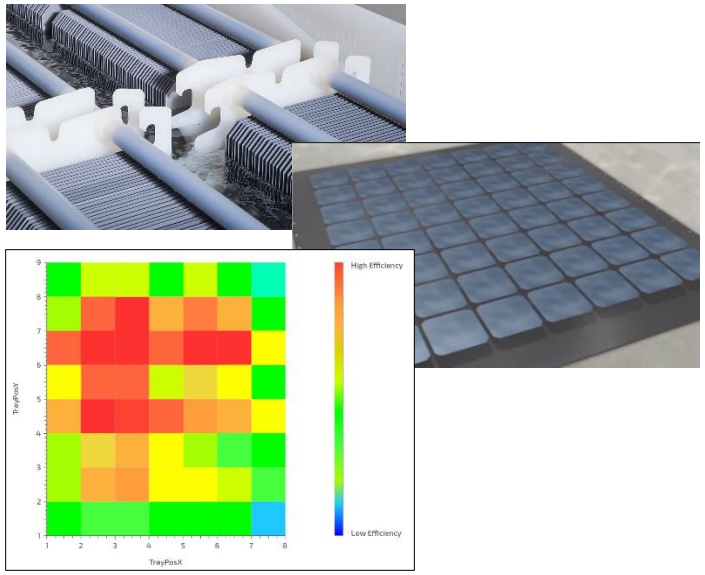
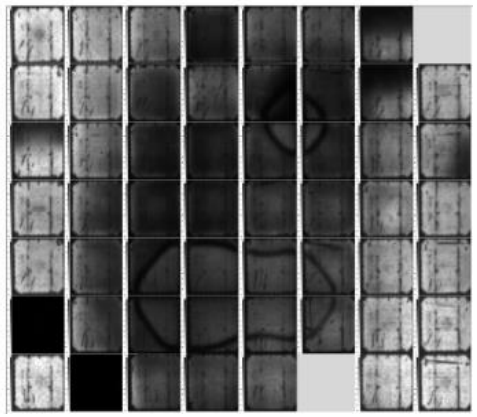
Use tracking info to map IV data to positions in processes

- Wet chemical processes
- PVD/PECVD processes
- Processing lanes and printing nets



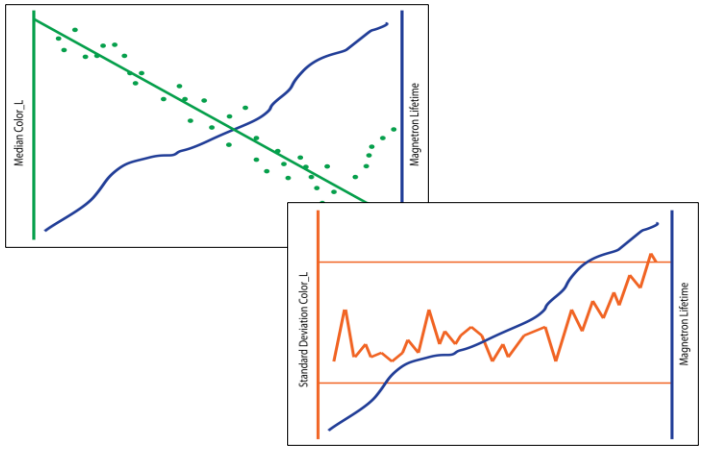
Extended process monitoring for tray processes e.g. PECVD

- Use image data (e.g. electro-luminescence) to detect wafer loss before deposition starts
- Detect potential hardware defects before they happen and trigger preventive maintenance



Monitoring target lifetime of sputtering processes

- Combined monitoring of cell IV and equipment data
- Using inline measurement data across multiple process steps to detect electrical deviations before yield loss happens



Opportunities with Digital Twins

From connected fabs to smart fabrication

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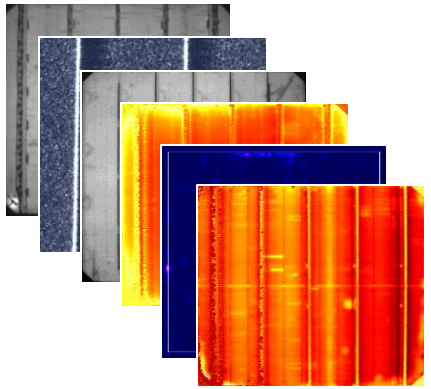
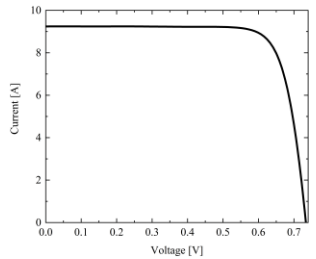
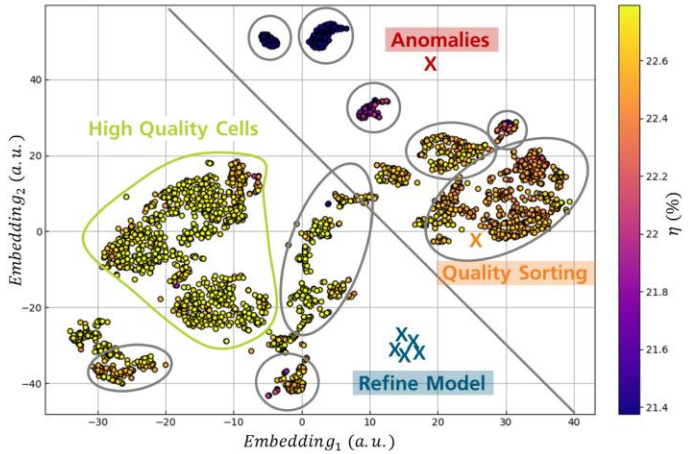
Empirical digital twin [1,2]

- Includes all inline and quality data
- Describes the state of the solar cell
- Quantifying defects and data patterns with impact to cell quality

→ For fast quality analysis



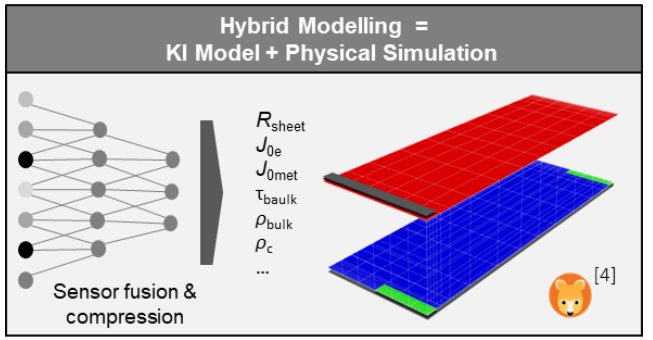




Physically interpretable digital twin [3]

- Based on physics-informed deep learning
- Predicts latent parameters, inaccessible by direct measurements
- Fast loss analysis and potential analysis

→ For fast loss and potential analysis



Fraunhofer ISE

Intersolar 2025, Booth A1.440

[1] Fraunhofer patent granted
[2] P. Kunze et al., 52. IEEE PVSC 2024, Seattle/USA
[3] M. Demant et al., EUPVSEC 2024, Vienna 09/2024
[4] www.quokka3.com

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Now it's your turn

Do you see AI shaping the future of your production?

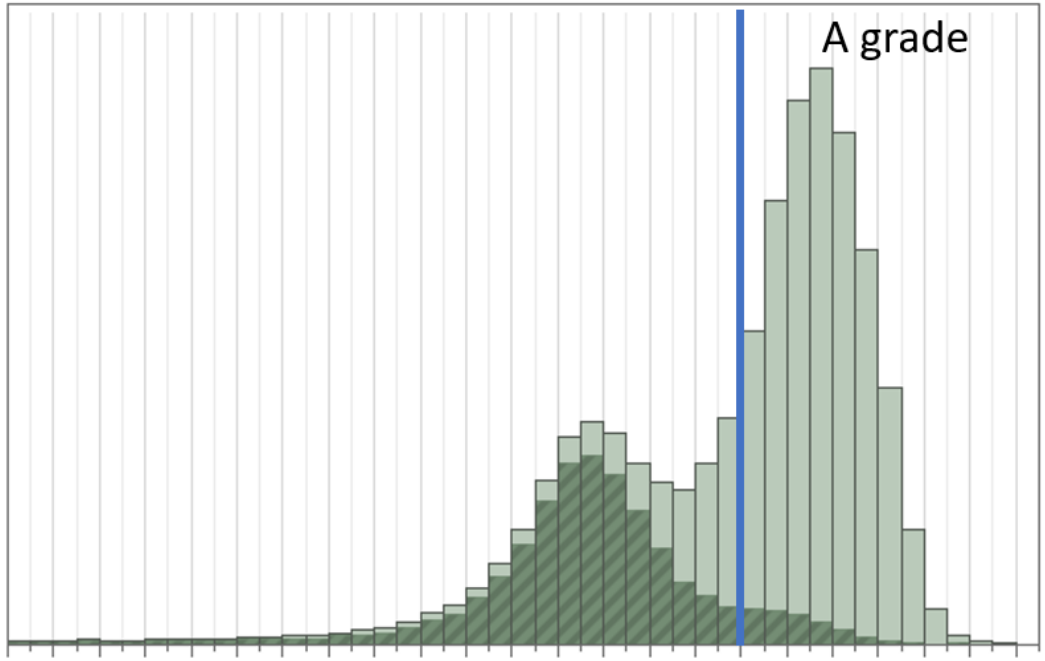
- I don't have AI implemented in production
- I already have applications using AI
- AI will be fully integrated for production control within 5 years
- The promises of AI won't take effect in the foreseeable future

6

Recent Examples

Recent examples

Problem with factory output (yield, performance)



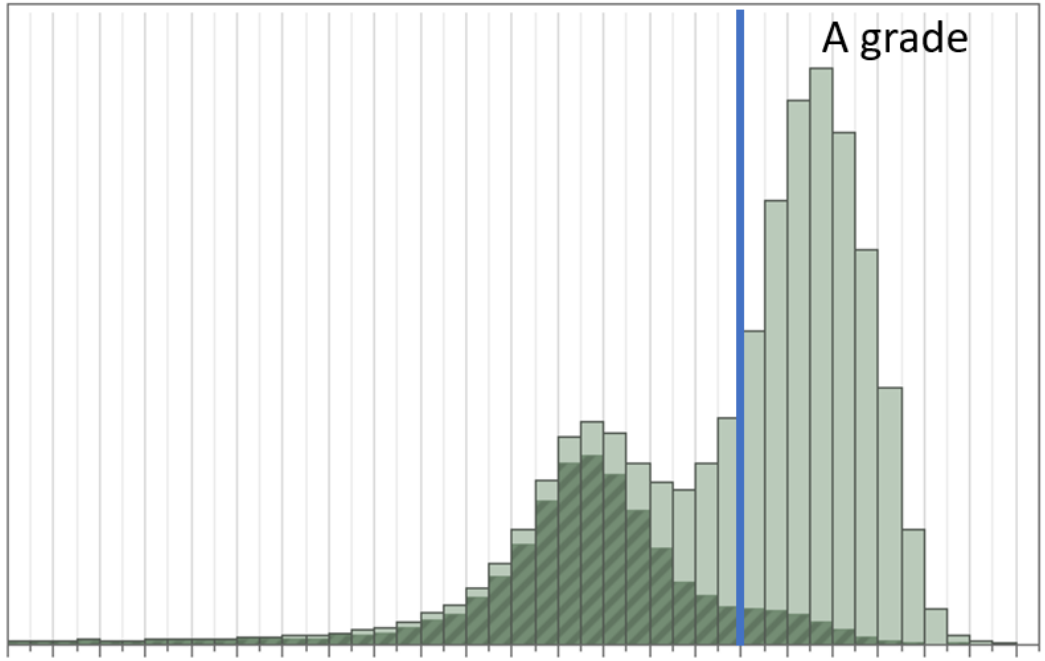
Starting point

Double hump efficiency distribution (due to Isc and Voc)!

~30% of cells affected

Recent examples

Problem with factory output (yield, performance)



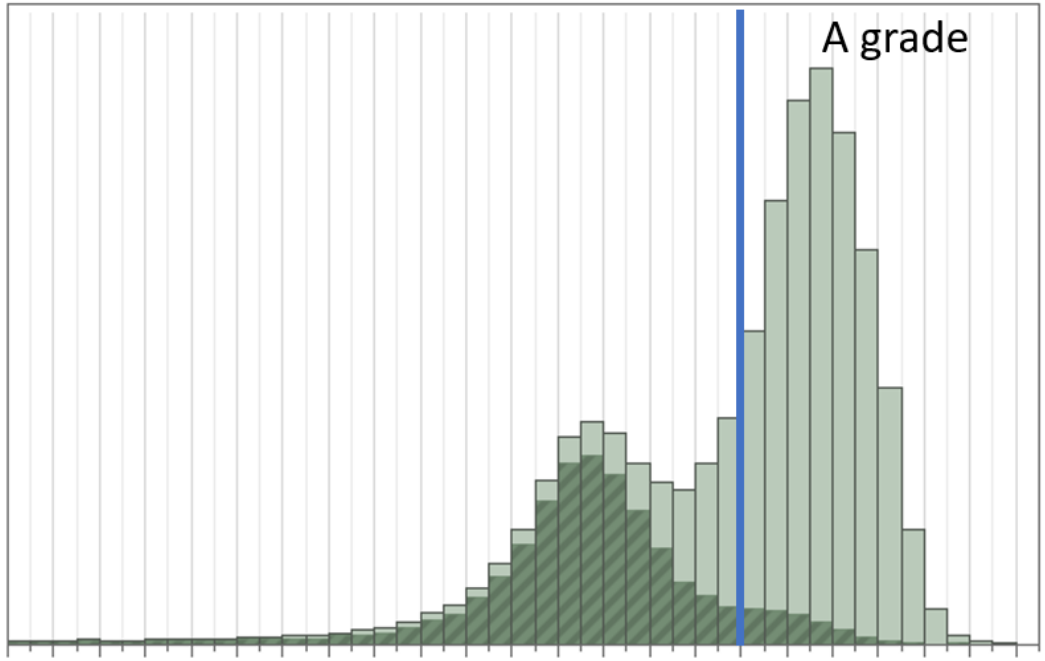
Eta (%)

Root cause analysis:

- **What does it correlate with?**
  - Underperforming tool in set (wetbench furnace, laser, ….)
  - Segment
    - Tube process position (non-uniformity of gas flow, temperature etc.)
    - PECVD boat position
    - Carrier position
    - Tester
  - …
- **How can it be fixed?**

Recent examples

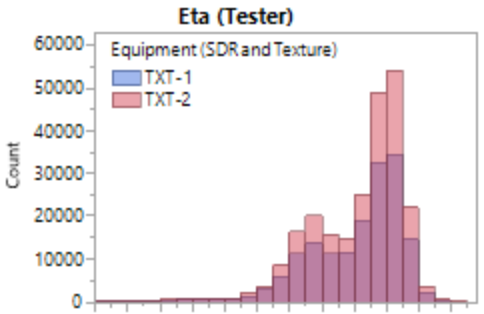
Problem with factory output (yield, performance)

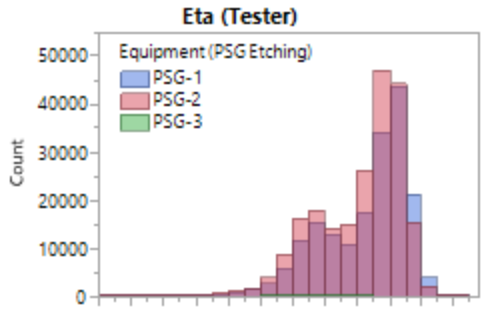


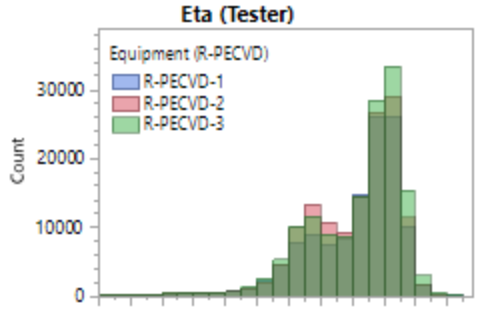
Eta (%)

Root cause analysis:

› Wetbench 1 vs. Wetbench 2 ...



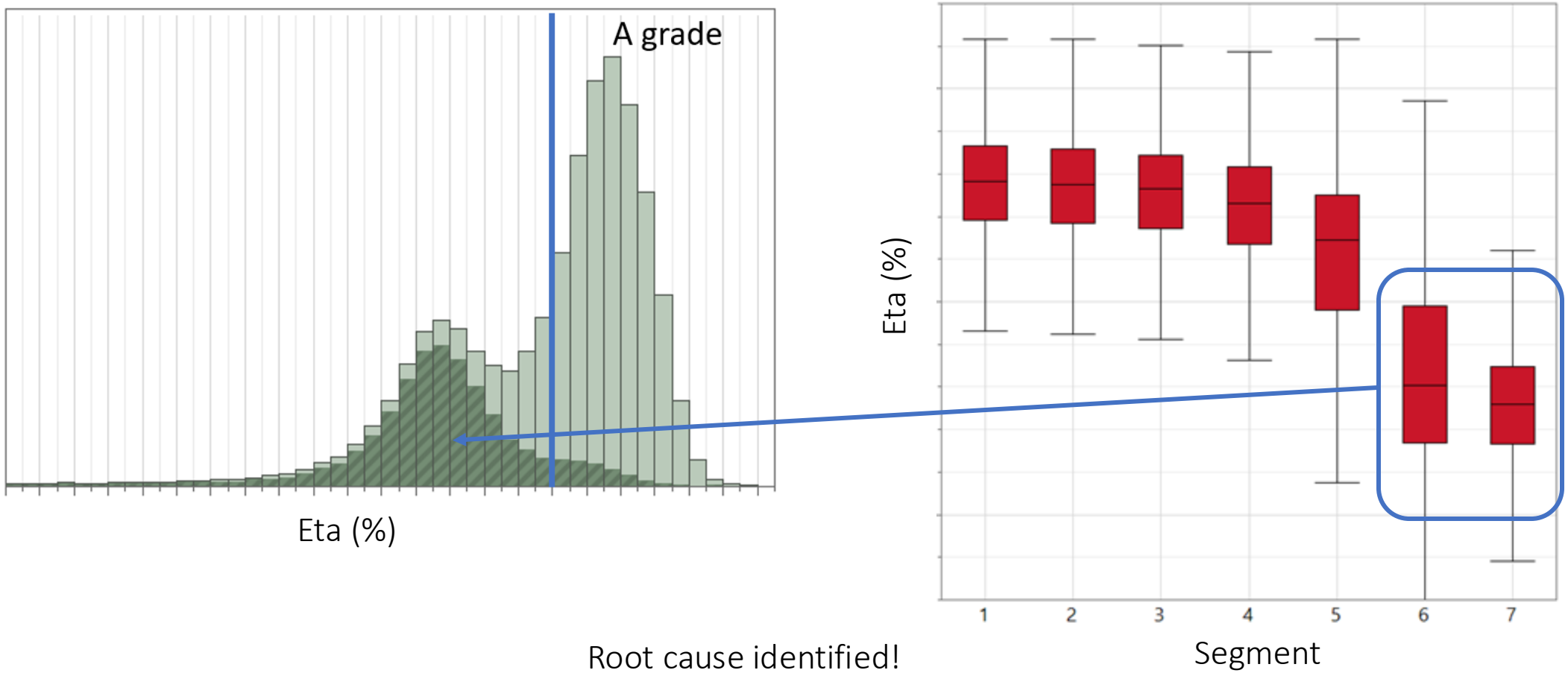




No correlation with single process equipment.
Deeper analysis needed!

Recent examples

Problem with factory output (yield, performance)



Root cause identified!

Recent examples

Problem with factory output (yield, performance)

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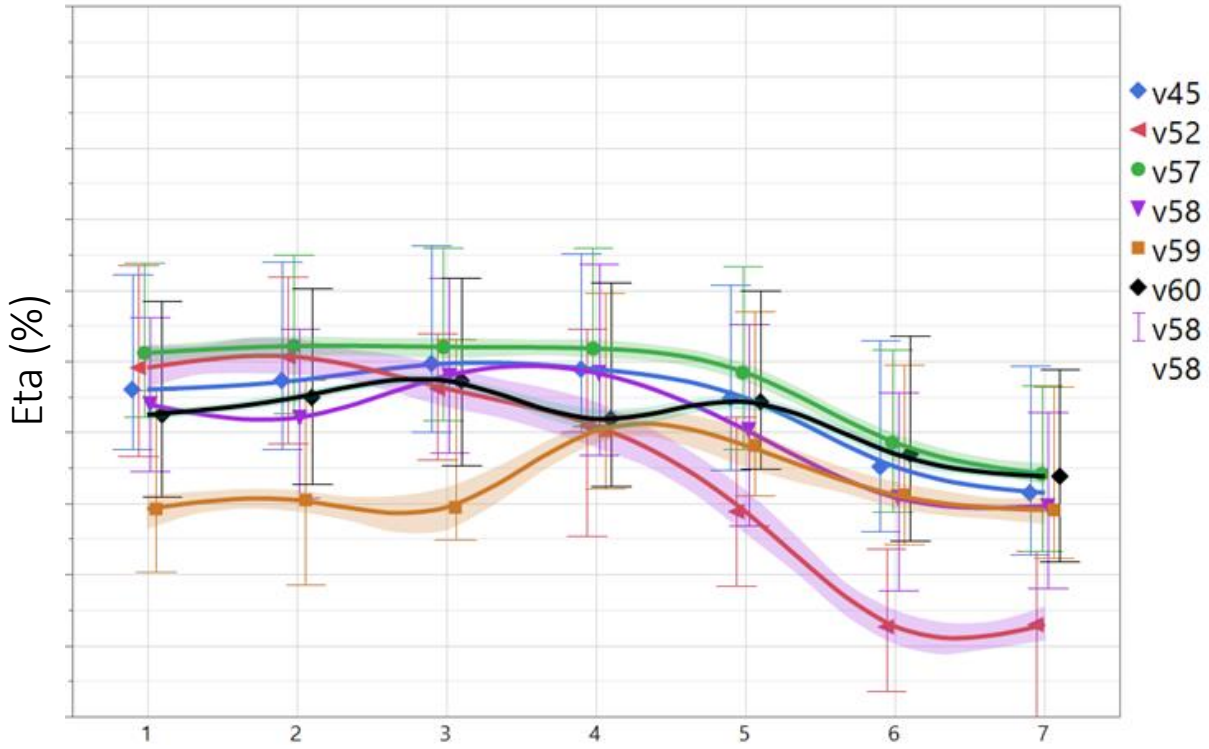
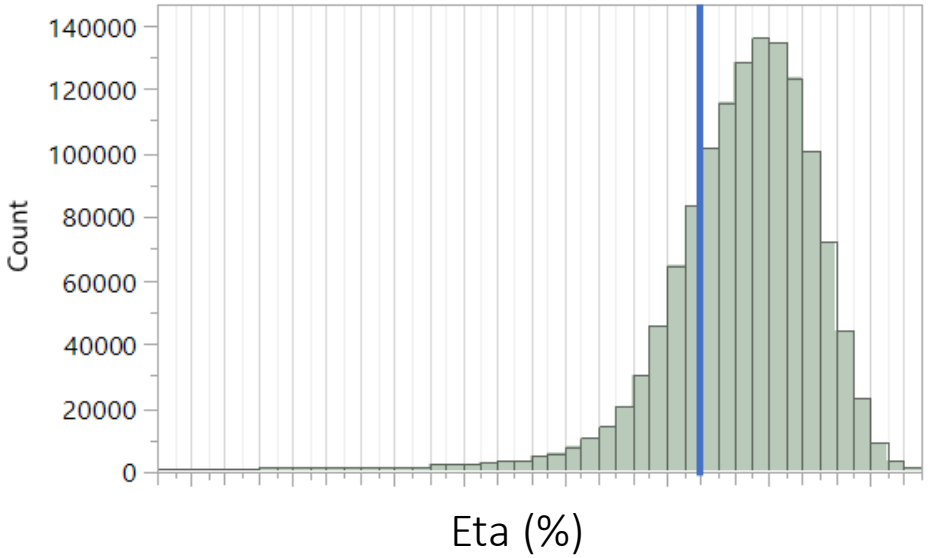
› Multi-recipe DOE optimization was performed (~60(!) different recipe tested)





3 weeks of work

Cost considerations

Scenario 1: Ramp-up

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	M1	M2	M3	M4	M5	M6	Total
Capacity	5%	10%	20%	30%	40%	50%	
Throughput daily	17,000	34,000	68,000	102,000	136,000	170,000	
Throughput monthly	510,000	1,020,000	2,040,000	3,060,000	4,080,000	5,100,000	
Yield without MES	5%	10%	20%	30%	40%	50%	
Yield with MES	5%	10%	20%	40%	60%	80%	

Costs through yield loss without MES	$ -391,476	$ -741,744	$ -1,318,656	$ -1,730,736	$ -1,977,984	$ -2,060,400	**$ -8,220,996**
Costs through yield loss with MES	$ -391,476	$ -741,744	$ -1,318,656	$ -1,483,488	$ -1,318,656	$ -824,160	**$ -6,078,180**

Capacity: 1 GW | Cells/day: 339,075 | Costs/cell: $ 0.81 ($ 0.1/W, 8.08 W/cell)

Cost considerations

Scenario 2: Process control

Monitoring by toolset	One of two wet benches runs at 50% yield, unnoticed contamination	
	Tool 1	Tool 2
Throughput @100% per tool	14,000	14,000
Yield	95%	50%
Yield loss detected after 5 days without MES	755,000	
Costs	$ -610,040	
Yield loss detected after 1 day with MES	151,000	
Costs	$ -122,008	

Benefits of single wafer tracking

Summary

Benefits of cell tracking during the ramp-up phase

- Rapid ramp-up with maximum efficiency
- Less engineering staff and less test wafers needed thanks to automatic data collection
- Good tracking allows a more complex Design of Experiments (DOE) with conclusive results
- Application of digital twins for fast quality analysis (root causes)

Benefits of cell tracking during operation phase

- Process improvements can be evaluated and introduced faster
- Automatic detection of equipment malfunctions or scheduling of maintenance tasks
- Fast identification of root-causes for product defects
- Use physical twins for fast loss and potential analysis

Your questions

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