Data Models in the Middle

Keynote 7th International Workshop on Business Processes Meet the Internet-of-Things (BP-Meet-IoT)

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The Internet-of-Production @ RWTH

- ~ 50 Mio €
- ~ 35 groups
- ~ 200 researchers
- Production and Computer Science
- Main concepts: World-Wide-Lab and Digital Shadows
- Process mining plays a key role in IoP

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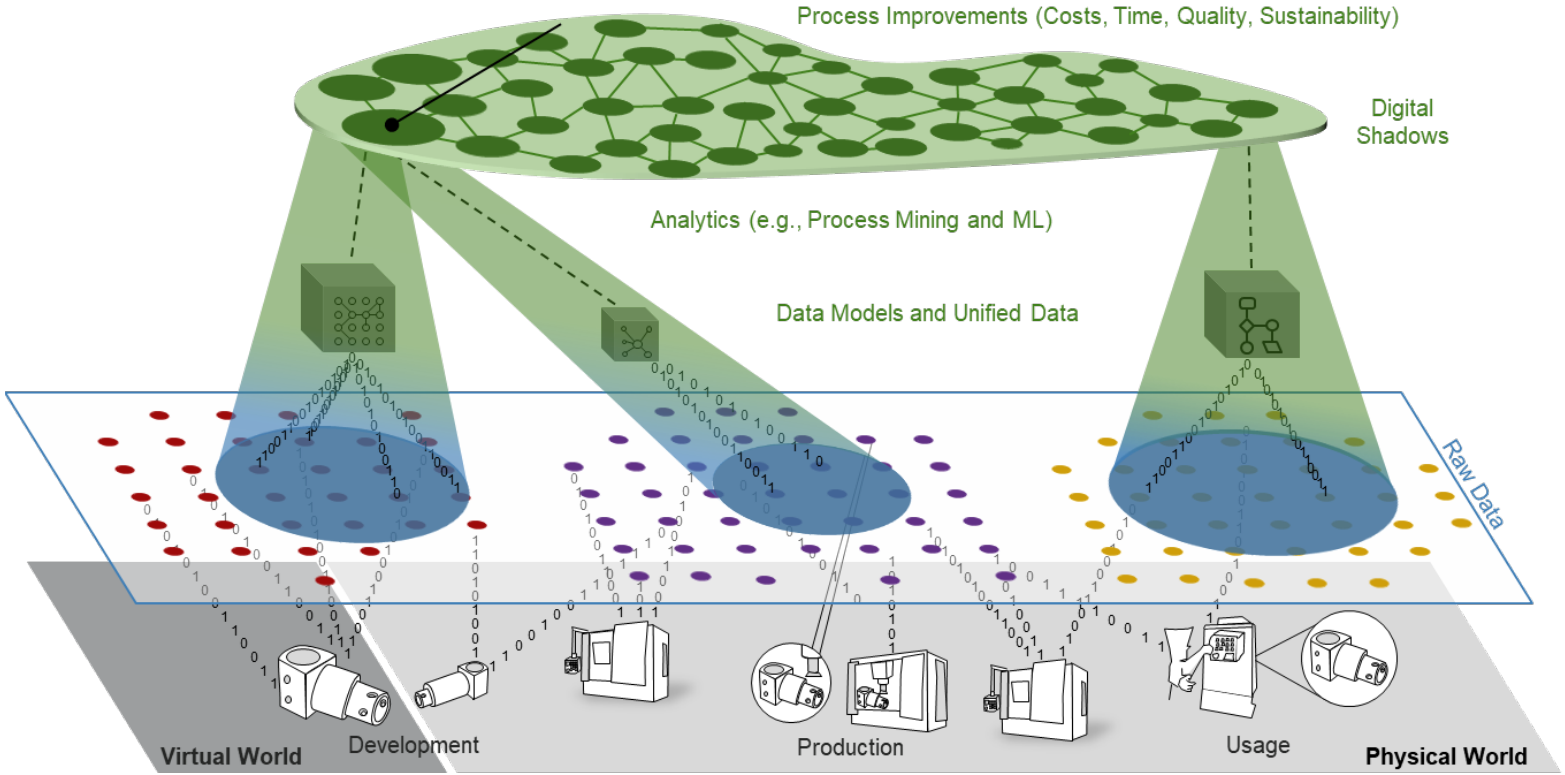
The Internet-of-Production @ RWTH



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Spectrum Internet-of-Production

Christian Brecher

Günther Schuh

from a single machine …

… to complete production systems

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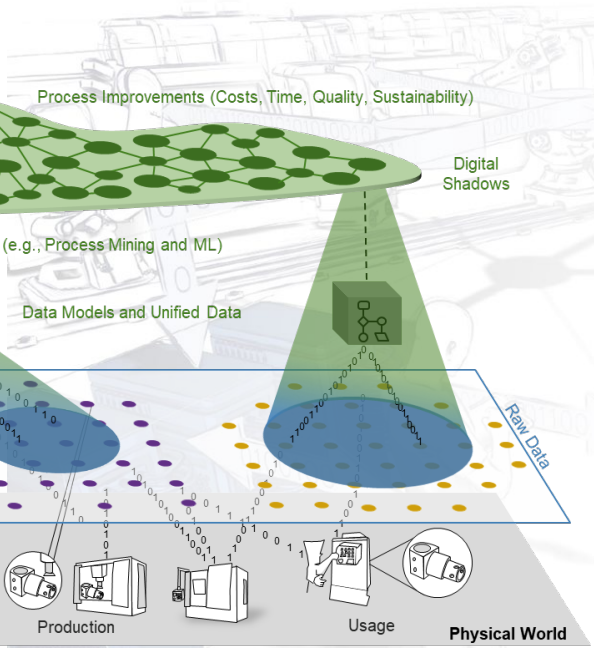
The Challenge

The Tower of Babel by Pieter Bruegel (1563)

- Different languages
  - different notations, terms, etc.
  - different disciplines
- Working at different levels
  - machine level
  - process/system/chain level
- This is not (just) a syntactical problem!
- When talking about (data) models, a “middle ground” is missing

The Challenge



Artificial Intelligence (AI), Machine Learning (ML), Data Science (DS), etc. Techniques and Tools

general purpose TXT, CSV, XLS, JSON, etc. files

ad-hoc collections of TXT, CSV, XLS, JSON, etc. files

Application-specific data (often stored in an ad-hoc manner without unified access and using no or heterogeneous data models)

Knime, RapidMiner, Scikit-learn, PyTorch, Tensorflow, Weka, ProM, Celonis, etc.

80+ different data sources

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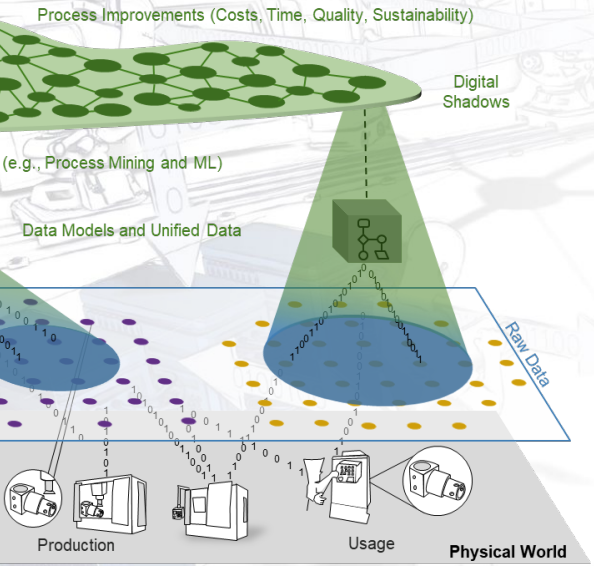
The Challenge



Artificial Intelligence (AI), Machine Learning (ML), Data Science (DS), etc. Techniques and Tools

general purpose TXT, CSV, XLS, JSON, etc. files

No explicit semantics, ad-hoc transformations, no reuse, no sharing, etc.

ad-hoc collections of TXT, CSV, XLS, JSON, etc. files

Application-specific data (often stored in an ad-hoc manner without unified access and using no or heterogeneous data models)

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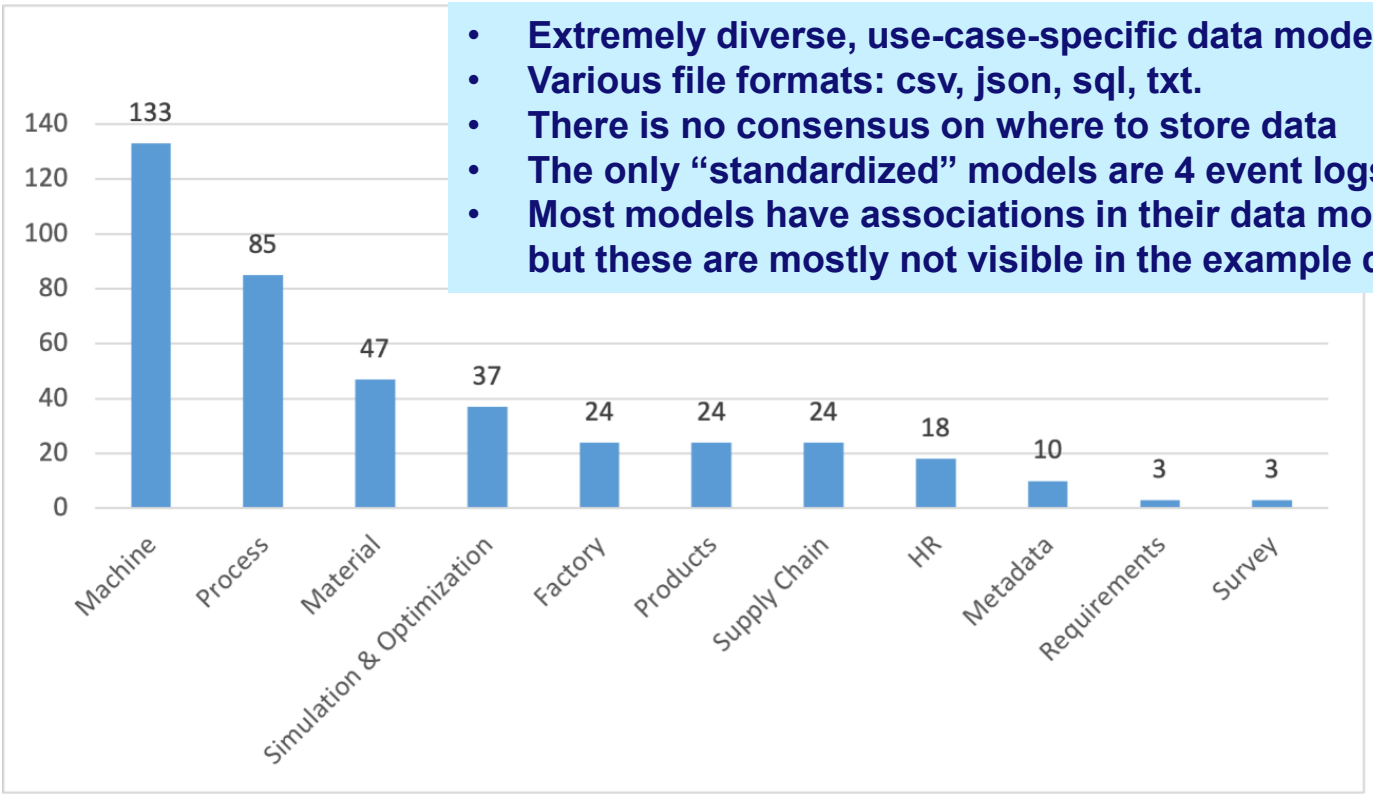
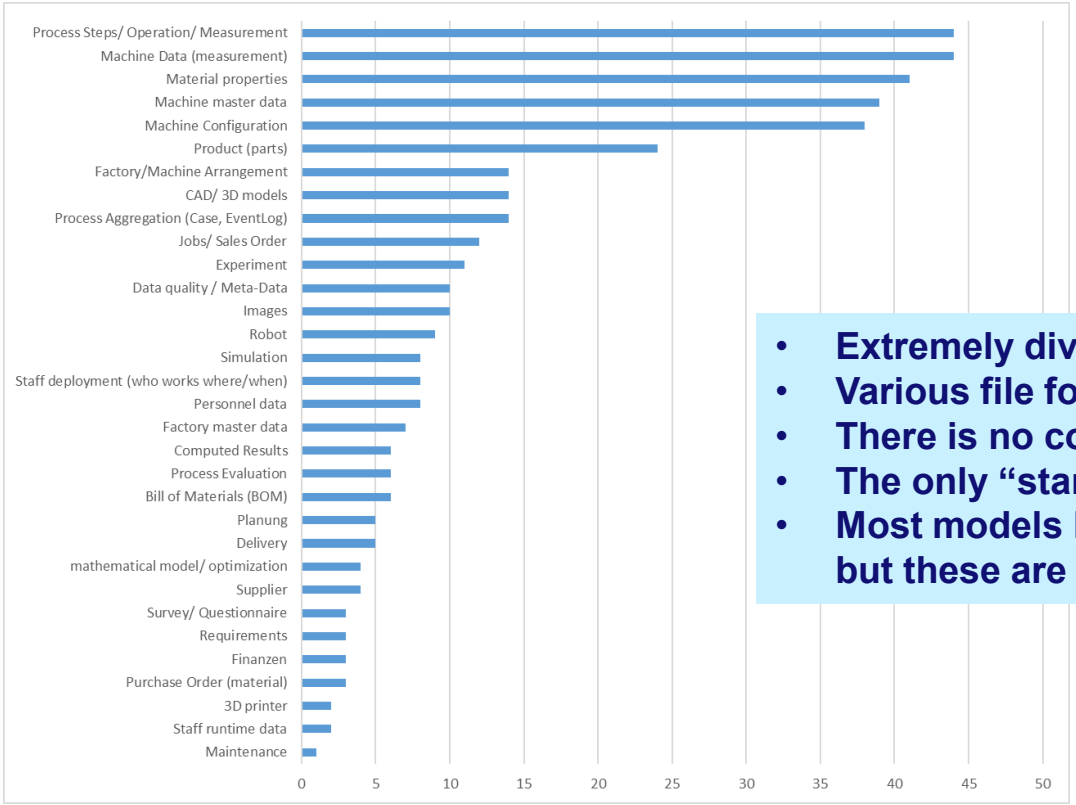
Empirical Analysis (80+ data models)



- Extremely diverse, use-case-specific data models
- Various file formats: csv, json, sql, txt.
- There is no consensus on where to store data
- The only “standardized” models are 4 event logs.
- Most models have associations in their data model, but these are mostly not visible in the example data.

One data model can be in multiple categories

Empirical Analysis (80+ data models)



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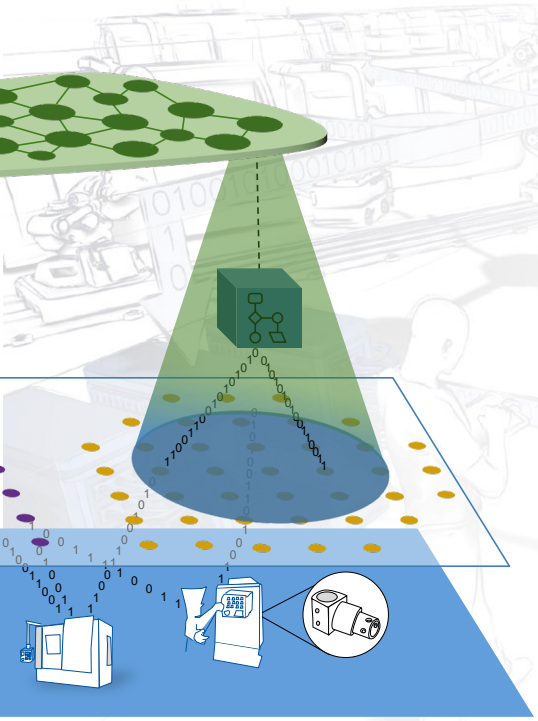
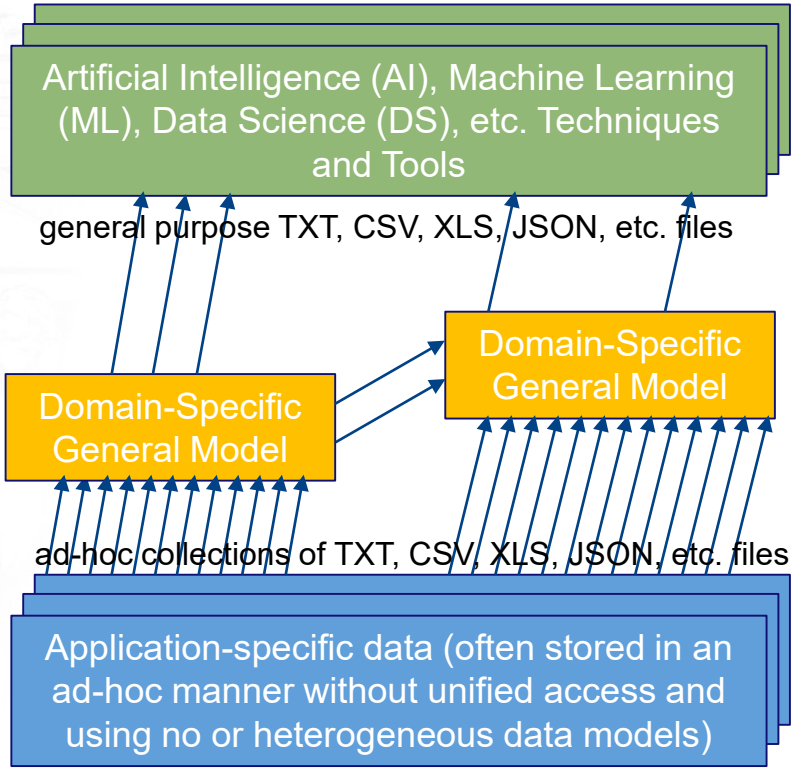
Proposed Solution: Models-in-the-Middle

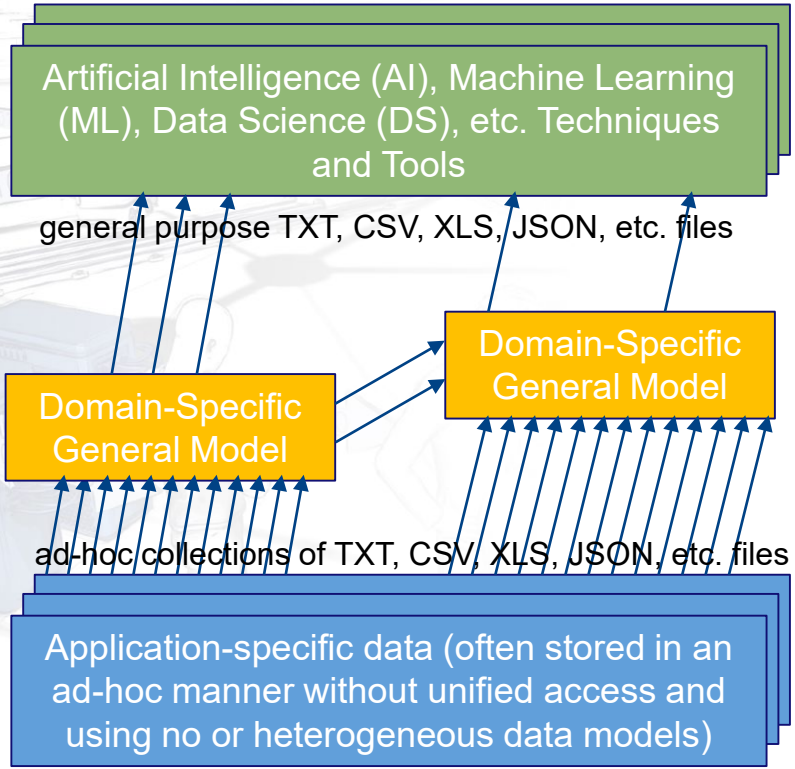




Knime, RapidMiner, Scikit-learn, PyTorch, Tensorflow, Weka, ProM, Celonis, etc.

80+ different data sources

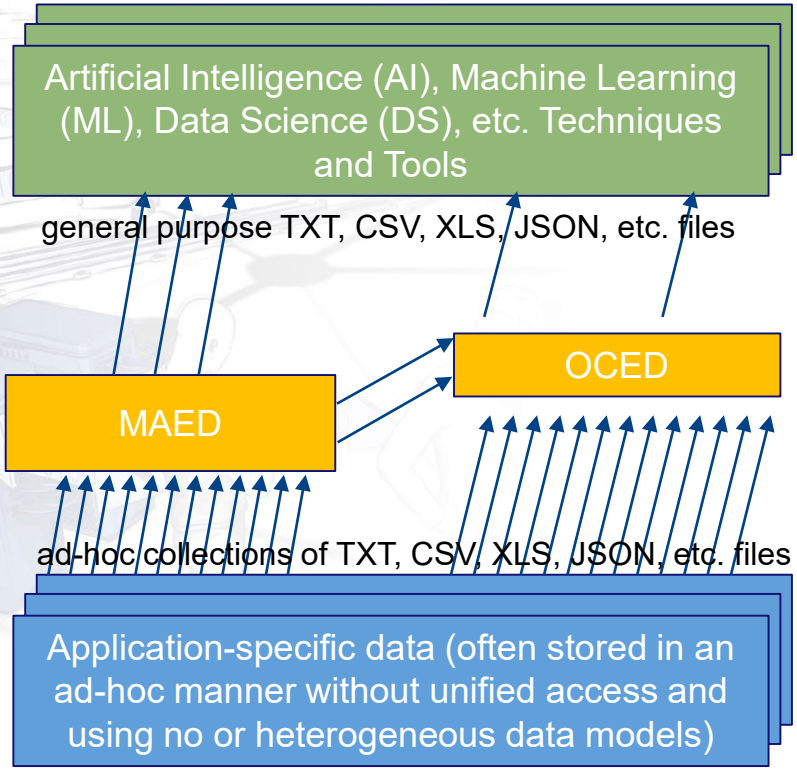
Picking The Right Level



Too high: Too far away from the application (mapping is difficult).

Too low: Not able to reuse efforts (need to develop ad-hoc analysis software).

Two Candidate Data Models



- **Measurement and Event Data (MAED)**
- **Object-Centric Event data (OCED)**

Disclaimer: There can be many more, but this is what we are developing!

Acknowledgements

- Leah Tacke genannt Unterberg, István Koren, and people from WZL: Measurement and Event Data (MAED)
- Alessandro Berti, Niklas Adams, István Koren, and many other PADS team members: Object-Centric Event data (OCED)
- István Koren, Judith Michael, and other SE & PADS members: Analysis and coding of the 80+ IoP data models

Thanks!

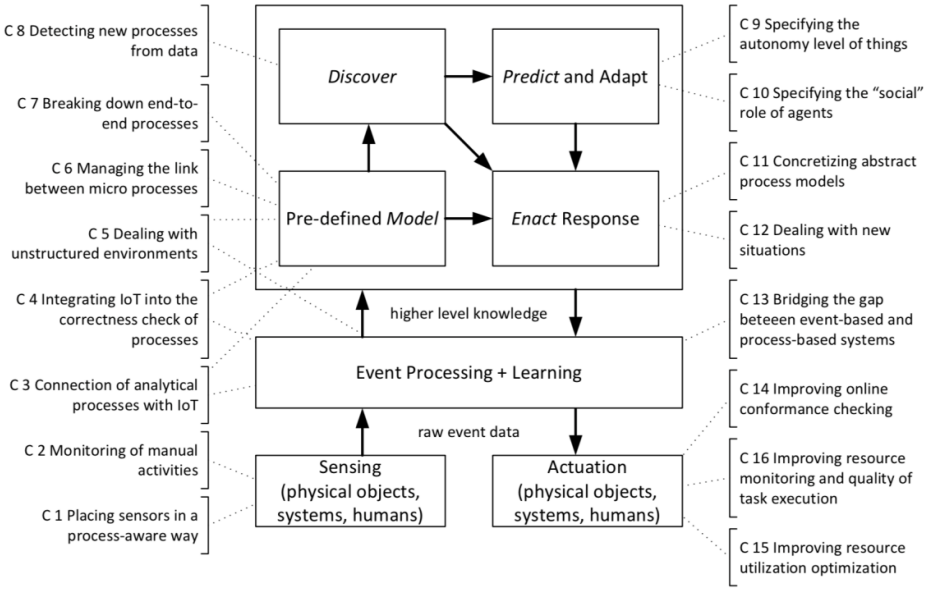
Internet-of-Things Meets BPM

"The Internet of Things Meets Business Process Management: A Manifesto," in *IEEE Systems, Man, and Cybernetics Magazine*, vol. 6, no. 4, pp. 34-44, Oct. 2020, doi: 10.1109/MSMC.2020.3003135.

The Internet-of-Things Meets Business Process Management. A Manifesto

Christian Janiesch, Agnes Koschmider, Massimo Mecella, Barbara Weber, Andrea Burattin, Claudio Di Ciccio, Giancarlo Fortino, Avigdor Gal, Udo Kannengiesser, Francesco Leotta, Felix Mannhardt, Andrea Marrella, Jan Mendling, Andreas Oberweis, Manfred Reichert, Stefanie Rinderle-Ma, Estefania Serral Asensio, WenZhan Song, Jianwen Su, Victoria Torres, Matthias Weidlich, Mathias Weske, and Liang Zhang

The Internet of Things (IoT) refers to a network of connected devices collecting and exchanging data over the Internet. These things can be artificial or natural and interact as autonomous agents forming a complex system. In turn, Business Process Management (BPM) was established to analyze, discover, design, implement, execute, monitor and evolve collaborative business processes within and across organizations. While the IoT and BPM have been regarded as separate topics in research and practice, we strongly believe that the management of IoT applications will strongly benefit from BPM concepts, methods and technologies on the one hand; on the other one, the IoT poses challenges that will require enhancements and extensions of the current state-of-the-art in the BPM field. In this paper, we question to what extent these two paradigms can be combined and we discuss the emerging challenges and intersections from a research and practitioner's point of view in terms of complex software systems development.



"Sensor data then must be aggregated and interpreted in order to detect activities that can be used as input for process mining algorithms supporting decision-making."

"A challenge is to bridge the gap between clouds of sensor data and event logs for process mining. Events captured by sensors are available in high volume, velocity, and variety."

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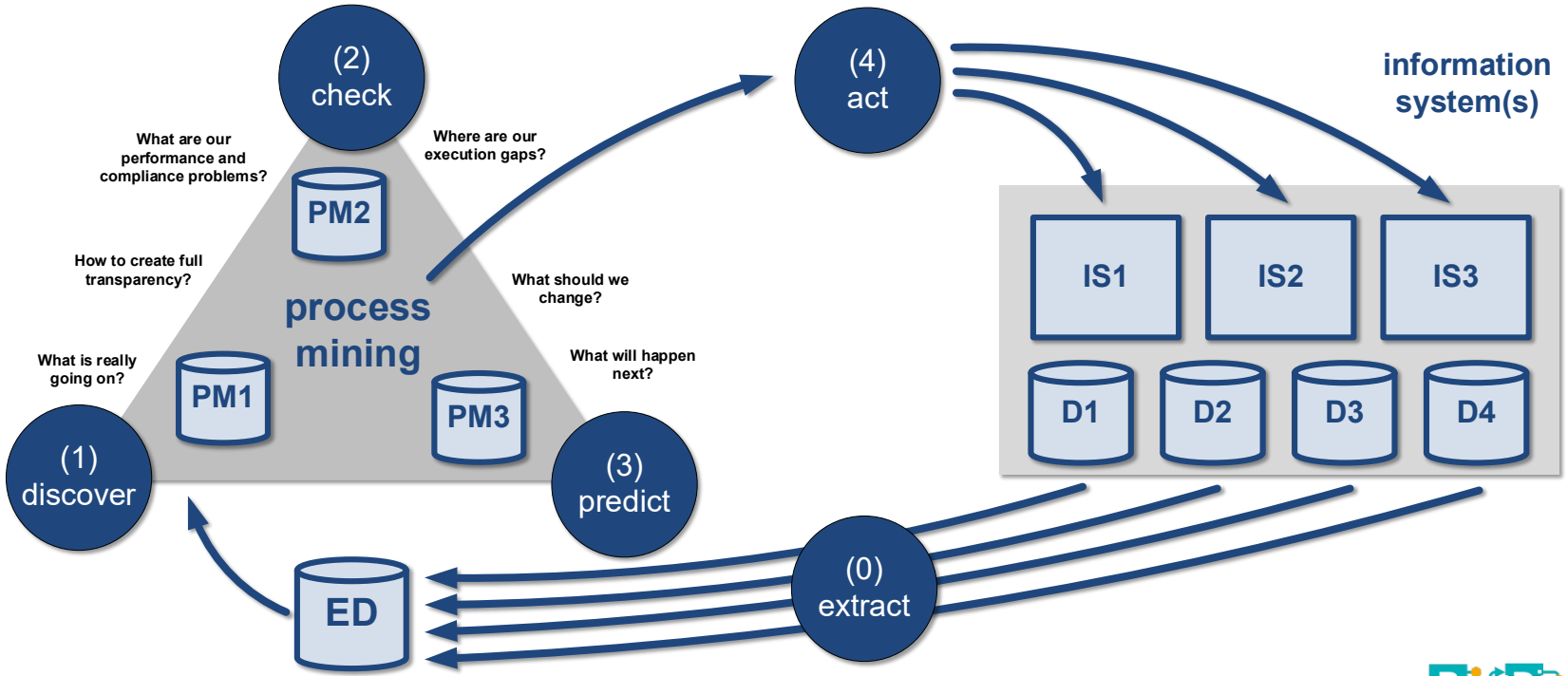
Process Mining: High-Level View



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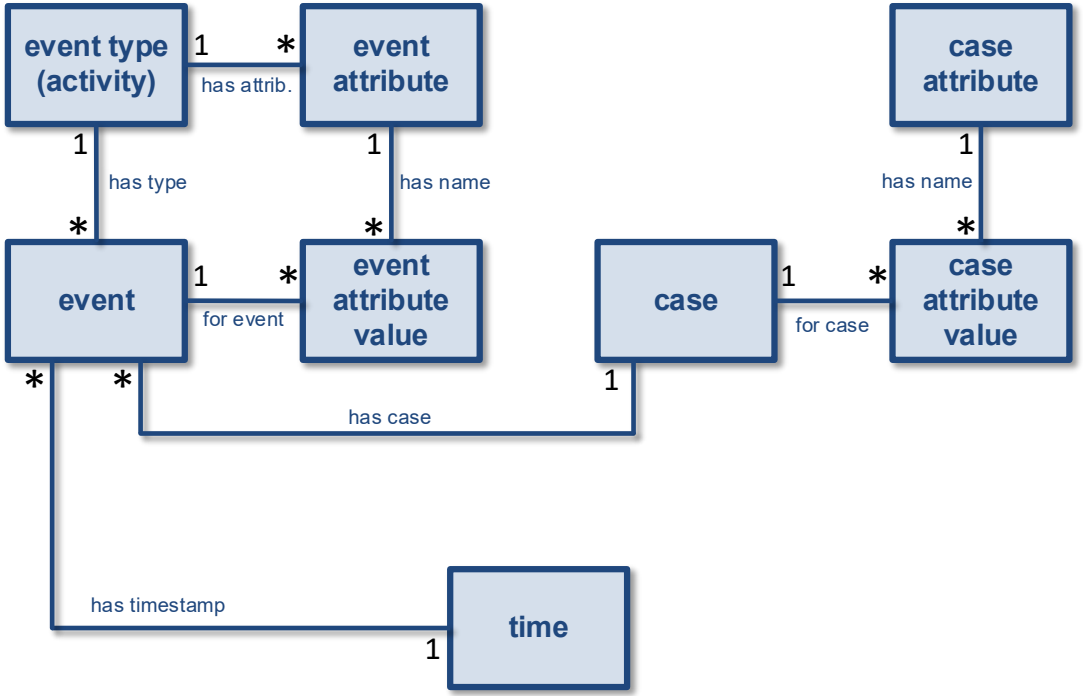
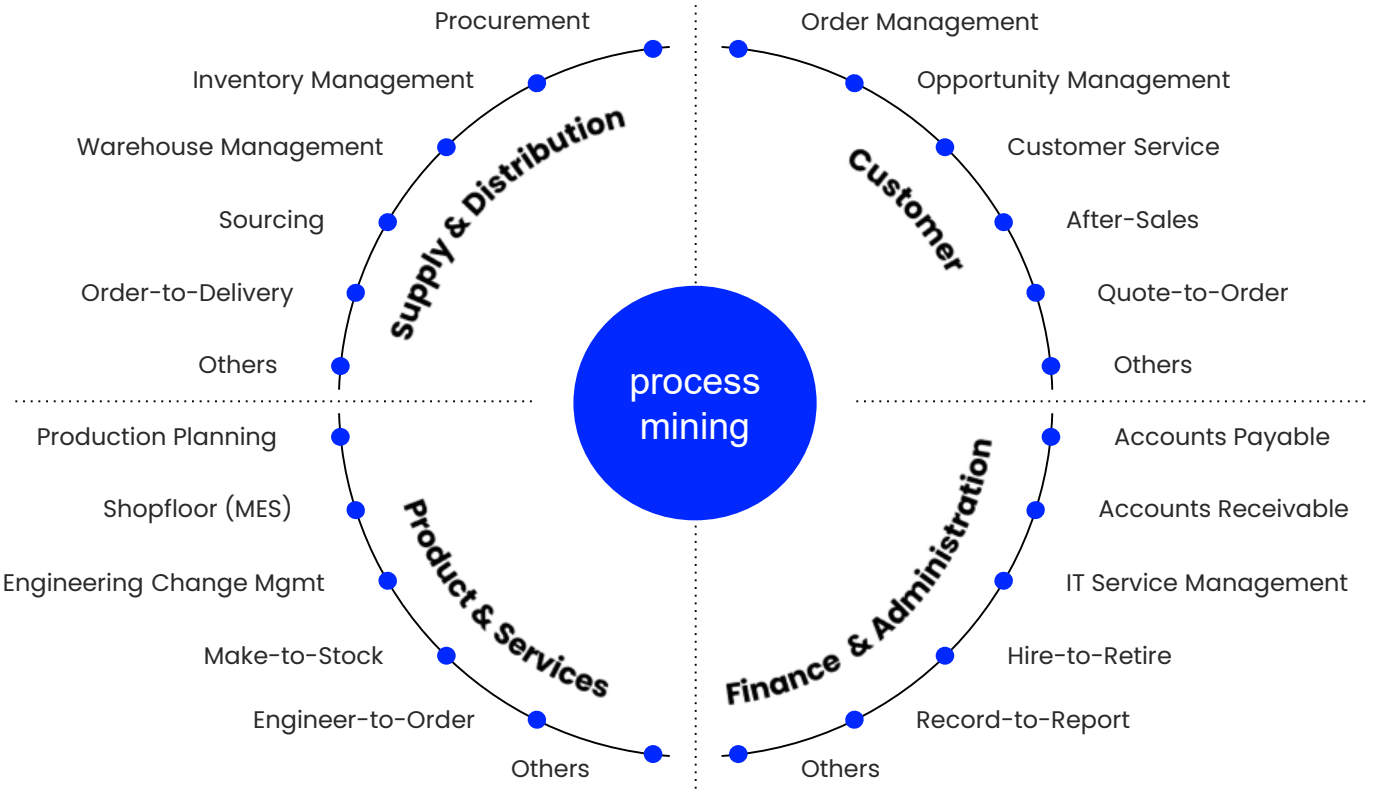
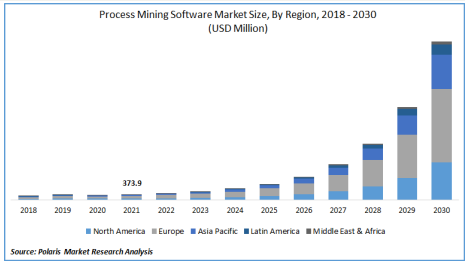
Traditional Event Data



- An event has a type (activity) and a timestamp, and refers to one case.
- Events and cases can have arbitrary other attributes (e.g., costs).

Good News





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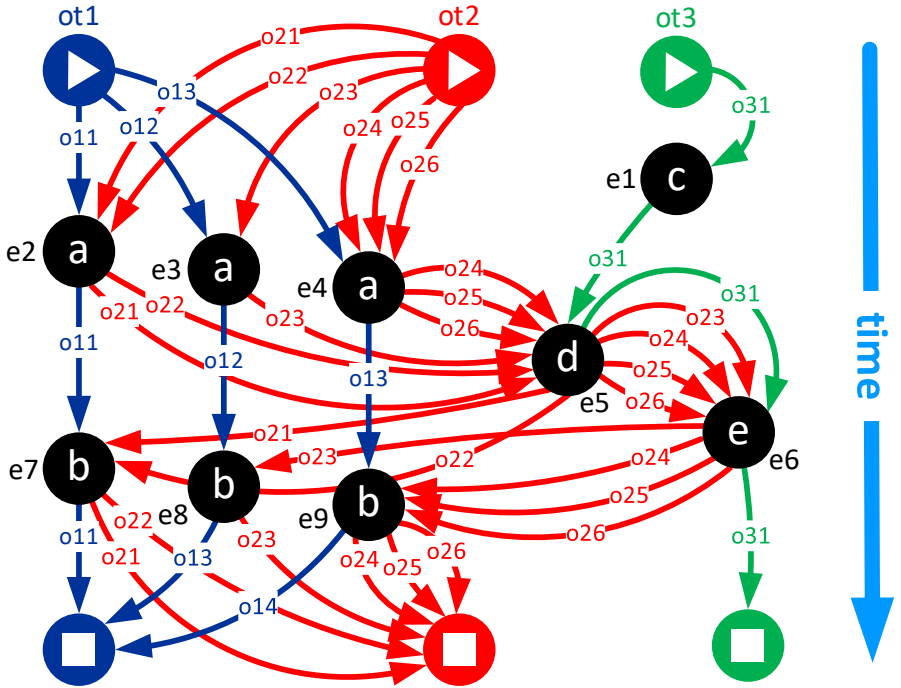
Bad News: What are my cases?

What are my cases?

Well-Known Problems

- The convergence problem: Events referring to multiple objects of the selected type are replicated, possibly leading to unintentional duplication. The replication of events can lead to misleading diagnostics.
- The divergence problem: There are multiple events that refer to the same case and activity, however, they differ with respect to one of the not-selected object types. In other words, events referring to different objects of a type not selected as the case notion become indistinguishable looking only at the case and activity (i.e., event type).

Visualizing Objects and Events

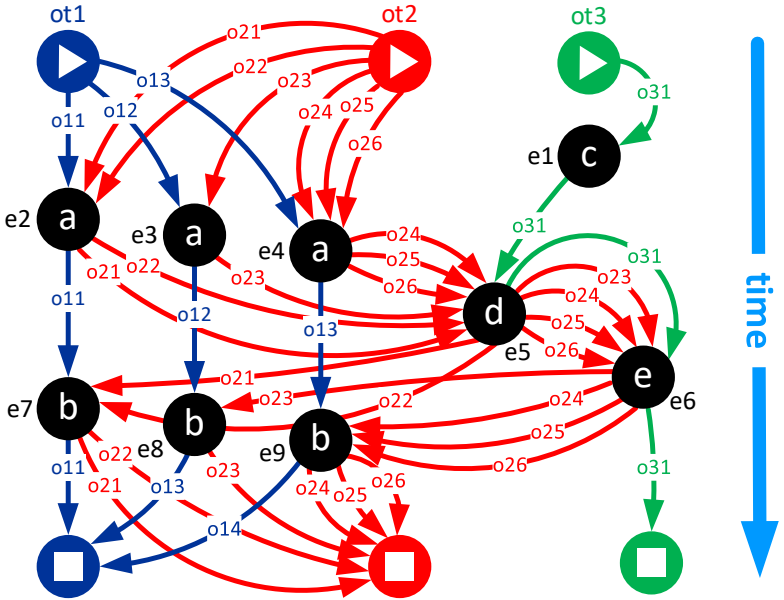


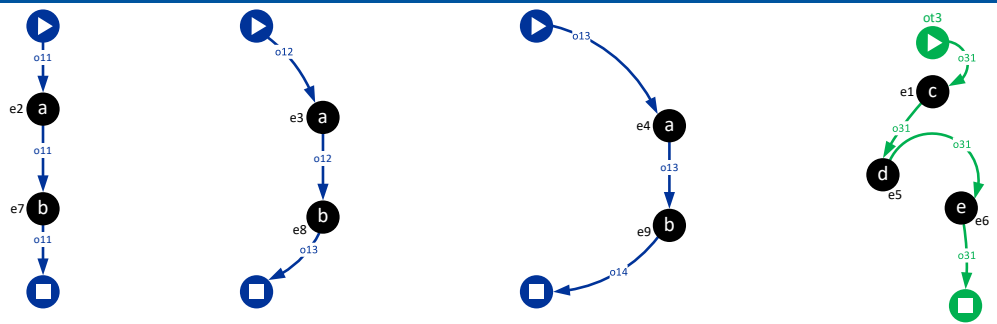
Example object types:

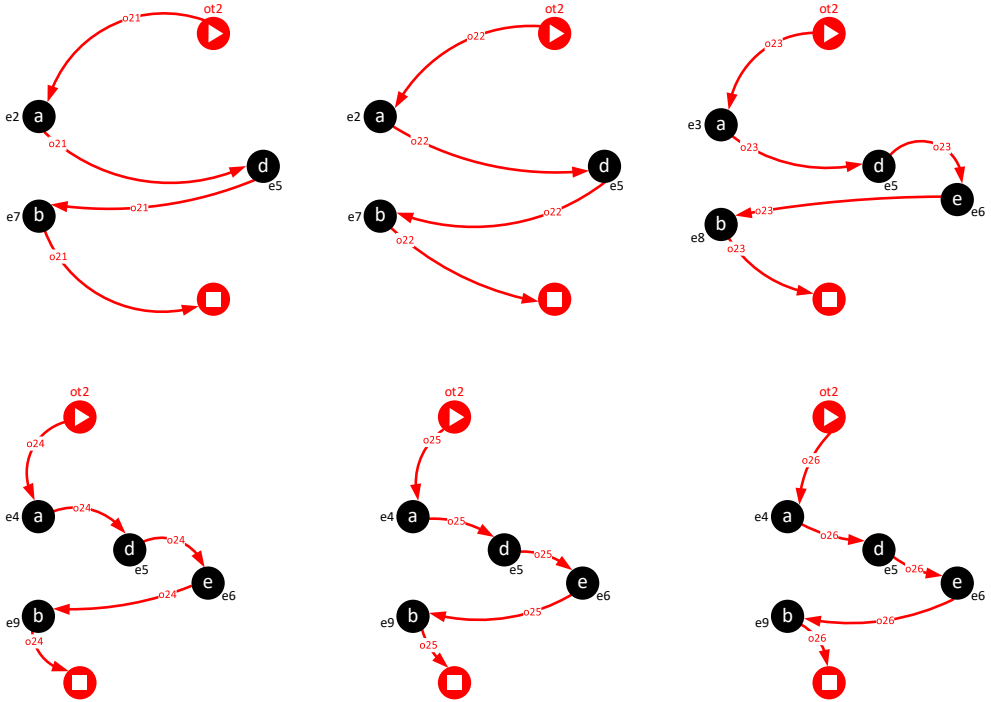
- Orders
- Items
- Packages
- Machines
- Employees
- Patients
- Customers
- Machines
- Containers
- Payments
- Car
- Room
- Etc.

Object flows

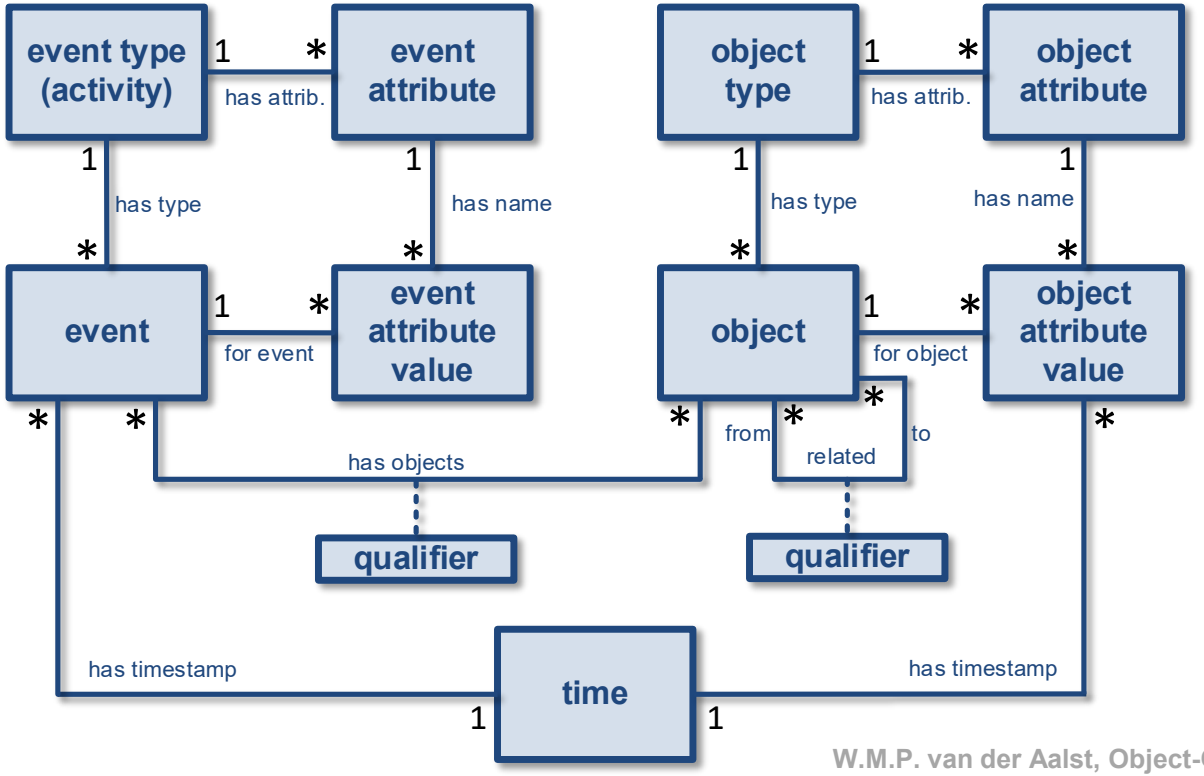
Note the convergence problem







Solved: Object-Centric Event Data



- An event has a type (activity) and a timestamp, and may refer to any number of typed objects (E2O relations).
- Objects are also typed.
- Both events and objects may have any number of additional attributes.
- Object attribute values may be timed.
- Objects may be related (O2O relations).
- E2O and O2O relations can be qualified.

W.M.P. van der Aalst, Object-Centric Process Mining: Unraveling the Fabric of Real Processes. Mathematics 2023, 11, 2691. https://doi.org/10.3390/math11122691

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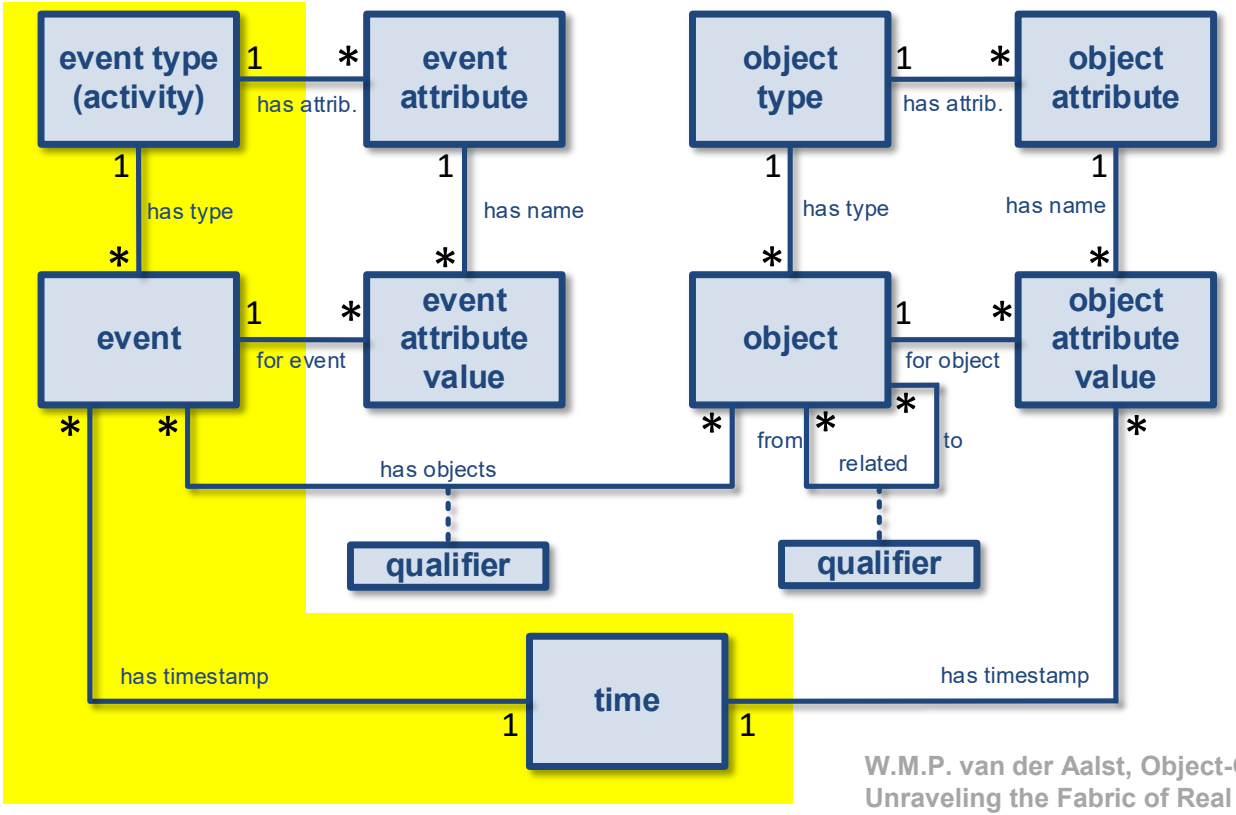

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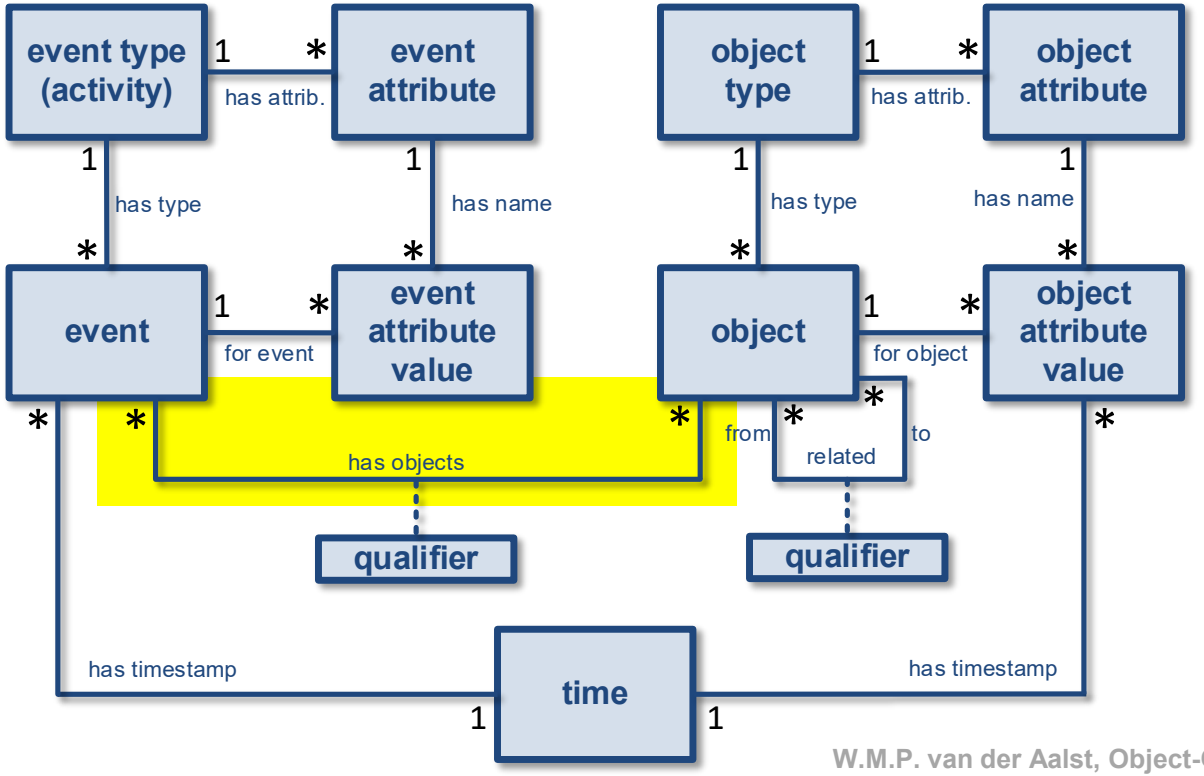

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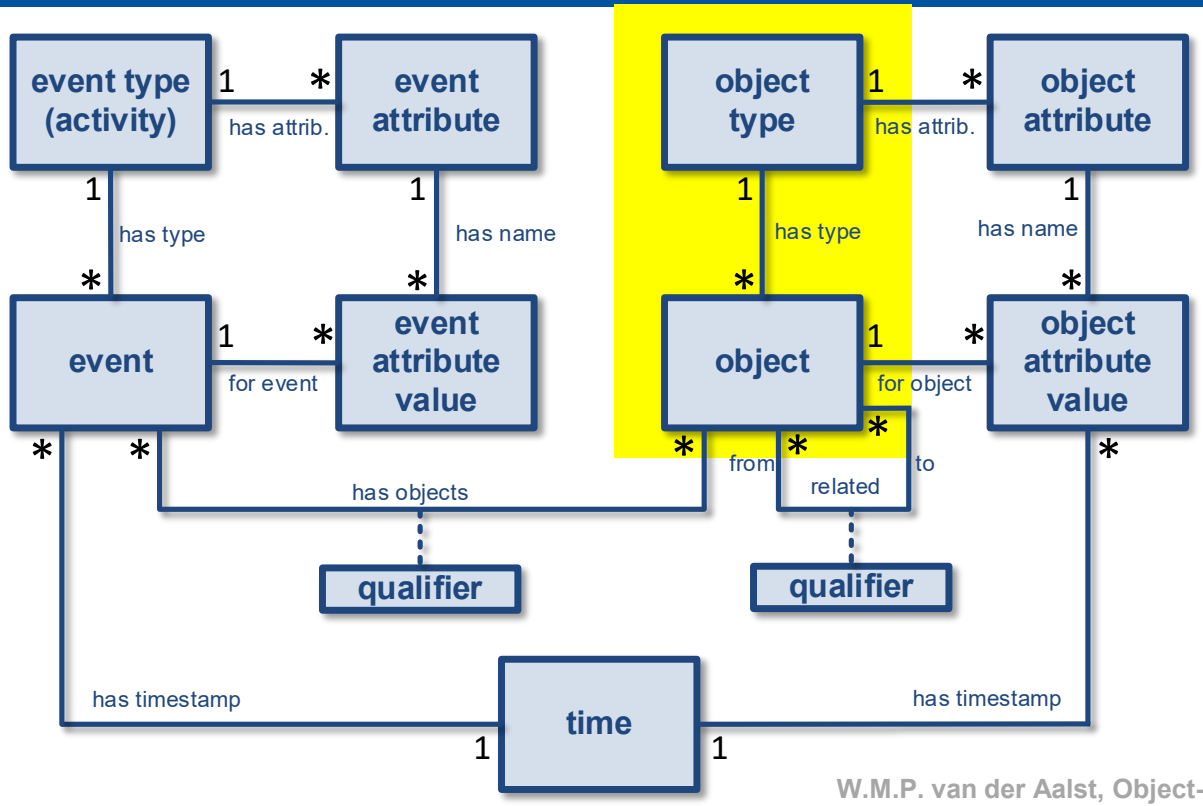

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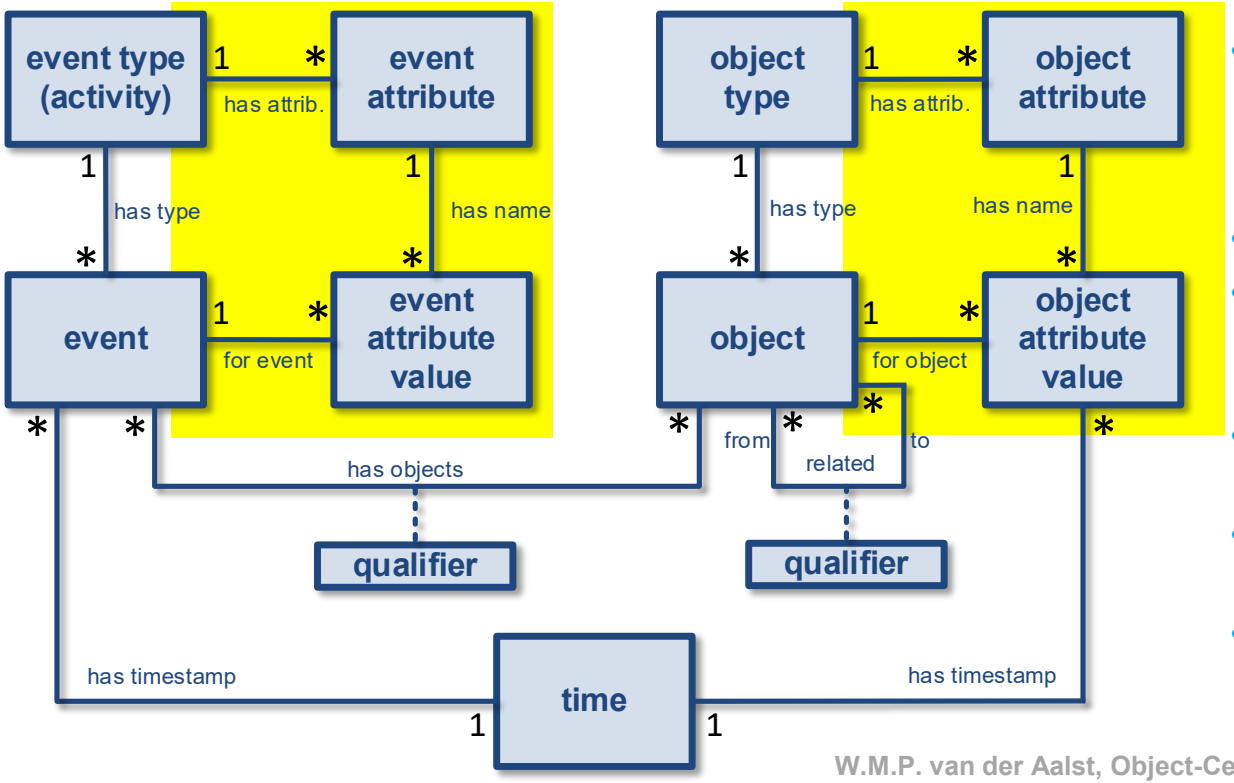

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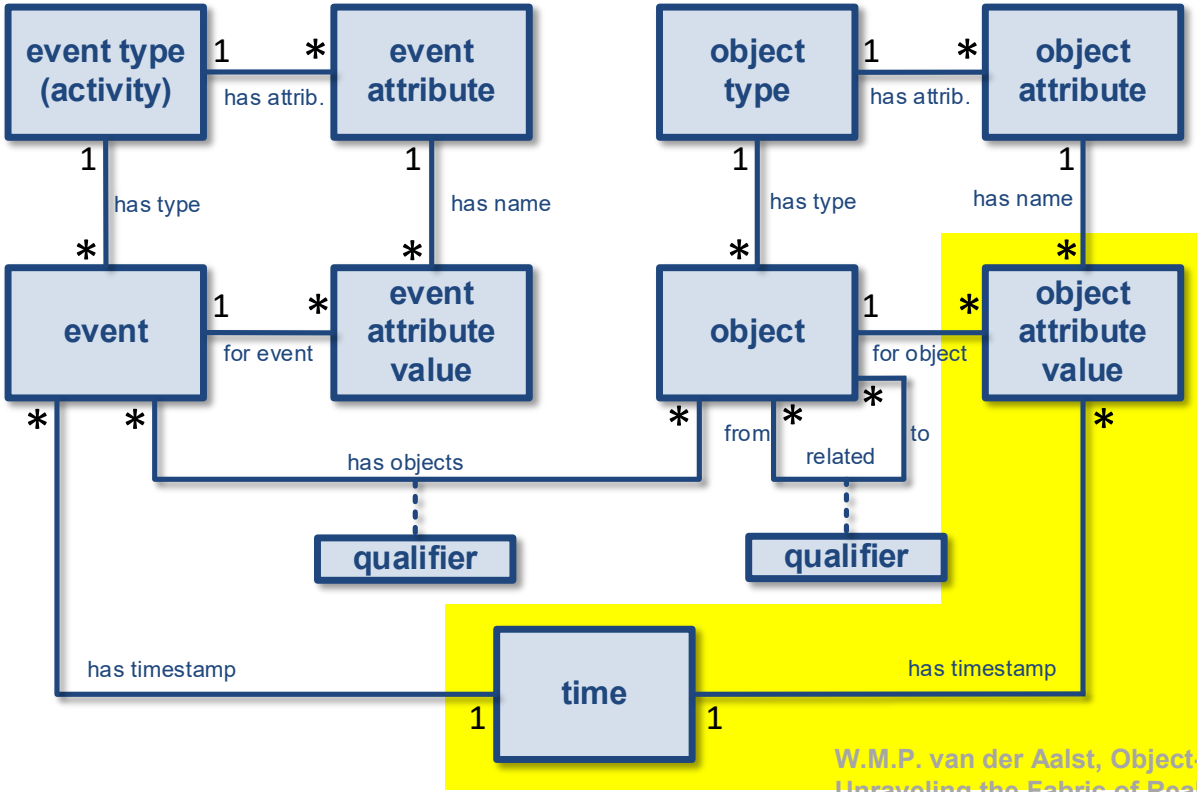

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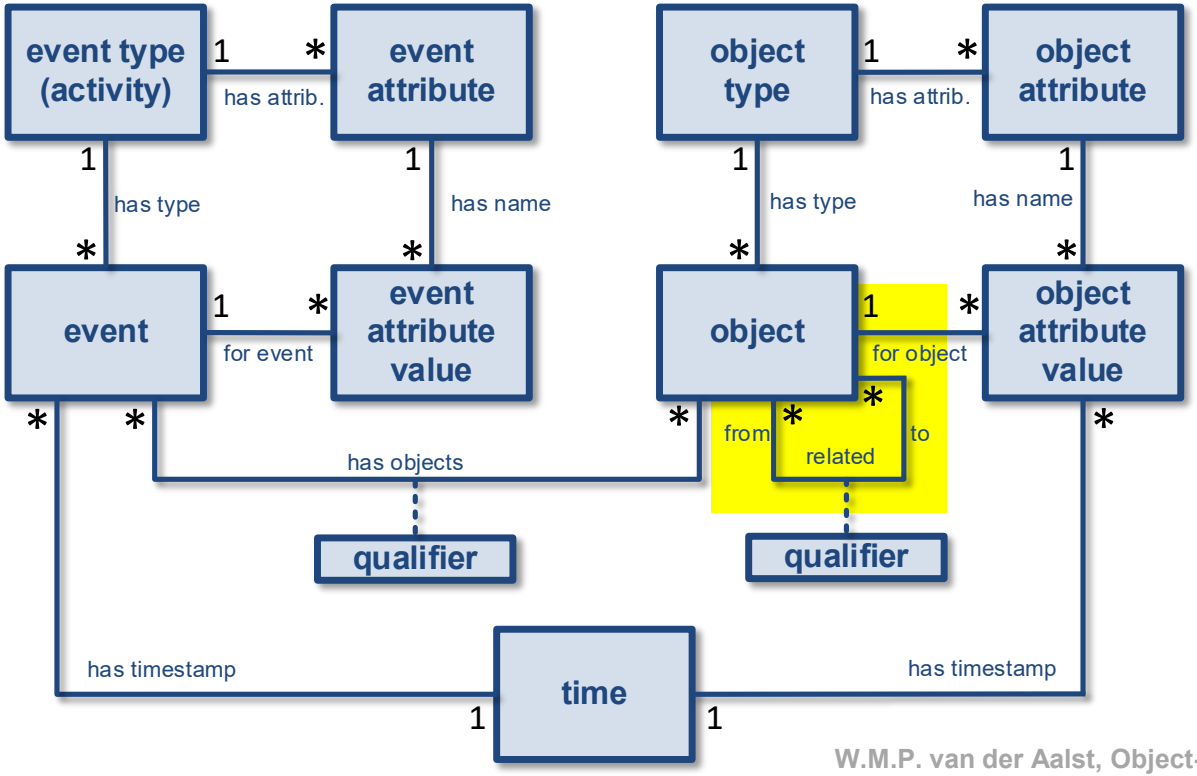

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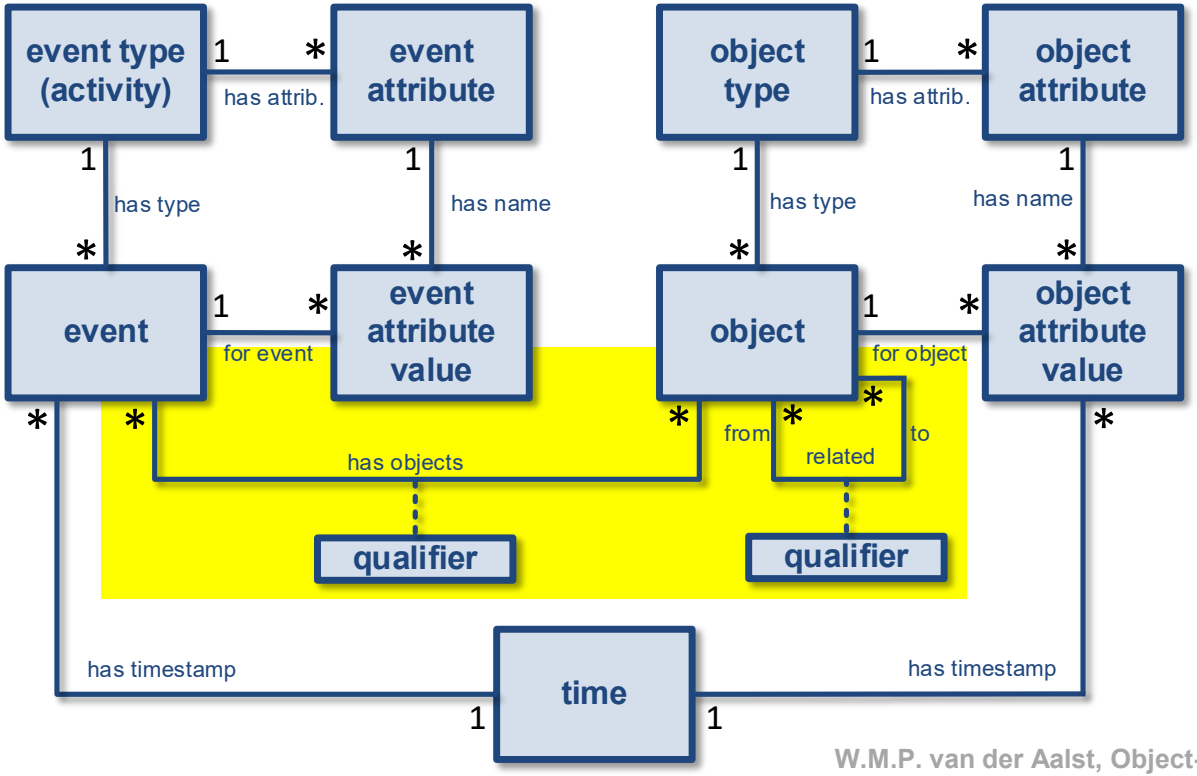

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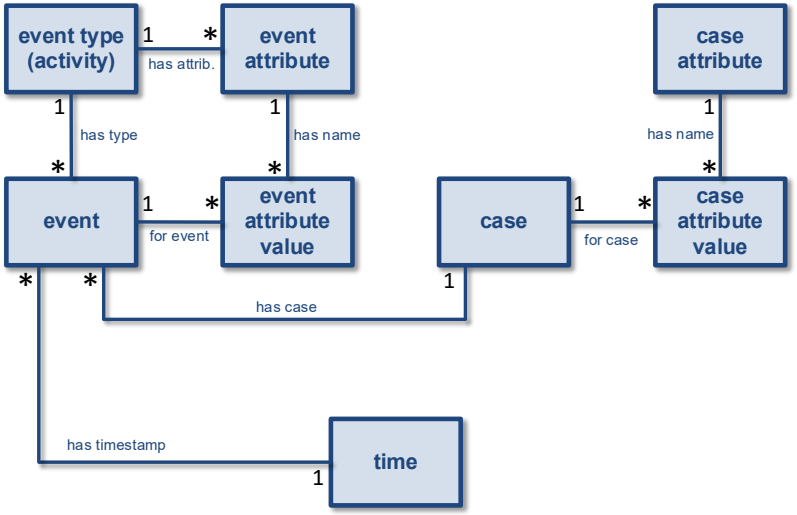
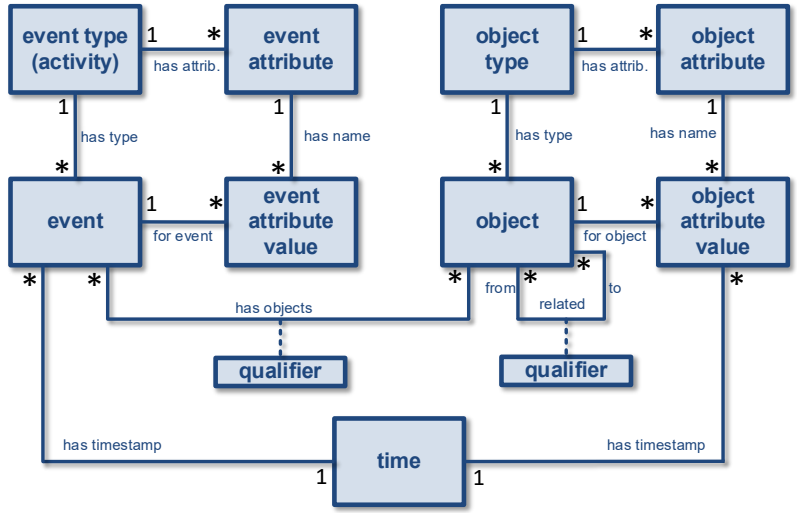
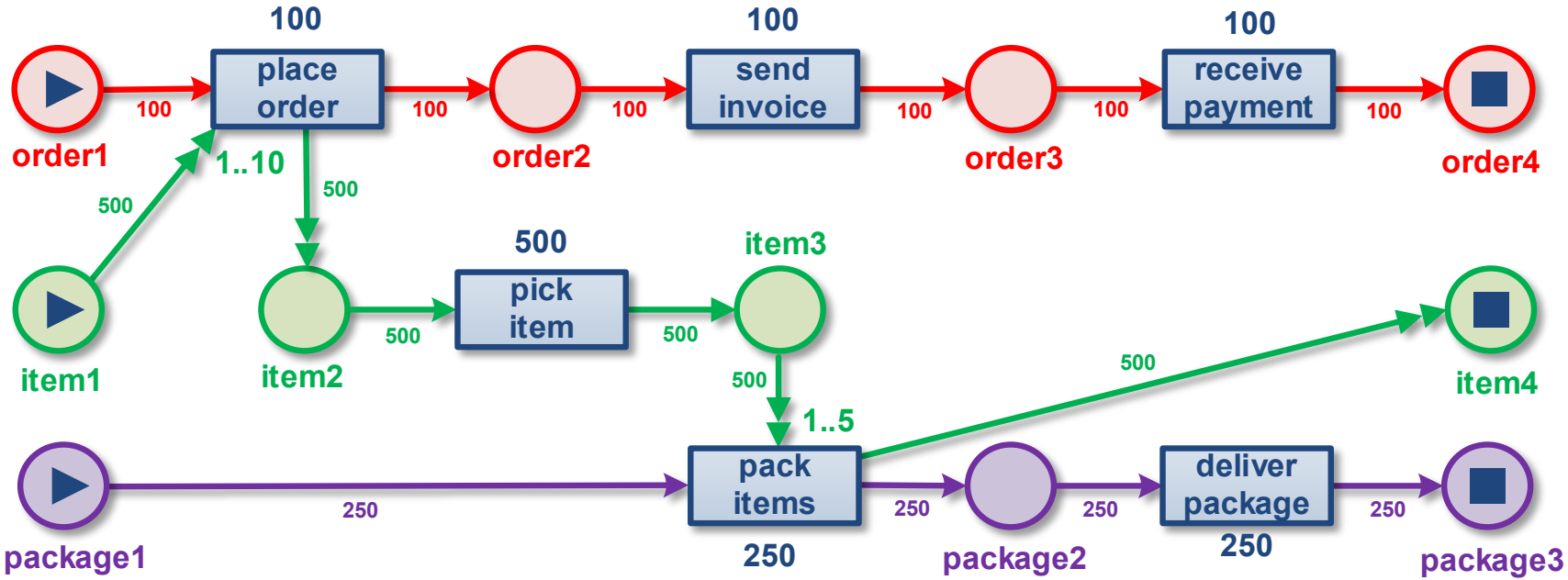
Summary Object-Centric Event Data





Sneak preview: OCEL 2.0 will be released before ICPM 2023!

All Process Mining Algorithms Need To Be Reinvented: Not So Hard As It Seems



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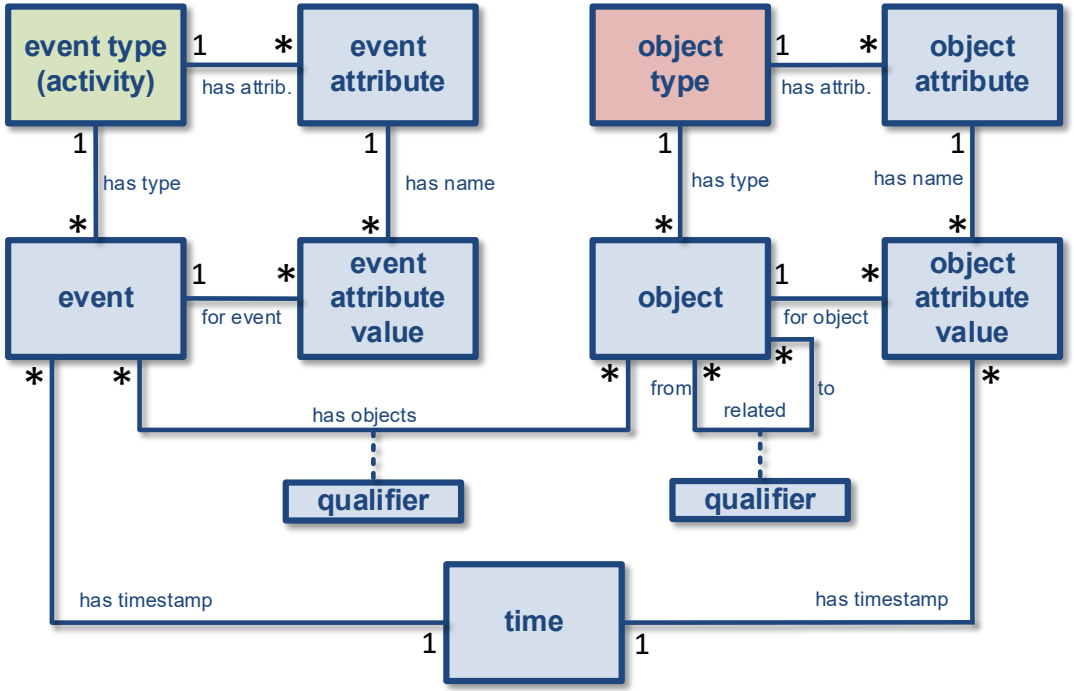
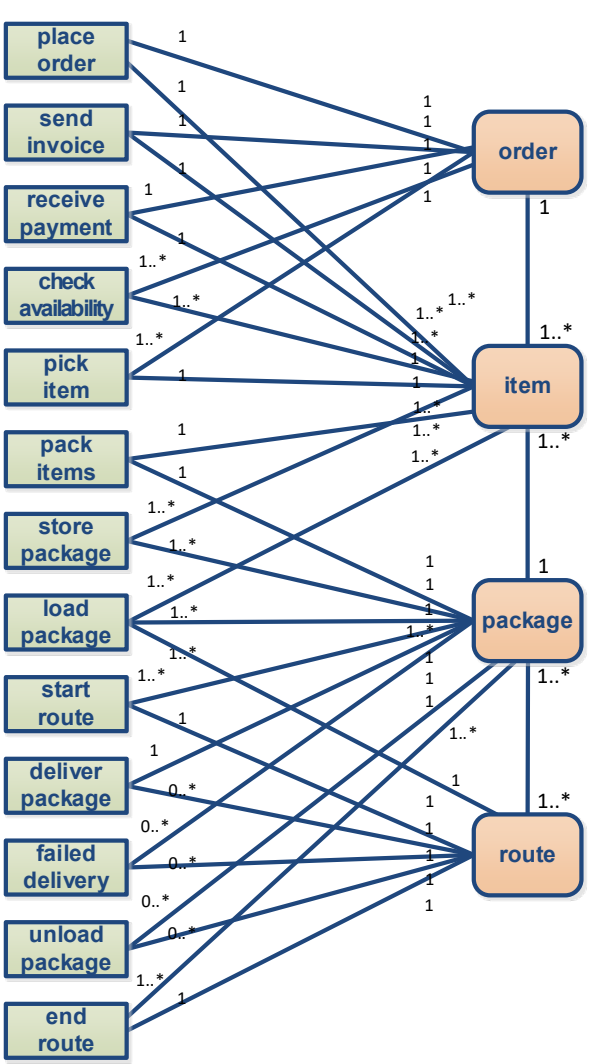
Managing Complexity



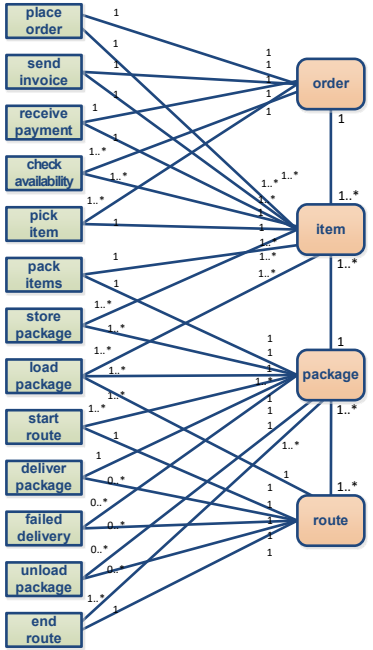


Managing Complexity

Pick the rows, columns, cells you need

Contingency Table

	Order	Item	Package	Route
place order	✓	✓		
send invoice	✓	✓		
receive payment	✓	✓		
check availability	✓	✓		
pick item	✓	✓		
pack items		✓	✓	
store package		✓	✓	
load package		✓	✓	✓
start route			✓	✓
deliver package			✓	✓
failed delivery			✓	✓
unload package			✓	✓
end route			✓	✓



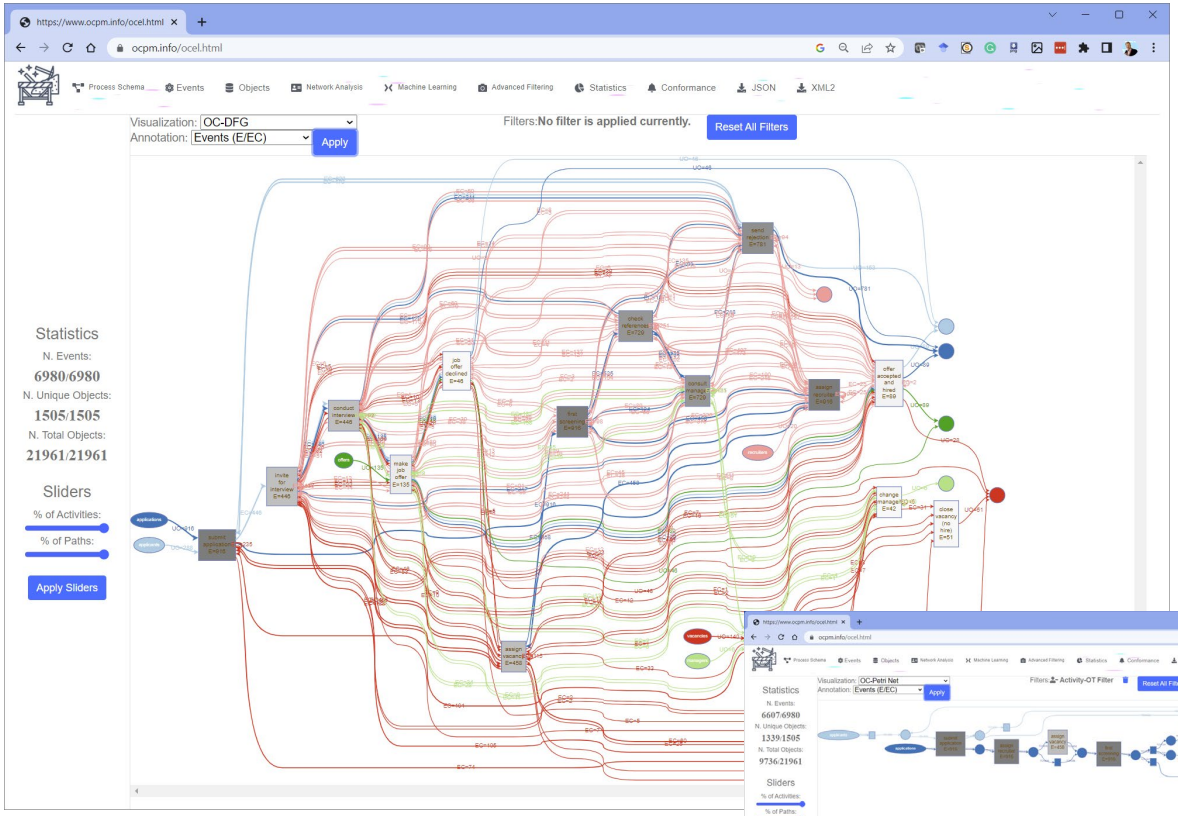
Profiles/Perspective: A selection of rows and columns or even individual cells

Advantages OCED and OCPM

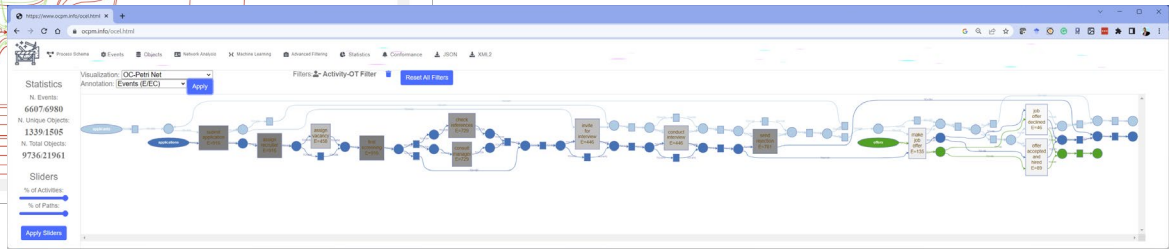
- View your processes from any perspective using a single source of truth.
- On-demand process-mining views as a way to manage complexity.
- Address otherwise invisble problems that often live at the intersection points.
- Obtain a three-dimensional dynamic view of the entire organization and its processes.

Tool Support (e.g. ocpm.info & ocpi.ai)

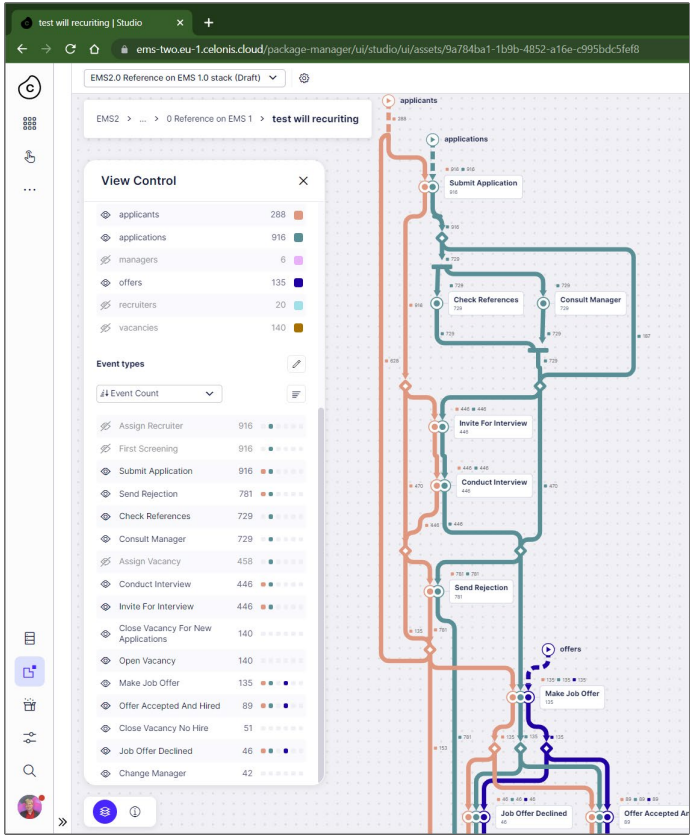
Alessandro Berti Niklas Adams

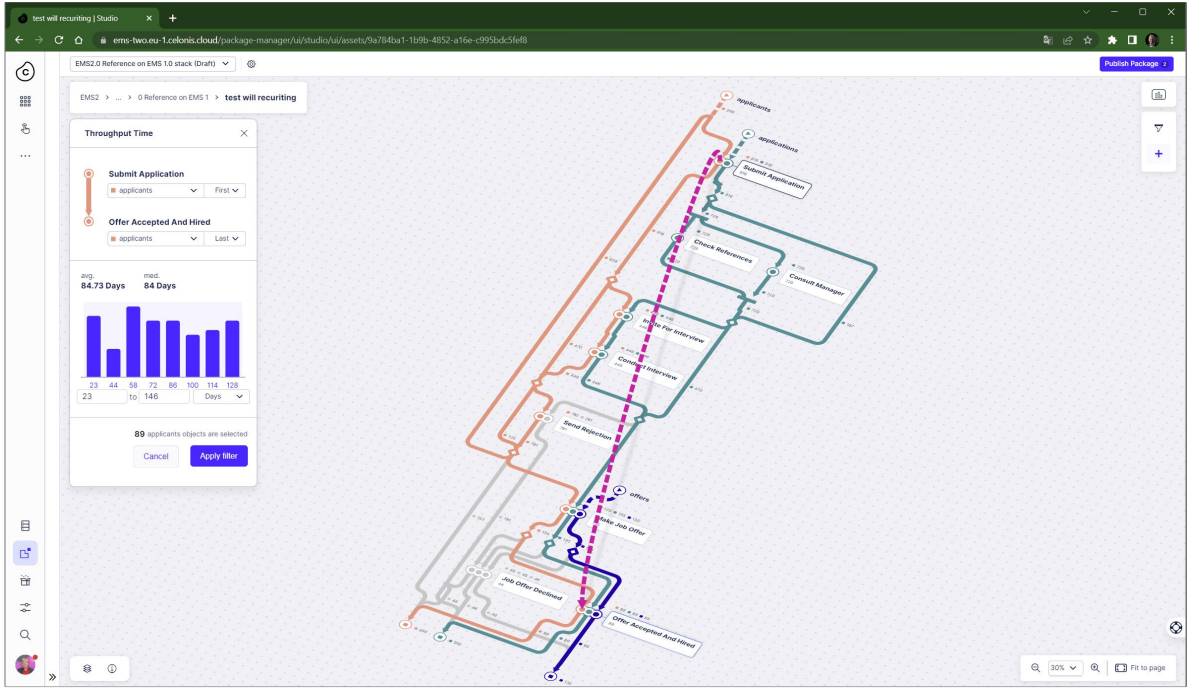


	vacancies	managers	applicants	applications	recruiters	offers
open vacancy	☑	UO=140 ☑	UO=140 ☑	☐	☐	☐
submit application	☑	UO=458 ☑	☐	UO=916 ☑	UO=916 ☑	☐
assign recruiter	☑	☐	☐	☐	UO=916 ☑	UO=2748 ☑
first screening	☑	☐	☐	☐	UO=916 ☑	UO=916 ☑
check references	☑	☐	☐	☐	UO=729 ☑	UO=1458 ☑
assign vacancy	☑	UO=458 ☑	☐	☐	UO=458 ☑	☐
send rejection	☑	☐	☐	UO=781 ☑	UO=781 ☑	UO=781 ☑
close vacancy for new applications	☑	UO=140 ☑	☐	☐	☐	☐
change manager	☑	UO=42 ☑	UO=84 ☑	☐	☐	☐
consult manager	☑	☐	UO=729 ☑	☐	UO=729 ☑	UO=729 ☑
invite for interview	☑	UO=446 ☑	☐	UO=446 ☑	UO=446 ☑	UO=892 ☑
conduct interview	☑	UO=446 ☑	UO=446 ☑	UO=446 ☑	UO=446 ☑	UO=446 ☑
make job offer	☑	UO=135 ☑	UO=135 ☑	UO=135 ☑	UO=135 ☑	UO=135 ☑	UO=135 ☑
offer accepted and hired	☑	UO=89 ☑	☐	UO=89 ☑	UO=89 ☑	UO=89 ☑	UO=89 ☑
job offer declined	☑	UO=46 ☑	☐	UO=46 ☑	UO=46 ☑	UO=46 ☑	UO=46 ☑
close vacancy (no hire)	☑	UO=51 ☑	☐	☐	☐	☐	☐



Tool Support (e.g. Celonis Process Sphere)





MOPE (Multi-Object Process Explorer) is already general availability

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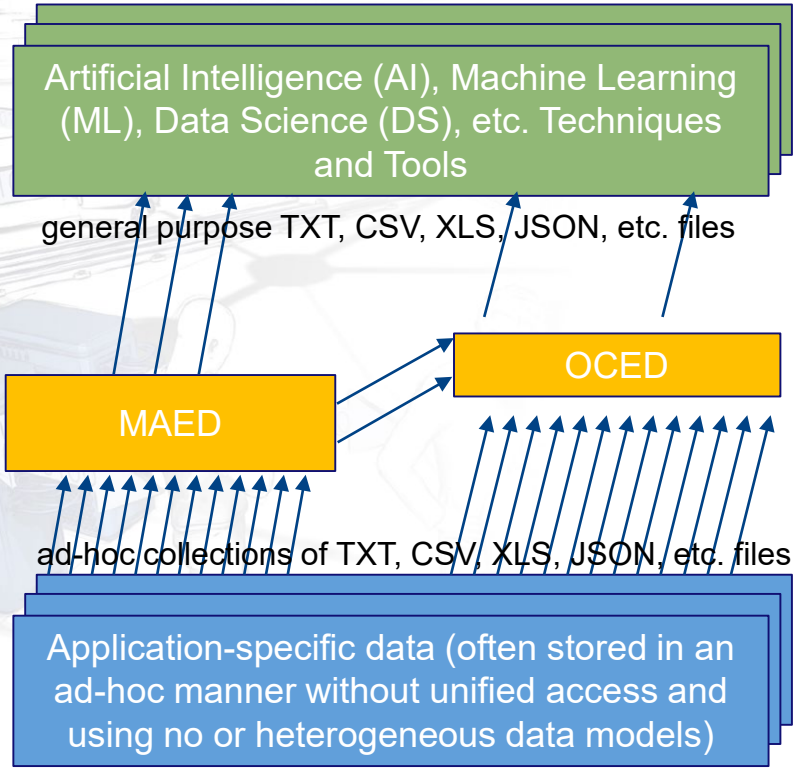
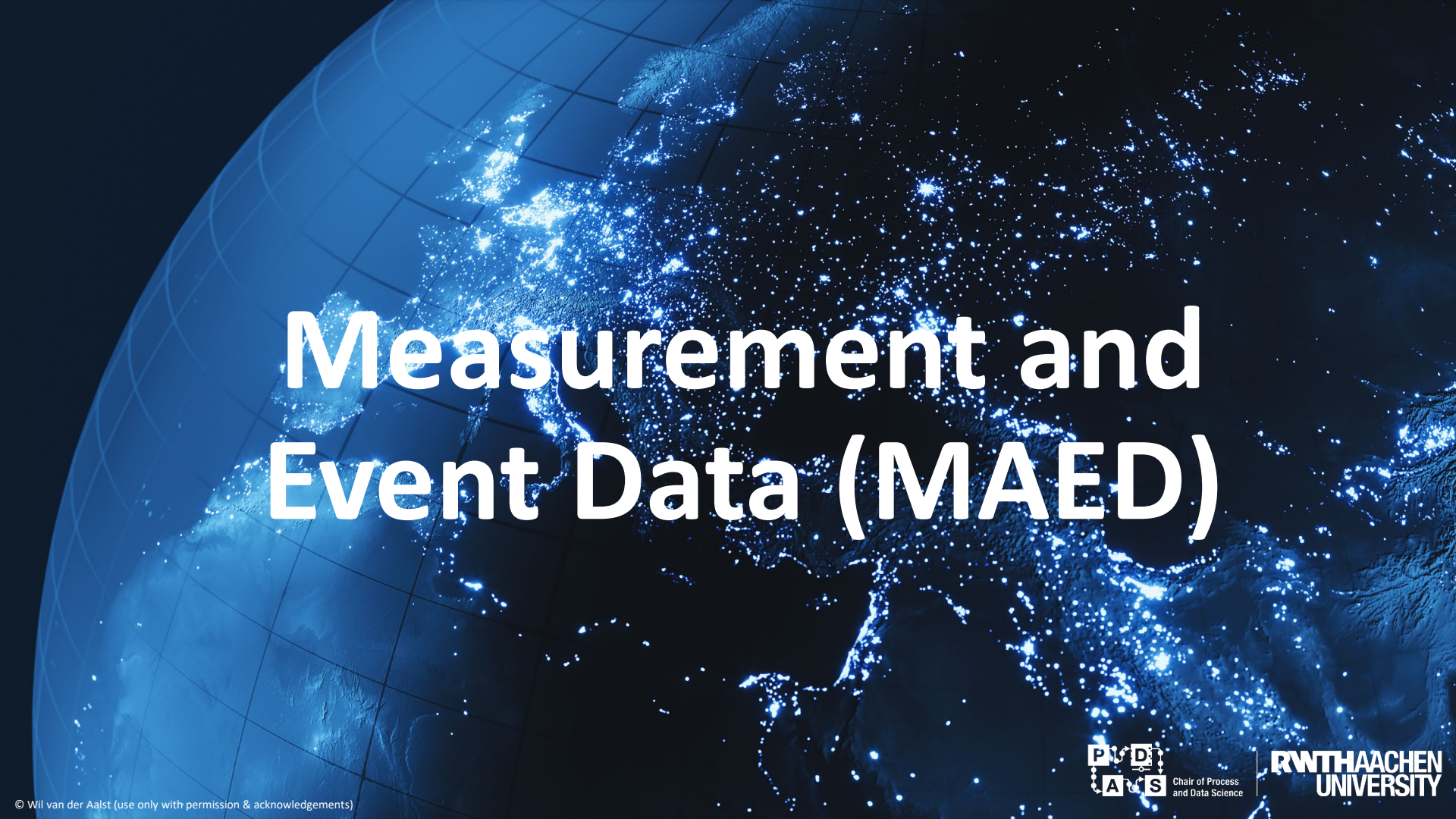
OCED Works! How about MAED?



- Object-Centric Event data (OCED)
- **Measurement and Event Data (MAED)**

Disclaimer: MAED is still under development and the presentation simplifies many things.



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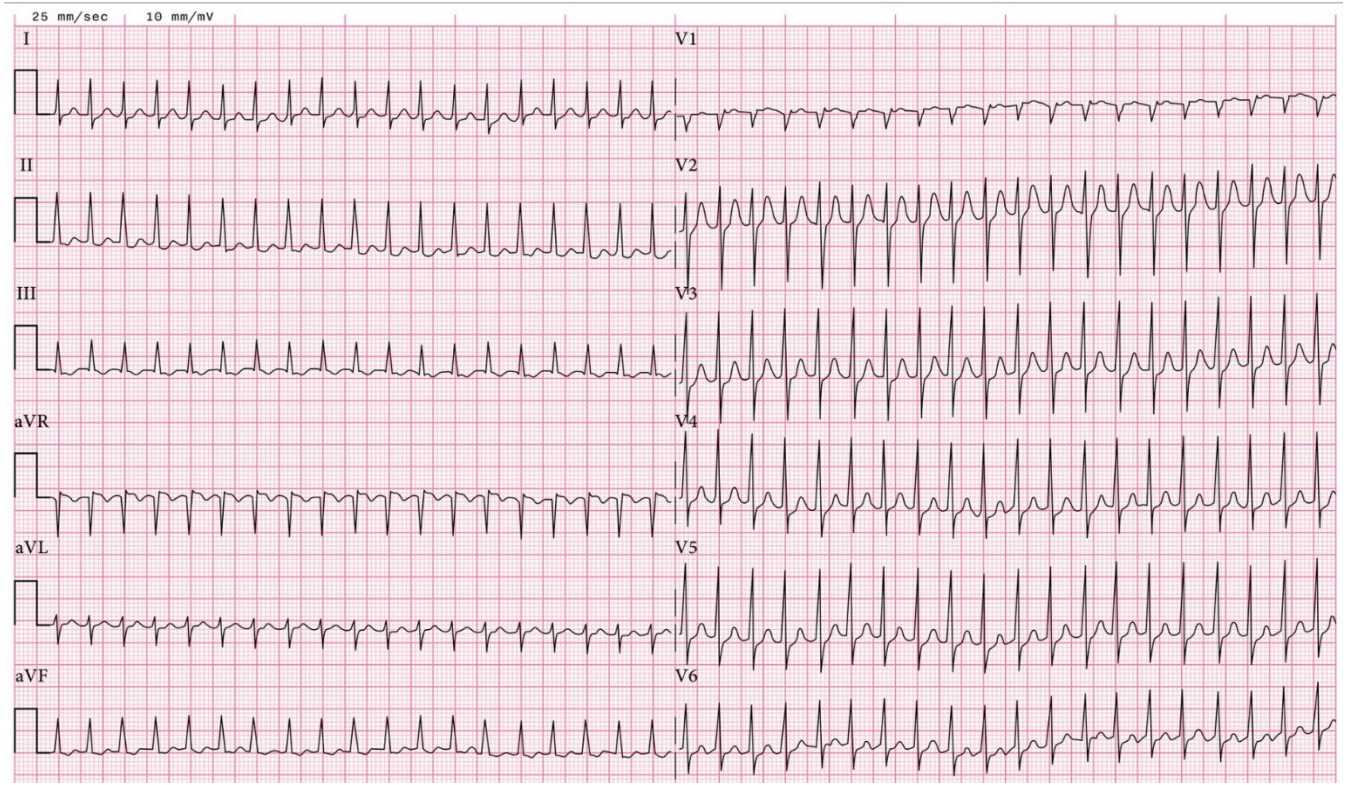
Event data are not enough!

Challenges Dealing With Machine Data

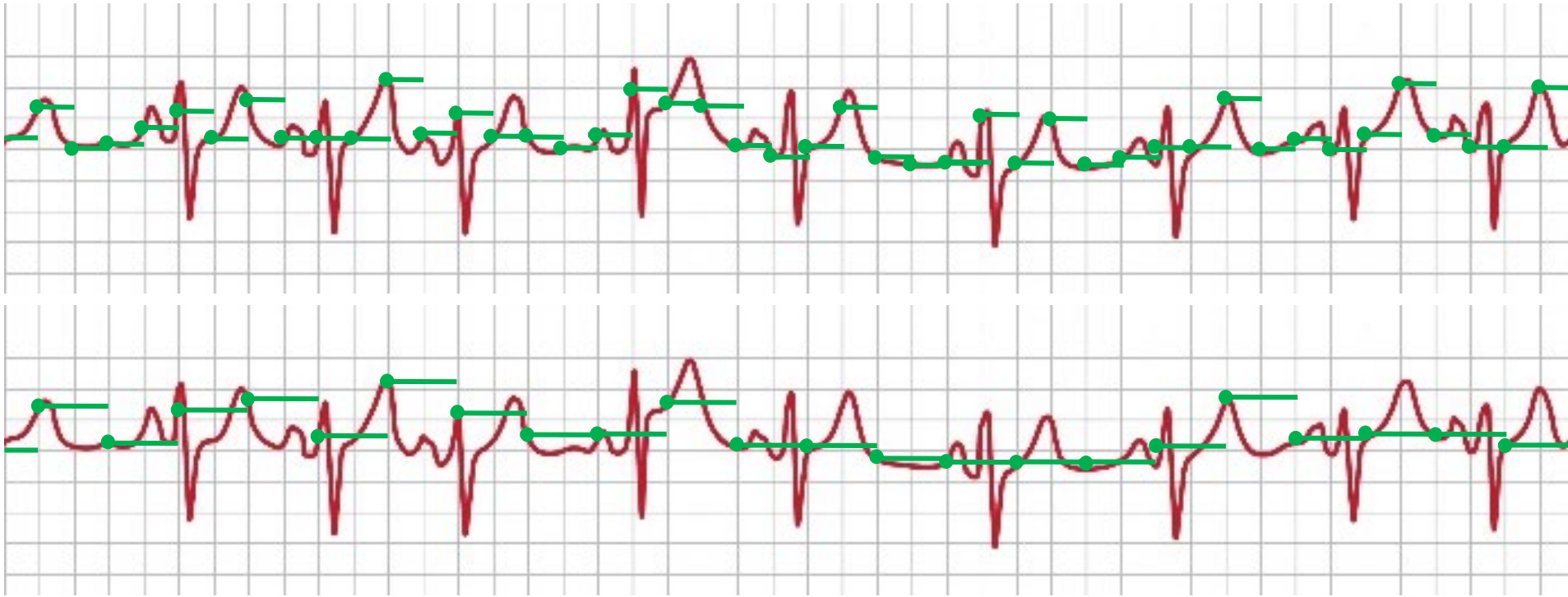
- There may be explicit events, but most data are low-level.
- Measurements are supposed to happen: Their occurrence carries no information (only the values).
- Continuous behavior mapped onto discrete data points (time series).
- Real-valued attributes (position, temperature, force, speed, etc.).

5-axis simultaneous machining/milling, i.e., cutting to remove material from the surface of a work piece

Time Series Data Are Everywhere

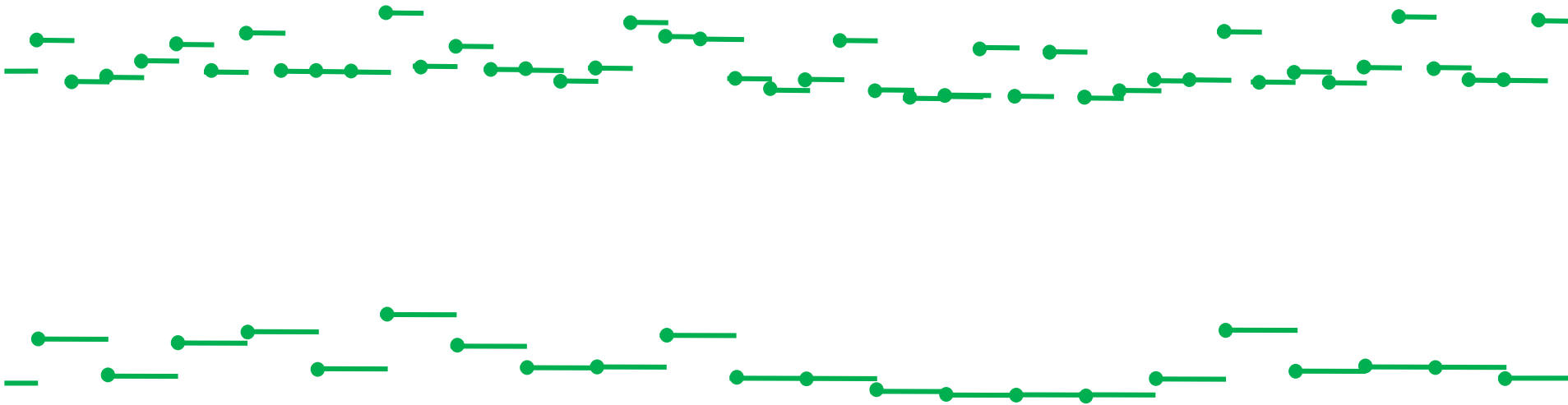


Time Series: Sampling Rate



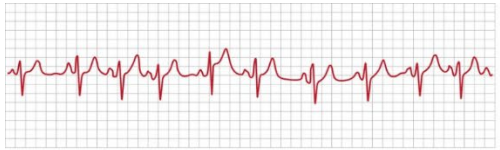
brianmcfee.net

Time Series: Sampling Rate

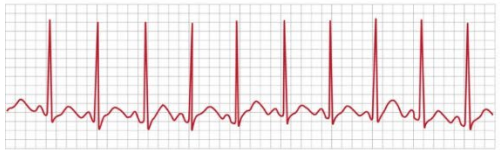


brianmcfee.net

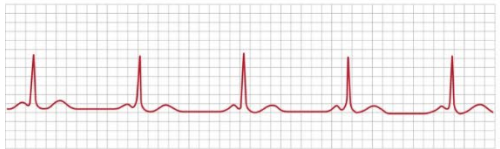
Time Series Data: Pattern Detection



Sinus arrhythmia

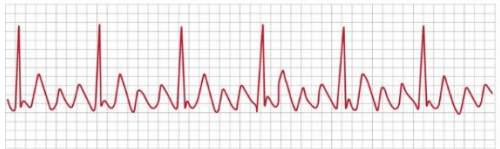


Sinus tachycardia



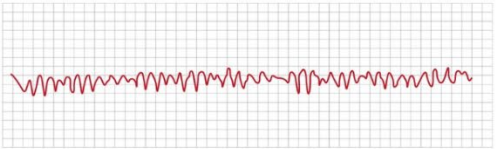
Sinus bradycardia

Atrial fibrillation

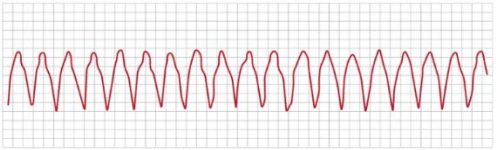


Atrial flutter

Atrioventicular block



Ventricular fibrillation



Ventricular tachycardia

Second-degree partial block

Third-degree partial block

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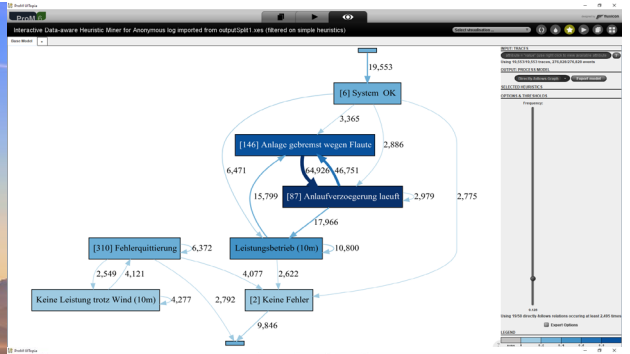
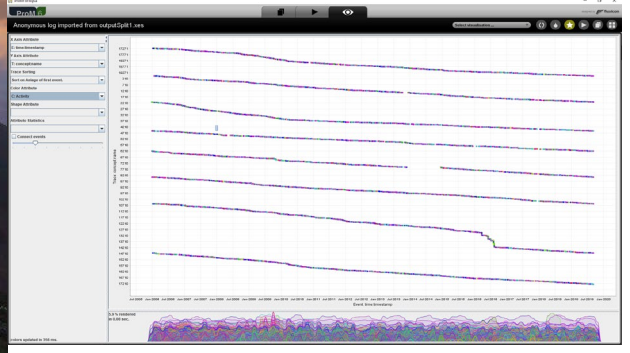
Wind Turbine Events and Measurements

Anlage	Start	Status	RS-Ereignis	Ursachenbereich	timestamp	case:concept:name
Offshore 05	30.11.2015 18:42:27	Anlage OK	System OK	[6] System OK	2015-11-30 18:42:27+00:00	10000
Offshore 05	30.11.2015 19:50:00	Anlage OK	z. Leistungsbetrieb	Leistungsbetrieb (10m)	2015-11-30 19:50:00+00:00	10000
Offshore 05	30.11.2015 19:51:49	Fehler	Turmschwingung	1771 Turmschwingung	2015-11-30 19:51:49+00:00	10000
Offshore 05	30.11.2015 20:00:00	Anlage OK	z. Leistungsbetrieb	Leistungsbetrieb (10m)	2015-11-30 20:00:00+00:00	10000
Offshore 05	30.11.2015 20:10:00	Warnmeldung	Keine Leistung trotz Wind	Keine Leistung trotz Wind (10m)	2015-11-30 20:10:00+00:00	10000
Offshore 05	30.11.2015 20:39:16	Anlage OK	Keine Fehler	[2] Keine Fehler	2015-11-30 20:39:16+00:00	10000
Offshore 05	30.11.2015 20:39:16	Service/ Reparatur	z. Fehlerquittierung	3310 Fehlerquittierung	2015-11-30 20:39:16+00:00	10000
Offshore 05	30.11.2015 20:39:16	Service/ Reparatur	Fern Stopp	60 Fern Halt	2015-11-30 20:39:16+00:00	10000
Offshore 05	30.11.2015 20:39:16	Anlage OK	System OK	[6] System OK	2015-11-30 20:39:16+00:00	10000
Offshore 05	30.11.2015 20:39:17	Anlage OK	z. Fern Start	50 Fern Start	2015-11-30 20:39:17+00:00	10000
Offshore 05	30.11.2015 20:39:17	Anlage OK	System OK	[6] System OK	2015-11-30 20:39:17+00:00	10000
Offshore 05	30.11.2015 20:40:00	Warnmeldung	Keine Leistung trotz Wind	Keine Leistung trotz Wind (10m)	2015-11-30 20:40:00+00:00	10000
Offshore 05	30.11.2015 20:50:00	Anlage OK	z. Leistungsbetrieb	Leistungsbetrieb (10m)	2015-11-30 20:50:00+00:00	10000
Offshore 05	01.12.2015 00:02:25	Warnmeldung (Information)	Flugbefeuerung Warnung	2740 Hind.befeuerung Umsch. auf Nebenpar	2015-12-01 00:02:25+00:00	10000
Offshore 05	01.12.2015 09:19:21	Wetter	z. Flaute	1440 Anlage gebremst wegen Flaute	2015-12-01 09:19:21+00:00	10000
Offshore 05	01.12.2015 12:18:39	Anlage OK	System OK	870 Anlaufverzogerung laeuft	2015-12-01 12:18:39+00:00	10000
Offshore 05	01.12.2015 13:00:00	Anlage OK	z. Leistungsbetrieb	Leistungsbetrieb (10m)	2015-12-01 13:00:00+00:00	10000
Offshore 05	07.12.2015 07:01:16	Stopp verfügbar	Selbsttest	1310 Rattotortest	2015-12-07 07:01:16+00:00	10000
Offshore 05	07.12.2015 07:03:31	Anlage OK	System OK	[6] System OK	2015-12-07 07:03:31+00:00	10000
Offshore 05	07.12.2015 07:50:00	Anlage OK	z. Leistungsbetrieb	Leistungsbetrieb (10m)	2015-12-07 07:50:00+00:00	10000
Offshore 05	07.12.2015 12:08:37	Wetter	z. Flaute	1440 Anlage gebremst wegen Flaute	2015-12-07 12:08:37+00:00	10000
Offshore 05	07.12.2015 12:11:40	Anlage OK	System OK	870 Anlaufverzogerung laeuft	2015-12-07 12:11:40+00:00	10000
Offshore 05	07.12.2015 12:12:12	Fehler	z. Nabenmschiner Fehler	1500 Kommunikationsfehler Pitchcontroller	2015-12-07 12:12:12+00:00	10000
Offshore 05	07.12.2015 12:12:13	Fehler	z. Pitch Fehler	1720 Sammelstoerung Pitchcontroller	2015-12-07 12:12:13+00:00	10000
Offshore 05	07.12.2015 12:16:00	Service/ Reparatur	z. Fehlerquittierung	3310 Fehlerquittierung	2015-12-07 12:16:00+00:00	10000
Offshore 05	07.12.2015 12:16:50	Service/ Reparatur	Fern Stopp	60 Fern Halt	2015-12-07 12:16:50+00:00	10000
Offshore 05	07.12.2015 12:16:52	Anlage OK	z. Fern Start	50 Fern Start	2015-12-07 12:16:52+00:00	10000
Offshore 05	07.12.2015 12:16:52	Anlage OK	System OK	[6] System OK	2015-12-07 12:16:52+00:00	10000
Offshore 05	07.12.2015 12:16:56	Anlage OK	Keine Fehler	[2] Keine Fehler	2015-12-07 12:16:56+00:00	10000





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Medical Events and Measurements

- **Measurements**
  (only value matters)
  - Blood pressure
  - SpO2%
  - …
- **Events**
  (occurrence matters)
  - Cardiac arrest
  - Surgery
  - …

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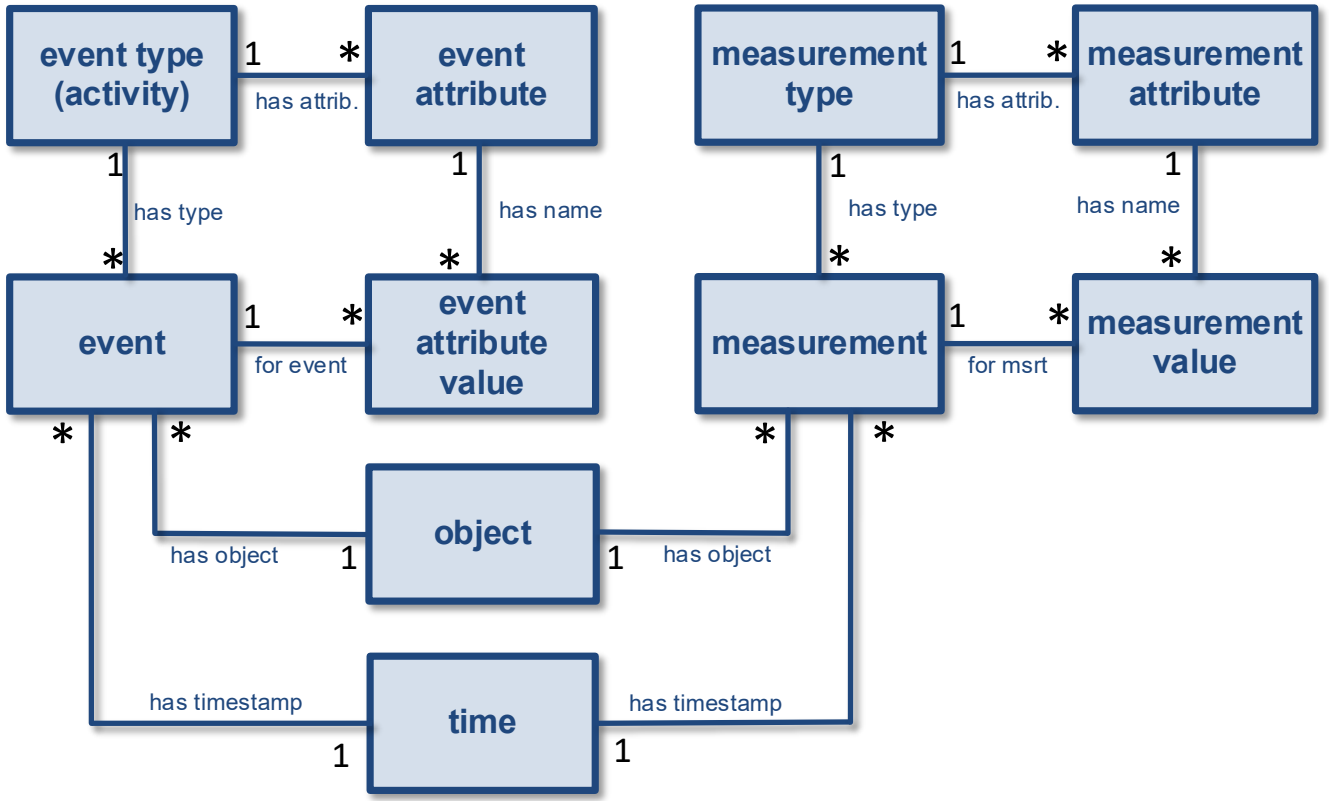
Measurement and Event Data (MAED)



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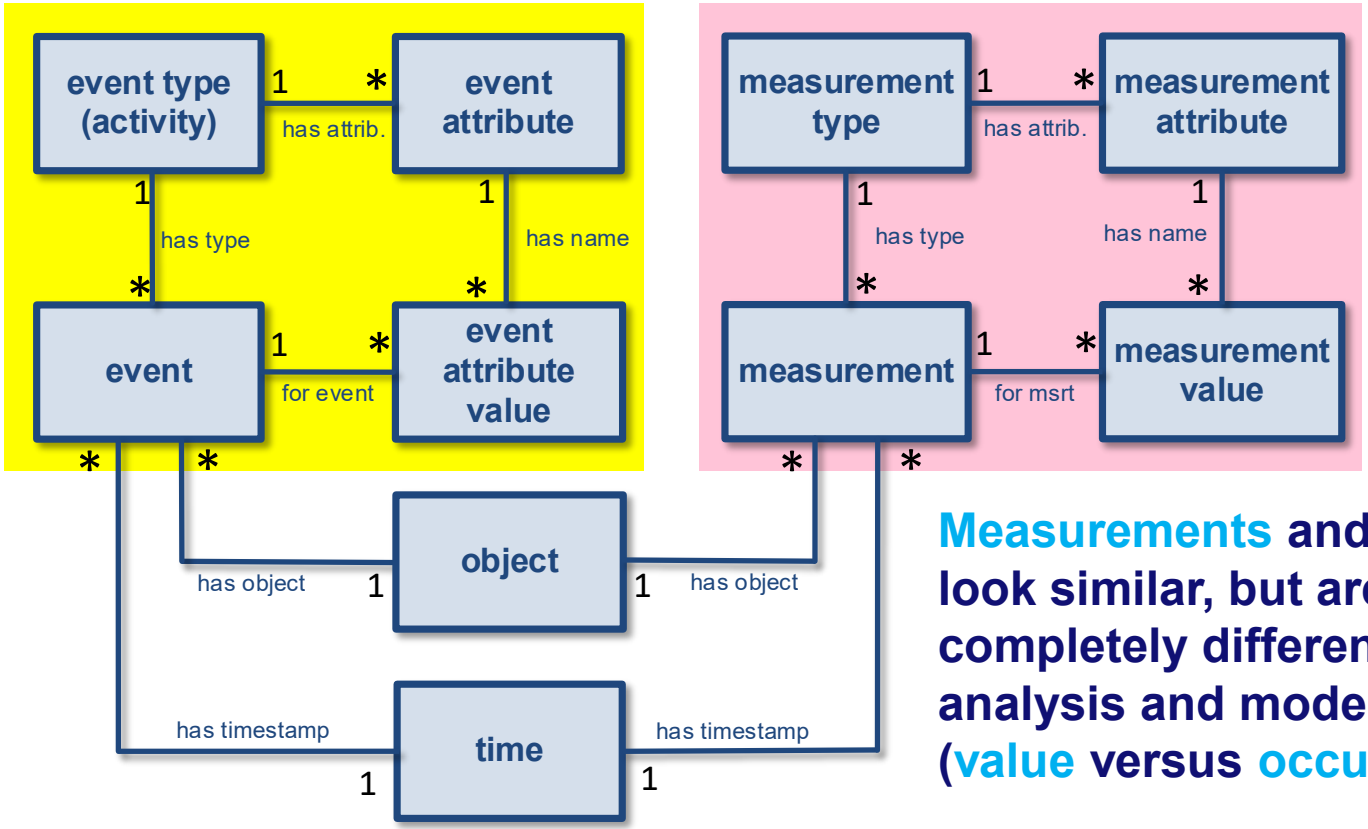
Measurement and Event Data (MAED)



Measurements and events look similar, but are handled completely different during analysis and model building (value versus occurrence).

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Example Milling WZL (Thanks to Leah Tacke genannt Unterberg and WZL)

MQTT is a machine-to-machine network protocol for message passing

Events
Temperature
Tool list
MQTT
Force
Speed
Current
Engagement
Position

physical machine

database representation

machine_tool

_id	UUID
id_serial	SERIAL
machine_hall	CHARACTER VARYING
company	CHARACTER VARYING
location	CHARACTER VARYING
name	CHARACTER VARYING
mqtt_topic	CHARACTER VARYING
show_on_dashboard	BOOLEAN
wqm_folder_name	CHARACTER VARYING

Foreign Key

machine_trace

id	UUID
id_serial	SERIAL
machine_id	INTEGER
nc_name	CHARACTER VARYING
time	TIMESTAMP(6) WITH TIME ZONE
time_end	TIMESTAMP(6) WITH TIME ZONE
wqm_data_available	BOOLEAN

Foreign Key

event_data

time	TIMESTAMP(6) WITH TIME ZONE
trace_id	INTEGER
name	CHARACTER VARYING
value	JSONB

Linked by timestamp

measurement_data_2

time	TIMESTAMP(6) WITH TIME ZONE
x1	DOUBLE PRECISION
y1	DOUBLE PRECISION
z1	DOUBLE PRECISION
a1	DOUBLE PRECISION
b1	DOUBLE PRECISION
xc	DOUBLE PRECISION
yc	DOUBLE PRECISION
zc	DOUBLE PRECISION

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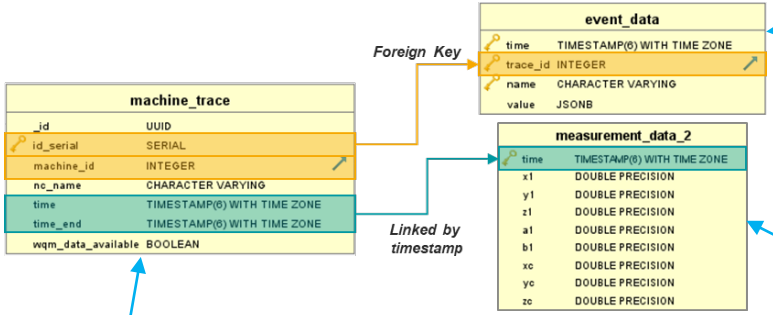
Example Milling WZL

	time	trace_id	name	value
1	2023-05-10 04:00:04.395+02	7879	X_ACTUAL_ZERO_POINT	{"fine": 0.0, "coarse": 416.15598033257}
2	2023-05-10 04:00:04.395+02	7872	X_ACTUAL_ZERO_POINT	{"fine": 0.0, "coarse": 0.0}
3	2023-05-10 04:00:04.395+02	7872	Y_ACTUAL_ZERO_POINT	{"fine": 0.0, "coarse": 0.0}
4	2023-05-10 04:00:04.395+02	7872	Z_ACTUAL_ZERO_POINT	{"fine": 0.0, "coarse": 0.0}

many rows per id



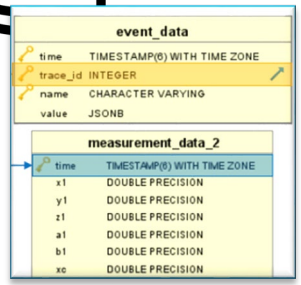
many rows per time period

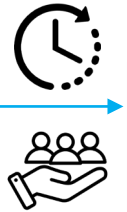
	time	tool_cent...	tool_center_point_position_wcs_vector_2	tool_center_point_position_wcs_vector_3	engagement_repeatedly...	in_tool_number_a
1	2023-05-11 10:18:46.979+02	-416.149963	253.990326	398.442841	0	
2	2023-05-10 16:27:24.264+02	-416.157898	253.987595	398.456329	0	
3	2023-05-10 16:23:52.478+02	-416.157928	253.987228	398.456421	0	
4	2023-05-11 10:21:29.731+02	-416.149963	253.990448	398.44278	0	
5	2023-05-10 15:26:43.406+02	-414.073669	-71.046631	395.321411	0	
6	2023-05-10 16:12:29.568+02	-416.157959	253.986557	398.457214	0	

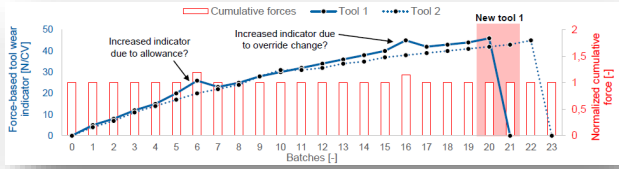
	_id	id_serial	machine_id	nc_name	time	time_end
1	f496279b-e543-4bf1-92eb-759234963dcb	7872	3	/_N_EXT_DIR/_N_EXTMOD_DIR/_N_CHAN1_DIR/_N_D65_000182_1_MPF	2023-05-10 09:06:59.183+02	2023-05-10 09:07:49.857+02
2	64ca14ee-cc27-41e9-9dc8-f96702856db6	7873	3	Idle	2023-05-10 09:07:49.857+02	2023-05-10 09:07:52.738+02
3	884a9594-67d2-4eb8-b598-c67428bebbec	7874	3	Idle	2023-05-10 09:07:52.738+02	2023-05-10 09:08:01.366+02
4	1d4890cd-9acb-4d35-a753-11cd827d9566	7875	3	/_N_EXT_DIR/_N_EXTMOD_DIR/_N_CHAN1_DIR/_N_D65_000182_1_MPF	2023-05-10 09:08:01.366+02	2023-05-10 09:08:20.252+02
5	73ca0aa0-2c5d-4600-be32-af0f348a030d	7876	3	Idle	2023-05-10 09:08:20.252+02	2023-05-10 09:08:24.498+02
6	837f7b33-7cbe-47d4-972a-03681b8d2774	7877	3	/_N_EXT_DIR/_N_EXTMOD_DIR/_N_CHAN1_DIR/_N_D65_000182_1_MPF	2023-05-10 09:08:24.498+02	2023-05-10 09:08:16.414+02

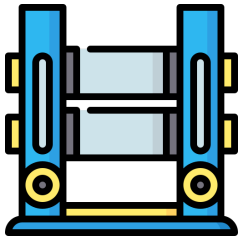
one row per id

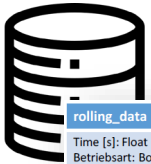
Current Situation: Application Specific and Limited Reuse

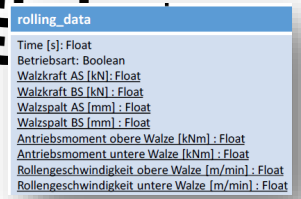












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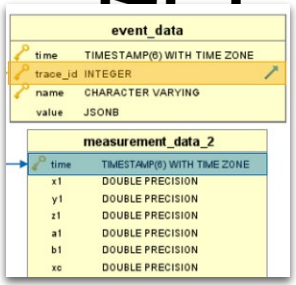
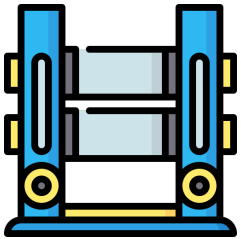
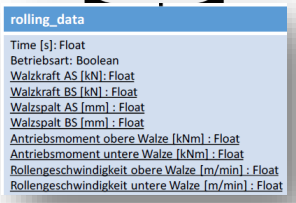
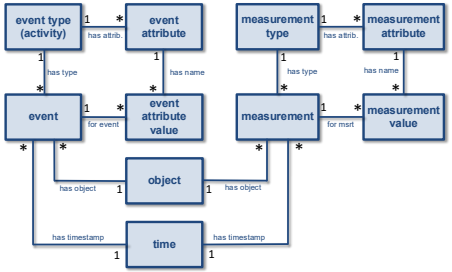
Using Our Model-in-the-Middle

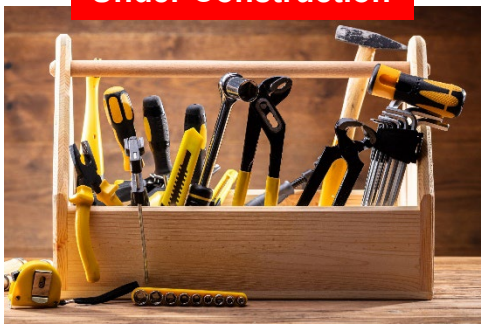






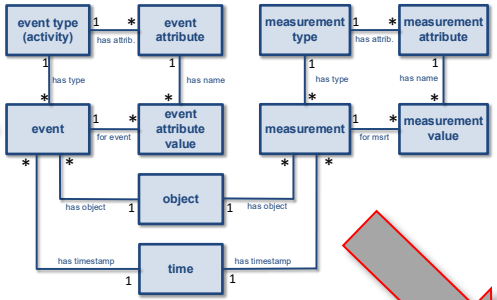


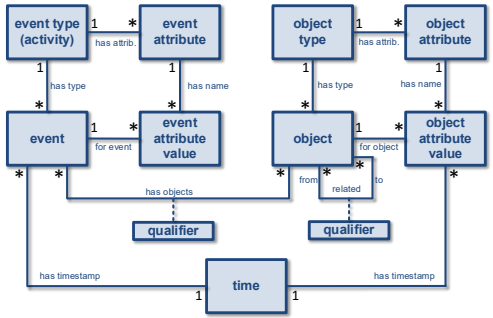
Under Construction



ProM for Machine Data

Connecting Both Worlds





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Conclusion

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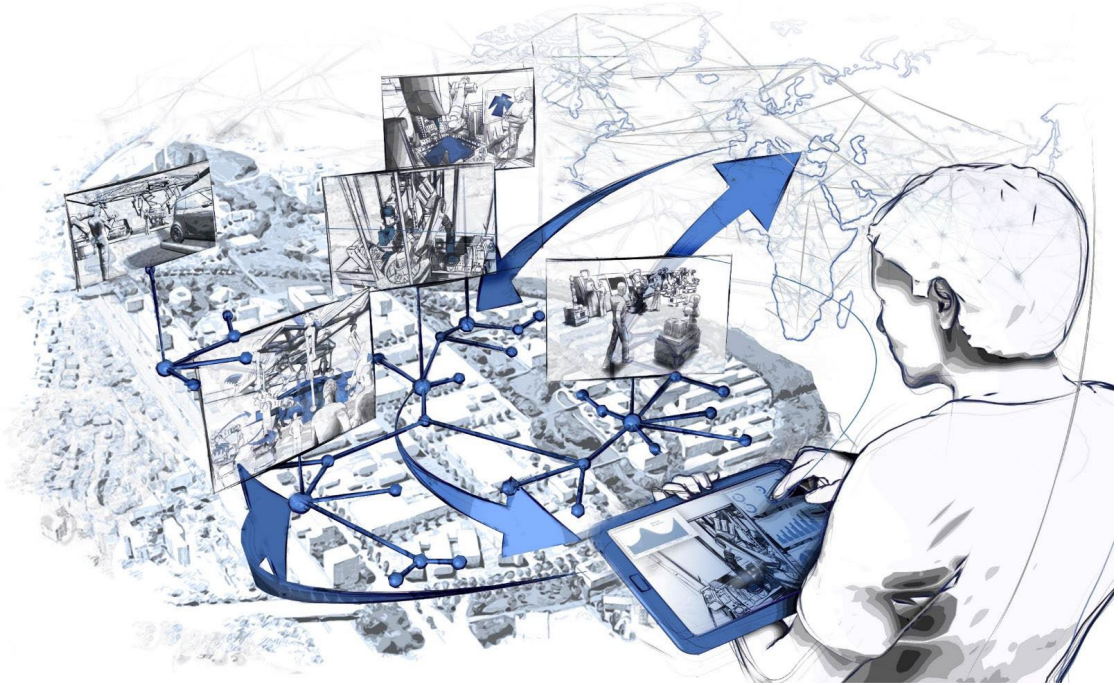
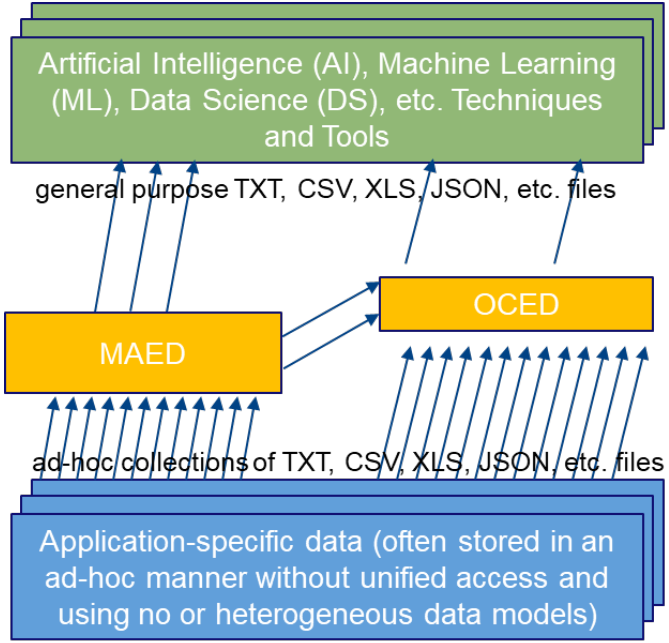
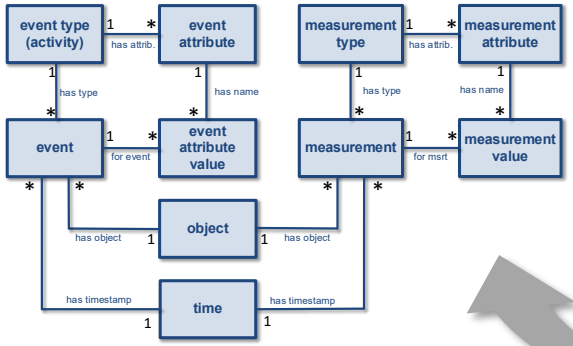
RWTH AACHEN UNIVERSITY

Models-in-the-Middle Inspired by IoP

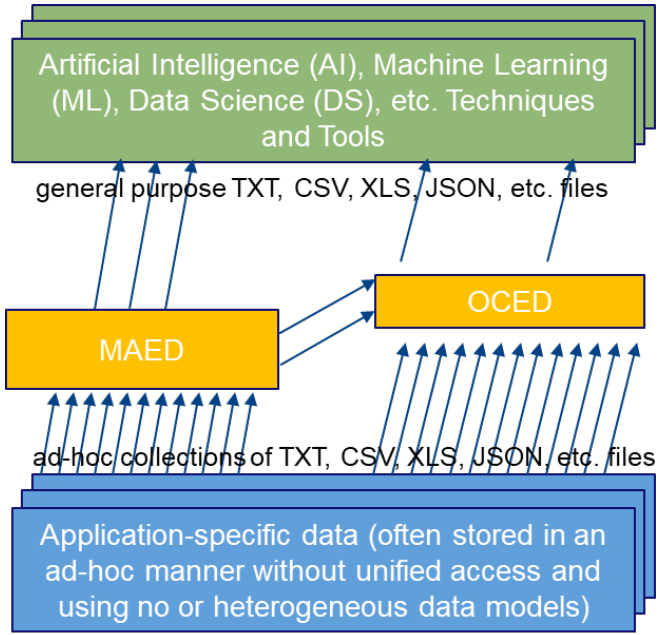


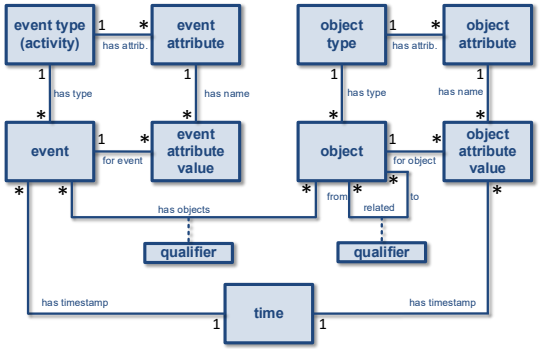


Two Selectively Chosen Examples



Under Construction





Upcoming Industry Standard

transfer experiences

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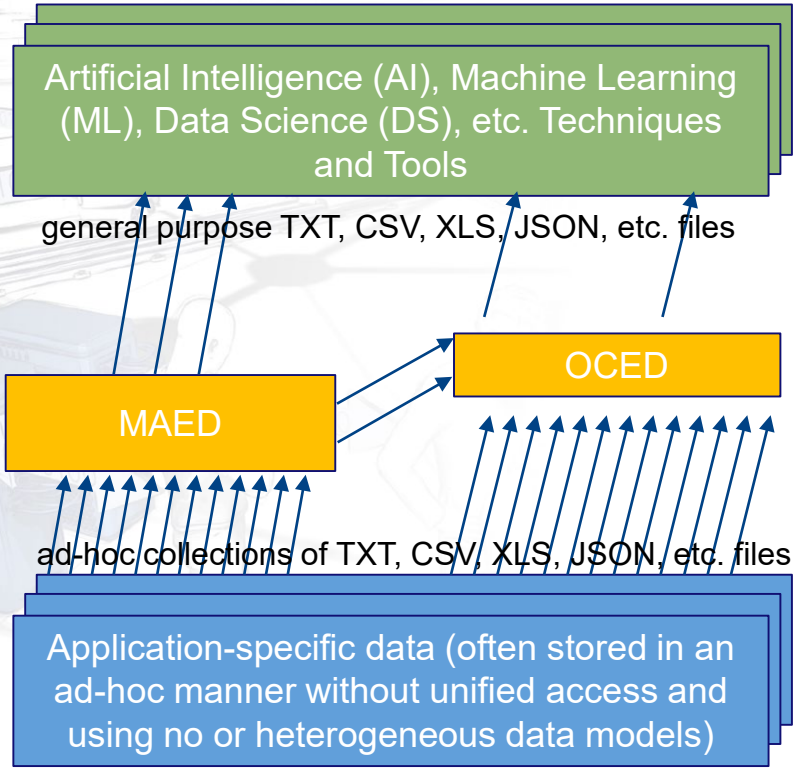
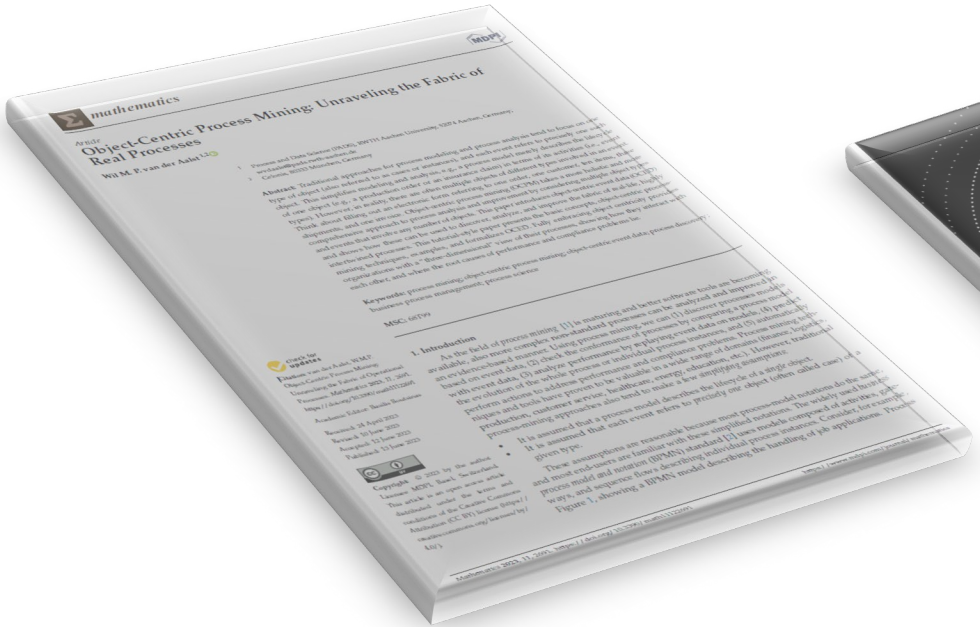
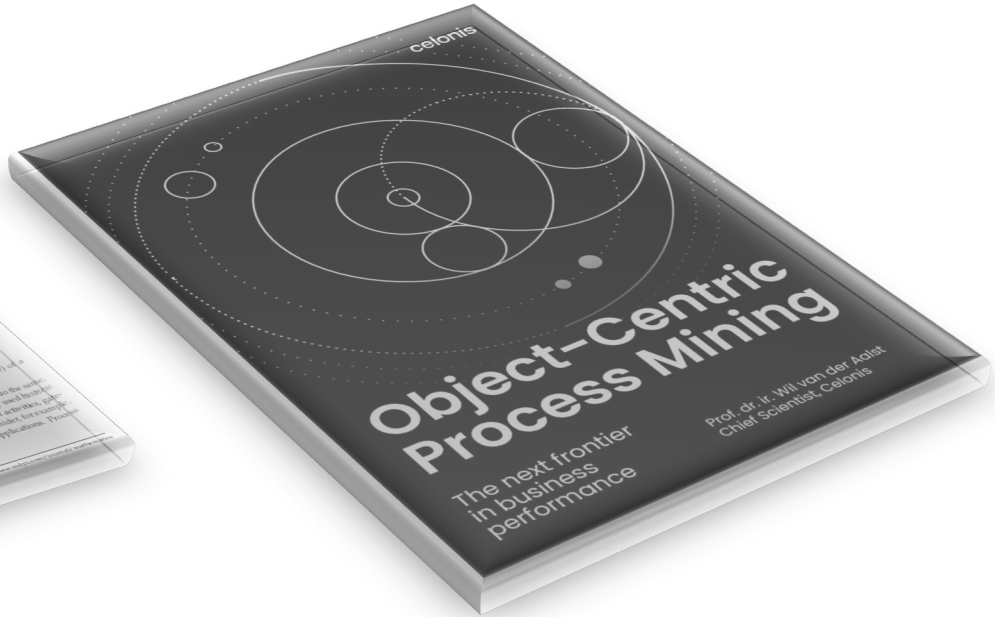
Outlook



- **Both trigger many research questions.**
- **MAED-to-OCED**
- **Hierarchies of Models-in-the-Middle.**
- **Domain-specific instances of these models (e.g., predefined event and object types organized in a taxonomy/ontology).**

More on Object-Centric Process Mining





W.M.P. van der Aalst, Object-Centric Process Mining: Unraveling the Fabric of Real Processes. Mathematics 2023, 11, 2691. https://doi.org/10.3390/math11122691

W. van der Aalst, Object-Centric Process Mining: The Next Frontier in Business Performance. 2023. Available online: celon.is/OCPM-Whitepaper

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