prof.dr.ir. Wil van der Aalst

www.vdaalst.com @wvdaalst www.pads.rwth-aachen.de Keynote 18th International Colloquium on Theoretical Aspects of Computing (ICTAC 2021)

NINTRA

Concurrency and Objects Matter! Disentangling the Fabric of Real Operational Processes

and the mark that the show



Recording and analyzing data about operational processes is not new

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F.W. Taylor. The Principles of Scientific Management. Harper and Bothers Publishers, New York, 1919.



The dream



Towards a Digital Twin of an Organization (DTO)

reality digital model

Examples: business process modeling, discrete event simulation, etc.



Towards a Digital Twin of an Organization (DTO)



Process mining is a key technology to create a digital shadow. 15 years ago we were already able to automatically create simulation models based on event data only!



Towards a Digital Twin of an Organization (DTO)



Towards a Digital Twin of an Organization (DTO)



Traditional process mining techniques and tools can create a digital shadow from event data.

To create a digital twin, process mining techniques need to be more forward looking. This includes:

- Operational support, including predictions and recommendations.
- Action-oriented process mining, triggering corrective workflows
 (Also see the Celonis Execution Management System.)



But, we need to have a digital shadow first!



Concurrency and Objects Matter! Disentangling the Fabric of Real Operational Processes to Create Digital Twins

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Abstract. Process mining dramatically changed the way we look at process models and operational processes. Even seemingly simple processes like Purchase-to-Pay (P2P) and Order-to-Cash (O2C) are often amazingly complex, and traditional hand-made process models fail to capture the true fabric of such processes. Many processes are inherently concurrent and in volve interaction between different objects (customers, suppliers, orders, items, shipments, payments, machines, workers, etc.). Process mining uses event data to construct process models that can be used to diagnose performance and compliance problems. If such models reflect reality well, they can be used for forward-locking forms of process mining, including predictive analytics, evidence-based automation, and what-if simulation. The ultimate goal is to create a "digital twin of an organization" that can be used to explore different improvement actions. This pape provides a highlevel overview of the different process mining tasks followed by a more detailed discussion on concurrency and object-centricity in process mining.

Keywords: Process Mining · Event Data · Concurrency · Digital Twins

1 Towards a Digital Twin of an Organization

The desire to adequately describe operational processes has been around since the 1890ties when the field of *scientific management* emerged. Scientific management is also known as Taylorism, named after its pioneer Frederick Winslow Taylor (1856-1915) who tried to systematically improve economic efficiency, especially labor productivity. Taylor systematically observed how eopole work and can be seen as the "irrst process miner" using pen and paper (see Figure 1). In 1950 computers started to influence business However, the systematic use of data about operational processes is much more recent [1].

The desire to build computer models that mimic organizations and processes is also not that new. Since the 1960-ties so-called *discrete event simulation* tools have been available with SIMULA [11] as one of the first influential examples. In discrete event simulation it is common to estimate parameters and distributions based on observed data (e.g., service times and arrival rates). However, one still needs to model the process by hand. The first comprehensive approaches to automatically learn complete simulation Mainstream process mining techniques have two difficulties:

- Dealing with concurrency
- Dealing with objects



Basic Process Mining Concepts



Starting point: Event data

	1		İ.		1		1	
Case ID	Activity	Resource	Timestamp	product	prod-price	quantity	address	
6350	place order	Aiden	2018/02/13 14:29:45.000	APPLE iPhone 6 16 GB	639,00€	5	NL-7751DG-21	event
6283	pay	Lily	2018/02/13 14:39:25.000	SAMSUNG Galaxy S6 32 GB	543.99	3	NL-7828AM-11a	
6253	prepare delivery	Sophia	2018/02/13 15:01:33.000	APPLE iPhone 6 16 GB	639,00€	3	NL-7887AC-13	
6257	prepare delivery	Aiden	2018/02/13 15:03:43.000	SAMSUNG Galaxy S6 32 GB	543.99	1	NL-9521KJ-34	
6185	confirm payment	Emily	2018/02/13 15:05:36.000	SAMSUNG Galaxy S4	329,00€	1	NL-9521GC-32	
6218	confirm payment	Emily	2018/02/13 15:08:11.000	APPLE iPhone 6s Plus 64 GB	969,00€	2	NL-7948BX-10	
6245	make delivery	Michael	2018/02/13 15:14:04.000	APPLE iPhone 6 16 GB	639,00€	3	NL-7905AX-38	
6272	pay	Emily	2018/02/13 15:20:36.000	APPLE iPhone 6 16 GB	639,00€	1	NL-7821AC-3	
6269	pay	Charlotte	2018/02/13 15:25:21.000	SAMSUNG Galaxy S4	329,00€	1	NL-7907EJ-42	
6212	prepare delivery	Sophia	2018/02/13 15:43:39.000	HUAWEI P8 Lite	234,00€	1	NL-7905AX-38	
6323	send invoice	Alexander	2018/02/13 15:46:08.000	APPLE iPhone 6 16 GB	639,00€	1	NL-7833HT-15	
6246	confirm payment	Jack	2018/02/13 15:56:03.000	SAMSUNG Galaxy S4	329,00€	3	NL-7833HT-15	
6347	send invoice	Jack	2018/02/13 15:57:42.000	SAMSUNG Galaxy S4	329,00€	3	NL-7905AX-38	
6351	place order	Zoe	2018/02/13 16:17:37.000	APPLE iPhone 5s 16 GB	449,00€	3	NL-9521GC-32	
6204	prepare delivery	Sophia	2018/02/13 16:31:28.000	SAMSUNG Core Prime G361	135,00€	1	NL-7828AM-11a	74.040
6204	make delivery	Kaylee	2018/02/13 16:51:54.000	SAMSUNG Core Prime G361	135,00€	1	NL-7828AM-11a	71,043 events
6265	confirm payment	Lily	2018/02/13 16:55:55.000	SAMSUNG Galaxy S4	329,00€	4	NL-9521GC-32	12 666 cases
6250	confirm payment	Jack	2018/02/13 17:03:26.000	MOTOROLA Moto G	199,00€	4	NL-7942GT-2	12,000 00303
6328	send invoice	Lily	2018/02/13 17:30:16.000	APPLE iPhone 6s 64 GB	858,00€	4	NL-9514BV-16	7 activities
6352	place order	Aiden	2018/02/13 17:53:22.000	APPLE iPhone 6 16 GB	639,00€	2	NL-9514BV-16	
6317	send invoice	Jack	2018/02/13 18:45:30.000	APPLE iPhone 6s 64 GB	858,00€	5	NL-7907EJ-42	
6353	place order	Sophia	2018/02/13 20:16:20.000	APPLE iPhone 5s 16 GB	449,00€	4	NL-7751AR-19	
								P U D

Science

Starting point: Event data

		_	_				
Case ID	Activity	Resource	Timestamp	product	prod-price	quantity	address
6350	place order	Aiden	2018/02/13 14:29:45.000	APPLE iPhone 6 16 GB	639,00€	5	NL-7751DG-21
6283	рау	Lily	2018/02/13 14:39:25.000	SAMSUNG Calaxy S6-32 GB	543.99	3	NL-7828AM-11a
6253	prepare delivery	Sophia	2018/02/13 15:01:33.000	APF China 6 CLB	63 <mark>9.00</mark> ≢	3	NL-7887AC-13
6257	prepare delivery	Aiden	2018/02/13 15:03:43.000	SAMSUNG Galaxy So 32 GB	543.99	1	NL-9521KJ-34
6185	confirm payment	Emily	2018/02/13 15:05:36.000	SAMSUNG Galaxy S4	329,00€	1	NL-9521GC-32
6218	confirm payment	Emily	2018/02/13 15:08:11.000	APPLE iPhone 6s Plus 64 GB	969,00€	2	NL-7948BX-10
6245	make delivery	Michael	2018/02/13 15:14:04.000	APF Enchance 5 Code -	€ <mark>9</mark> 00€	3	NL-7905AX-38
6272	рау	Emily	2018/02/13 15:20:36.000	APP has been	€_9,00€	1	NL-7821AC-3
6269	рау	Charlotte	2018/02/13 15:25:21.000	SAMSUNG Galaxy S4	329,00€	1	NL-7907EJ-42
6212	prepare delivery	Sophia	2018/02/13 15:43:39.000	HUAWEI P8 Lite 🗖	<mark>_</mark> 234,00€	1	NL-7905AX-38
6323	send invoice	Alexander	2018/02/13 15:46:08.000	APP h n 5 J (B	JE DO E	1	NL-7833HT-15
6246	confirm payment	Jack	2018/02/13 15:56:03.000	SA SAN STALLS	29, €	3	NL-7833HT-15
6347	send invoice	Jack	2018/02/13 15:57:42.000	SAMSUNG Galaxy S4	329,50€	3	NL-7905AX-38
6351	place order	Zoe	2018/02/13 16:17:37.000	APPLE iPhone 5s 16 GB	449,00€	3	NL-9521GC-32
6204	prepare delivery	Sophia	2018/02/13 16:31:28.000	SAMSI G TO COM			NL-7828AM-11a
6204	make delivery	Kaylee	2018/02/13 16:51:54.000	SAMSU IG to e F in a store			NL-1928AM-11a
6265	confirm payment	Lily	2018/02/13 16:55:55.000	SAMSUNG Galaxy S4	329,00€	4	NL-9521GC-32
6250	confirm payment	Jack	2018/02/13 17:03:26.000	MOTOROLA Moto G	199,00€	4	NL-7942GT-2
6328	send invoice	Lily	2018/02/13 17:30:16.000	APPLE iPhone 6s 64 GB	858,00€	4	NL-9514BV-16
6352	place order	Aiden	2018/02/13 17:53:22.000	APPLE iPhone 6 16 GB	639,00€	2	NL-9514BV-16
6317	send invoice	Jack	2018/02/13 18:45:30.000	APPLE iPhone 6s 64 GB	858,00€	5	NL-7907EJ-42
6353	place order	Sophia	2018/02/13 20:16:20.000	APPLE iPhone 5s 16 GB	449,00€	4	NL-7751AR-19



Case ID	Activity	Timestamp
6350	place order	2018/02/13 14:29:45.000
6351	place order	2018/02/13 16:17:37.000
6352	place order	2018/02/13 17:53:22.000
6352	send invoice	2018/02/19 09:20:28.000
6351	send invoice	2018/02/19 16:08:07.000
6350	send invoice	2018/02/21 09:38:16.000
6350	рау	2018/03/02 12:39:37.000
6352	рау	2018/03/05 15:46:47.000
6351	cancel order	2018/03/06 10:17:01.000
6350	prepare delivery	2018/03/07 13:50:35.000
6350	make delivery	2018/03/07 16:41:01.000
6350	confirm payment	2018/03/07 16:53:00.000
6352	prepare delivery	2018/03/07 17:05:59.000
6352	confirm payment	2018/03/07 17:59:55.000
6352	make delivery	2018/03/08 09:54:36.000



Case ID	Activity	Timestamp
6350	place order	2018/02/13 14:29:45.000
6351	place order	2018/02/13 16:17:37.000
6352	place order	2018/02/13 17:53:22.000
6352	send invoice	2018/02/19 09:20:28.000
6351	send invoice	2018/02/19 16:08:07.000
6350	send invoice	2018/02/21 09:38:16.000
6350	рау	2018/03/02 12:39:37.000
6352	рау	2018/03/05 15:46:47.000
6351	cancel order	2018/03/06 10:17:01.000
6350	prepare delivery	2018/03/07 13:50:35.000
6350	make delivery	2018/03/07 16:41:01.000
6350	confirm payment	2018/03/07 16:53:00.000
6352	prepare delivery	2018/03/07 17:05:59.000
6352	confirm payment	2018/03/07 17:59:55.000
6352	make delivery	2018/03/08 09:54:36.000

place send pay prepare make confirm order send novoice pay delivery delivery confirm



Case ID	Activity	Timestamp
6350	place order	2018/02/13 14:29:45.000
6351	place order	2018/02/13 16:17:37.000
6352	place order	2018/02/13 17:53:22.000
6352	send invoice	2018/02/19 09:20:28.000
6351	send invoice	2018/02/19 16:08:07.000
6350	send invoice	2018/02/21 09:38:16.000
6350	рау	2018/03/02 12:39:37.000
6352	рау	2018/03/05 15:46:47.000
6351	cancel order	2018/03/06 10:17:01.000
6350	prepare delivery	2018/03/07 13:50:35.000
6350	make delivery	2018/03/07 16:41:01.000
6350	confirm payment	2018/03/07 16:53:00.000
6352	prepare delivery	2018/03/07 17:05:59.000
6352	confirm payment	2018/03/07 17:59:55.000
6352	make delivery	2018/03/08 09:54:36.000

Order 6350





Case ID	Activity	Timestamp
6350	place order	2018/02/13 14:29:45.000
6351	place order	2018/02/13 16:17:37.000
6352	place order	2018/02/13 17:53:22.000
6352	send invoice	2018/02/19 09:20:28.000
6351	send invoice	2018/02/19 16:08:07.000
6350	send invoice	2018/02/21 09:38:16.000
6350	рау	2018/03/02 12:39:37.000
6352	рау	2018/03/05 15:46:47.000
6351	cancel order	2018/03/06 10:17:01.000
6350	prepare delivery	2018/03/07 13:50:35.000
6350	make delivery	2018/03/07 16:41:01.000
6350	confirm payment	2018/03/07 16:53:00.000
6352	prepare delivery	2018/03/07 17:05:59.000
6352	confirm payment	2018/03/07 17:59:55.000
6352	make delivery	2018/03/08 09:54:36.000

Order 6350 place send prepare make confirm pay delivery order invoice delivery payment **Order 6351** place send cancel order invoice order **Order 6352** confirm make place send prepare pay order invoice delivery delivery payment



Case ID	Activity	Timestamp
6350	place order	2018/02/13 14:29:45.000
6351	place order	2018/02/13 16:17:37.000
6352	place order	2018/02/13 17:53:22.000
6352	send invoice	2018/02/19 09:20:28.000
6351	send invoice	2018/02/19 16:08:07.000
6350	send invoice	2018/02/21 09:38:16.000
6350	рау	2018/03/02 12:39:37.000
6352	рау	2018/03/05 15:46:47.000
6351	cancel order	2018/03/06 10:17:01.000
6350	prepare delivery	2018/03/07 13:50:35.000
6350	make delivery	2018/03/07 16:41:01.000
6350	confirm payment	2018/03/07 16:53:00.000
6352	prepare delivery	2018/03/07 17:05:59.000
6352	confirm payment	2018/03/07 17:59:55.000
6352	make delivery	2018/03/08 09:54:36.000

Order 6350





Let's look at the whole event log again



Chair of Process and Data Science

Using the whole event log



and Data Science

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Performance and Compliance



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Reality is not so simple







Reality is not so simple

It is common to find thousands of different variants for simple core processes like P2P and O2C!

Caused by hand-offs, rework, duplication, ineffective communication, etc.

Over 35 process mining vendors today



Example: Celonis, Germany's first Decacorn





A Decacorn is a startup company valued at over \$10 billion



Many of the larger organizations in Europe are using process mining already (and we are just at the beginning!)



Why DFGs are not enough



Directly-Follows Graph (DFG)







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DFGs cannot capture concurrency

DFGs cannot capture concurrency

and Data Science

Filtering does not help



Inductive mining finds the right model



BPMN notation (Petri nets and process trees under the hood)



Directly-Follows Graphs (DFGs)

- Easy to create and scalable.
- Show paths, frequencies, and times.
- Can be simplified easily using filters.

- Filtering needs to be done with the utmost care.
- DFGs cannot capture concurrency.





Fortunately, there are many techniques that can discover concurrency



E.g. the inductive mining approaches

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Back to the two problems: Concurrency and Objects



Organizations are highly concurrent!



More about concurrency





More about concurrency: Example runs









A run defines a partial order of activities.

One partial order may correspond to many traces!



One run with 7*6 = 42 firing sequences!

Why 7*6? There are 7 positions where t41 and t61 can occur, but they cannot be at the same position.



We need to cope with this!



If we assume that t3 (re-examination) is executed at most 5 times, then there are :

- 2(1+1+1+1+1) = 12 runs, and
- 2(13*12+11*10+9*8+7*6+5*4+3*2) = 812
 firing sequences.

Why 2(13*12+11*10+9*8+7*6+5*4+3*2)? The 2 refers to the choice between t5 or t6. Assume this fixed and t3 is executed k times. There are n=k+1+k+1+1 firings in the middle part. t4 and t5 (or t6) can be at any position but not at the same position.



Why a single case notion is not enough



Example illustrating object-centric PM







PV AVS

UNIVERSITY



Example illustrating object-centric PM

(No activities, just describing the relationships among objects)



and Data Science

Ultimate Goal: One model showing multiple object types



Chair of Process and Data Science

PV AV B

UNIVERSITY

See Wil van der Aalst: Object-Centric Process Mining: Dealing with Divergence and Convergence in Event Data. SEFM 2019, 3-25 https://doi.org/10.1007/978-3-030-30446-1_1

Let's make the following assumption

activity	time	orders	items	packages	customers	products	price	weight
pick item	2019-12-26 12:04:46	991224}	{884803}	{}	{Wil van der Aalst}	{iPhone 8}	529.0	0.21
reorder item	2019-12-26 12:37:26	991271}	{885002}	{}	{Mohammadreza Fani Sani}	{Kindle Paperwhit	129.0	0.495
place order	2019-12-26 12:44:23	991283}	{885038,885039}	{}	{Luis Santos}	{MacBook Air,iPa	2700.0	1.733
pick item	2019-12-2014:01:16	991266}	{884983}	{}	{Marco Pegoraro}	{MacBook Air}	2200.0	1.25
create package	2019-12 26 1 :01:16	991265}	{884975,89 74 84 78, 84 71,384970,884973}	{660798}	{Seran Uysal}	{Fire Stick 4K, iPad Pro, iPad Pro, iPad Pro, are tip K dler	3506.97	112
send package	2019-12- <u>26 14</u> :16:11	991265}	{ 349 5, a. 74, 94978, 884971, 884970, 884973}	{660798}	{Seran Uysal}	{Fire Stick 4K, iPad Pro, iPad Pro, iPad Pro, Fire Stick, Kinese}	3506.97	2 12
pick i	2019-11 26 14:16:48	991279}	{< 5 ⁷ 7}		sCI ur a Graf	ATL 0. Stur	799.0	0 1.66
confirm	2019-11 20 14:26:01	991283} 💙	{885038,885039}	8	🤨 s 🐨 s	Macton Air,iPad}	2700.0	1 33
reord r item	2019-12	991251}	{884912}	{}	{Tobias Brockhoff}	{Fire Stick}	39.99	0.1
confirm order	2019-17	991282}	{885036,885037}	{}	{Lisa Mannel}	{Echo,Echo Dot}	134.98	1.16
pick item	2019-12 2 :33:28	991278}	{885024}	{}	{Junxiong Gao}	{MacBook Pro}	2500.0	1, ³ 7
place or .	2019-12 26-1 :48:33	991284}	{885040,8850,,381, 42,, 143,885044}	<u>{}</u>	{Christine Dobbert}	<pre>/iPhone X,Fire Stick,MacBook A, ,Euro 1 (0) 3, i</pre>	4222.98	2.19
failed delivery	2019-12-26-15:04:53	991240,99116	i 🚰 48 93 4501 84 3,004913,884876,884938,8 914, 49	(66 90)		ViPad Air, Echo Studio, Echo Studio, Kindle, Kindle, Echo, iP on ini, iPad Pro, iPad P	5982.95	7, 42
ріск іценн	2019-1. 7 1 :20:05	991278}	{ 5 0. 1	8		ne X}	699.0 📄	¹ 72
contaer	2019-12-26 15:25:00	991258}	{884938,884939,884940,884941,884942,884943}		Tob. rockh	,Fire Stick,iPad mini,iPad Pro,iPad Pro,iPad Air}	3267.9	2 C <mark>66</mark>
send ack ge	2019-11 2 1 :26:49	991247,99125	{884902,884922,884923,885004,885005,884901}	{660796	Mohammadreza Fani Sani}	{MacBook Air, iPad mini, iPad Pro, iPhone 11 Pro, iPad Pro, MacBook Pro}	8496.0	4.054
failed	2019-12-26-15:36:16	991265}	{884975,884974,884978,884971,884970,884973}	{660798}	{Seran Uysal}	{Fire Stick 4K, iPad Pro, iPad Pro, iPad Pro, Fire Stick, Kindle}	3506.97	2.4 <mark>12</mark>
confirmenter	2019-11 26 15:40:51	991274}	{885008,885009,885010,885011}	{}	{Junxiong Gao}	{Kindle, iPhone X, Fire Stick Phone 8}	1352.98	1
failed de linery	2019-11 20 15:46:21	991128,99125	{884424,88493; 38499; ,o 50 8,8 50 9; co5011, 84903}	{660797}	{Junxiong Gao}	{Echo Show 8,Kindle Paper, while, in a mini Kindle, iPhone X, iPhone 8, Echo Show	2145.97	
payment reminder	2019-12-20-13:54:44	991169	{ <u>54</u> 55 58456 15 68 45 ²¹	{}	{Gyunnim Park}	{iPhone 8,Echo Plus,iPa, Air,iPa 🐨 /i}	1608.99	1
pick item	2019 12 10 10:55:38	991201	84 17	0		{Echo Show 8}	129.99	1 8
pick item	2019-100:38	991251	{884912}	8	ob s	{Fire Stick}	39.99	0.2
reorder item	2019-12-26 16:04:42	991265	{884977}		{Seran Uysal}	{Fire Stick 4K}	89.99	0.28
payment reminder	2019-12-26 16:11:39	991164}	{884542,884543,884544,884545,884546,884547}	{}	{Junxiong Gao}	{Kindle Paperwhite, iPad Air, iPhone 11, MacBook Air, iPad mini, Ecno Dot}	4087.99	3.011
pick item	2019-12-26 16:22:04	991241}	{884882}	{}	{Lisa Mannel}	{iPhone 8}	529.0	0.21
create package	2019-12-26 16:22:04	991263,99126	{884967,884964,884966}	{660799}	{Luis Santos}	{iPad Air,iPhone 8,iPad}	1500.0	1.133

event = activity + timestamp + objects + attributes

See Wil van der Aalst: Object-Centric Process Mining: Dealing with Divergence and Convergence in Event Data. SEFM 2019, 3-25 https://doi.org/10.1007/978-3-030-30446-1_



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a "place order" event may refer to multiple items

the following assumption

a "failed delivery"

						a funca activity		
activity	time	order	items	packages	customers	event refers to one	price	weig
pick item	2019-12-26 12:04:46	991224}	{884803}	{}	{Wil van der Aalst}		529.0	0.21
reorder item	2019-12-26 12:37:26	991271}	\$85002}	{}	{Mohammadreza Fani Sani}	package, one or	129.0	0.495
place order	2019-12-26 12:44:23	991283}	{885038,885039}	{}	{Luis Santos}	paonago, ono or	2700.0	1.733
pick item	2019-12-2014:01:16	991266}	{884983}	{}	{Marco Pegoraro}	more items one or	2200.0	1.25
create package	2019-12 26 1 :01:16	991265}	{\$ 8 4975,884974,884978,884971,884970,884973}	{660798}	{Seran Uysal}		3506.97 🥖	112
send package	2019-12-26 14:16:11	991265}	84975,884974,884978,884971,884970,884973}	{660798}	{Seran Uysal}	moro ordore oto	3506.97	2 12
pick i	2019-11 26 14:16:48	991279	885027}	{}	{Claudia Graf}		799.0	0 1.66
confirm de	2019-11 20-14:26:01	991	{885038,885039}	{}	{Luis Santos}		2700.0	1 33
reord r ite n	2019-12		{884912}	{}	{Tobias Brockhoff}	{Fire	39.99	0.1
confirm order	2010-12 .22.		1995036,885037}	{}	{Lisa Mannel}	Ju	134.98	1.1 6
				{}	{Junxiong Gao}	K Pro}	2500.0	1.37
o línio	le itam?		885041,885042,885043,885044}	{}	{Christine Dobbert}	none X,Fire Stick,MacBook Air,Echo Show 8,iPhone 11 Pro}	4222.98	2.79
a più	кпет	ever	1 884561,884873,884913,884876,884938,884914,884941,	{660790}	{Tobias Brockhoff}	{iPad Air,Echo Studio,Echo Studio,Kindle,Kindle,Echo,iPad mini,iPad Pro,iPad P	5982.95	7, 42
				{}	{Junxiong Gao}	{iPhone X}	699.0	172
reter	s to one	e iten	384939,884940,884941,884942,884943}	{}	{Tobias Broom	{Echo,Fire Stick,iPad mini,iPad Pro,iPad Pro,iPad Air}	3267.9	2 66
			384922,884923,885004,885005,884901}	{660796}	{Mohanadreza Fani Sani}	{MacBook Air, iPad mini, iPad Pro, iPhone 11 Pro, iPad Pro, MacBook Pro}	8496.0 🐧	4.054
			,884974,884978,884971,884970,884973}	{660798}	{S an Uysal}	{Fire Stick 4K, iPad Pro, iPad Pro, iPad Pro, Fire Stick, Kindle}	3506.97	2.412
confirence	2019-11 26 15:40:51	991274}	{885008,885009,885010,885011}	{}	{Junxiong Gao}	{Kindle,iPhone X,Fire Stick,iPhone 8}	1352.98	1. J65
failed de linery	2019-11 20 15:46:21	991128,99125	{884424,884932,884999,885008,885009,885011,884903}	{660797}	{Junxiong Gao}	{Echo Show 8,Kindle Paperwhite,iPad mini,Kindle,iPhone X,iPhone 8,Echo Sho	2145.97	
payment reminder	2019-12-20-13:54:44	991169}	{884565,884566,884567,884568}	{}	{Gyunam Park}	{iPhone 8,Echo Plus,iPad Air,iPad mini}	1608.99	21
pick item	2019 12 10 10:55:38	991201}	{884717}	{}	{Seran Uysal}	{Echo Show 8}	129.99	0.8
pick item	2019-12 2013:00:38	991251}	{884912}	{}	{Tobias Brockhoff}	{Fire Stick}	39.99	0.2
reorder item	2019-12-26 16:04:42	991265}	{884977}		{Seran Uscal}	{Fire Stick 4K}	89.99	0.28
payment reminder	2019-12-26 16:11:39	991164}	{884542,884543,884544,884545,884546,884547}	1		{Kindle Paperwhite,iPad Air,iPhone 11,MacBook Air,iPad mini,Echo Dot}	4087.99	3.011
pick item	2019-12-26 16:22:04	991241}	{884882}	N	(Lis Mari)	{iPhone 8}	529.0	0.21
create package	2019-12-26 16:22:04	991263,99126	{884967,884964,884966}	{660799}	{L	{iPad Air,iPhone 8,iPad}	1500.0	1.133

Objects are typed and events may have any number of objects.



PVD) AVS

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How to load this in your favorite process mining tool ???

ity	time	orders	items	nackages	customers	products	nrice	weight
item	2019-12-26 12:04:46	991224}	{884803}	{} {}	{Wil van der Aalst}	{iPhone 8}	529.0	0.21
der item	2019-12-26 12:37:26	991271}	{885002}	0 {}	{Mohammadreza Fani San	{Kindle Paperwhite}	129.0	0.495
order	2019-12-26 12:44:23	991283}	{885038.885039}			MacBook Air.iPad}	2700.0	1.733
item	2019-12-2014:01:16	991266}	{884983}		W rco a weak	CBook Air}	2200.0	1.25
e package	2019-12 26 1 :01:16	991265}	{884975,884974,884978,884971,884970,884973}	{660798}	{Seratoysal}	{Fire Stick 4K, iPad Pro, iPad Pro, iPad Pro, Fire Stick, Kindle}	3506.97	112
package	2019-12- <u>26 14</u> :16:11	991265}	{884975,884974,884978,884971,884970,884973}	{660798}	{Seran Uysal}	{Fire Stick 4K, iPad Pro, iPad Pro, iPad Pro, Fire Stick, Kindle}	3506.97	2 12
	2019-11 26 14:16:48	991279}	{885027}	{}	{Claudia Graf}	{iPhone 11}	799.0	0 166
PPP Jub	2019-11 20 14:26:01	991283}	{885038,885039}	0	{Luis Santos}	{MacBook Air,iPad}	2700.0	1 33
r ite n	2019-11 :32:43	991251}	{884912}	{}	{Tobias Brockhoff}	{Fire Stick}	39.99 🔄	0.1
rm order	2019-17	991282}	{885036,885037}	{}	{Lisa Mannel}	{Echo,Echo Dot}	134.98	1.1 <mark>6</mark>
tem	2019-12 2019:33:28	991278}	{885024}	{}	{lunxiong Gao}	{MacBook Pro}	2500.0	1, 7
Oru	2019-12 26-1 :48:33	991284					4222.98	2.19
delivery	2019-12-26 15:04:53	991240					5982.95	- 42
item	2019-11 2 1 :20:05	991278					699.0 📄	72
er	2019-12-26 15:25:00	991258					3267.9	66
ack ze	2019-11 2 1 :26:49	99124					8496.0	4.054
d ery	2019-12-20 15:36:16	99126					3506.97	2.4 <mark>12</mark>
er	2019-11 26 15:40:51	991274					1352.98	1. 65
d de lin ery	2019-11 20 15:46:21	991128				ho Shor	2145.97	
nent reminder	2019-12-20 13:54:44	991169					1608.99	1
item	2019 12 10 10:55:38	99120:					129.99	2 8
item	2019-10 2019:00:38	99125:					39.99	0.2
der item	2019-12-26 16:04:42	99126					89.99	0.28
nent reminder	2019-12-26 16:11:39	991164}	{884542,884543,884544,884545,884546,884547}	{}	{Junxiong Gao}	{Kindle Paperwhite, iPad Air, iPhone 11, MacBook Air, iPad mini, Echo Dot}	4087.99	3.011
item	2019-12-26 16:22:04	991241}	{884882}	{}	{Lisa Mannel}	{iPhone 8}	529.0	0.21
e package	2019-12-26 16:22:04	991263,99126	{884967,884964,884966}	{660799}	{Luis Santos}	{iPad Air,iPhone 8,iPad}	1500.0	1.133



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activ pick reor plac pick crea send pick cont reor con pick plac faile pic con send faile con faile payı pick pick reor payı pick crea

Need to flatten the event data when using a conventional process mining technique

EVE: RWTHAACHEN

- Pick an object type as the case notion.
- Replicate each event for each object of the corresponding type.



Order as a case notion

activity	time	orders	items	packages
place order	2020-6-20	{99001}	{88001, 88002}	{}
pick item	2020-6-22	{99001}	{88001}	{ }
pick item	2020-6-23	{99001}	{88002}	{}
send package	2020-6-25	{99001, 99002}	{88002, 88003, 88004}	{66001}

Events may be duplicated

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activity	time	orders	items	packages
place order	2020-6-20	99001	{88001, 88002}	{}
pick item	2020-6-22	99001	{88001}	{}
pick item	2020-6-23	99001	{88002}	{}
send package	2020-6-25	99001	{88002, 88003, 88004}	{66001}
send package	2020-6-25	99002	{88002, 88003, 88004}	{66001}

Item as a case notion

activity	time	orders	items	packages
place order	2020-6-20	{99001}	{88001, 88002}	{}
pick item	2020-6-22	{99001}	{88001}	{ }
pick item	2020-6-23	{99001}	{88002}	{ }
send package	2020-6-25	{99001, 99002}	{88002, 88003, 88004}	{66001}

Events may be duplicated

\checkmark				
activity	time	orders	items	packages
place order	2020-6-20	{99001}	88001	{}
place order	2020-6-20	{99001}	88002	{}
pick item	2020-6-22	{99001}	88001	{ }
pick item	2020-6-23	{99001}	88002	{ }
send package	2020-6-25	{99001, 99002}	88002	{66001}
send package	2020-6-25	{99001, 99002}	88003	{66001}
send package	2020-6-25	{99001, 99002}	88004	{66001}



Package as a case notion

activity	time	orders	items	packages
place order	2020-6-20	{99001}	{88001, 88002}	{}
pick item	2020-6-22	{99001}	{88001}	{}
pick item	2020-6-23	{99001}	{88002}	{}
send package	2020-6-25	{99001, 99002}	{88002, 88003, 88004}	{66001}



activity	time	orders	items	packages
send package	2020-6-25	99002	{88002, 88003, 88004}	66001

Events may disappear



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Possible problems

- Deficiency: Events in the original event log that have no corresponding events in the flattened event log may unintentionally disappear from the data set.
- Convergence: Events referring to multiple objects of the selected type are replicated, possibly leading to unintentional duplication.
- Divergence: Events referring to different objects of a type not selected as the case notion are considered to be causally related.



See Wil van der Aalst: Object-Centric Process Mining: Dealing with Divergence and Convergence in Event Data. SEFM 2019, 3-25 https://doi.org/10.1007/978-3-030-30446-1_1

Convergence

Events referring to multiple objects of the selected type are replicated, possibly leading to unintentional duplication

activity	time	orders	items	packages
place order	2020-6-20	{99001}	{88001, 88002}	{}
pick item	2020-6-22	{99001}	{88001}	{ }
pick item	2020-6-23	{99001}	{88002}	{ }
send package	2020-6-25	{99001, 99002}	{88002, 88003, 88004}	{66001}

How to compute costs, times, frequencies, etc. when events are replicated?

activity	time	orders	items	packages
place order	2020-6-20	{99001}	88001	{ }
place order	2020-6-20	{99001}	88002	{}
pick item	2020-6-22	{99001}	88001	{ }
pick item	2020-6-23	{99001}	88002	{ }
send package	2020-6-25	{99001, 99002}	88002	{66001}
send package	2020-6-25	{99001, 99002}	88003	{66001}
send package	2020-6-25	{99001, 99002}	88004	{66001}

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Divergence

Events referring to different objects of a type not selected as the case notion are considered to be causally related

activity	time	orders	items	packages
place order	2020-6-20	{99001}	{88001, 88002, 88003}	{}
pick item	2020-6-22	{99001}	{88001}	{}
pick item	2020-6-23	{99001}	{88002}	{}
pack item	2020-6-22	{99001}	{88002}	{ }
pack item	2020-6-23	{99001}	{88001}	{}
pick item	2020-6-22	{99001}	{88003}	{ }
pack item	2020-6-23	{99001}	{88003}	{}



activity	time	orders	items	packages
place order	2020-6-20	99001	{88001, 88002, 88003}	{}
pick item	2020-6-22	99001	{88001}	{ }
pick item	2020-6-23	99001	{88002}	{ }
pack item	2020-6-22	99001	{88002}	{ }
pack item	2020-6-23	99001	{88001}	{ }
pick item	2020-6-22	99001	{88003}	{ }
pack item	2020-6-23	99001	{88003}	{ }

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pick item

Divergence

Events referring to different objects of a type not selected as the case notion are considered to be causally related

activity

. . .

time

. . .

place order	2020-6-20	99001	{88001, 88002, 88003}	{}
pick item	2020-6-22	99001	{88001}	()
pick item	2020-6-23	99001	{88002}	
pack item	2020-6-22	99001	{88002}	TF
pack item	2020-6-23	99001	{88001}	{}
pick item	2020-6-22	99001	{88003}	
pack item	2020-6-23	99001	{88003}	1)

. . .

orders

items

. . .



Things happen in a fixed

order but this is not visible!

pack item

packages

. . .

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Concurrency and causality!

Divergence

Events referring to different objects of a type not selected as the case notion are considered to be causally related

activity	time	orders	items	packages
place order	2020-6-20	99001	{88001, 88002, 88003}	{}
pick item	2020-6-22	99001	{88001}	{ }
pick item	2020-6-23	99001	{88002}	{ }
pack item	2020-6-22	99001	{88002}	{ }
pack item	2020-6-23	99001	{88001}	{ }
pick item	2020-6-22	99001	{88003}	{ }
pack item	2020-6-23	99001	{88003}	{ }





Very few relations are one-to-one!

Hence, a single case notion is not enough!

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Event Logs Tool Support

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The purpose of the **OCEL** standard is to provide a general standard to interchange object-centric event data with multiple case notions. We set the following goals for the standard:

- Interoperability: with the provision of the OCEL standard and JSON/XML serializations of OCEL, we want to support a widespread collection of languages and systems.
- Generalization: the standard supports the storage of events, objects, and their attributes. Furthermore, the standard can be extended.
- Provision of a collection of examples: example logs, extracted from information systems supporting some widespread business processes, are provided for the OCEL standard.
- Tool/Library Support: to support the implementation of OCEL in custom applications, tool/library support shall be provided.



<events>

<event>
<string key="id" value="e1"/>
<string key="activity" value="place_order"/>
<date key="timestamp" value="2020-07-09T08:20:01.527+01:00"/>
<list key="omap">
 <string key="object-id" value="i1"/>
 <string key="object-id" value="i1"/>
 <string key="object-id" value="i1"/>
 <string key="object-id" value="i2"/>
 <string key="object-id" value="i2"/>
 <string key="resource" value="Alessandro"/>
 <float key="prepaid-amount" value="200.0"/>
 </list>
</event>
<string key="id" value="e2"/>
 <string key="id" value="e2"/>
 <string key="id" value="e2"/>
 <string key="id" value="e2"/>
 <string key="imestamp" value="2020-07-09T08:21:01.527+01:00"/>

http://ocel-standard.org/

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PROCESS AND DATA SCIENCE GROUP RWTH AACHEN UNIVERSITY

OCEL Standard

Authors: Anahita Farhang Ghahfarokhi Gyunam Park Alessandro Berti Wil van der Aalst



January 8th, 2020

How to deal with this?

Directly extracting one or more conventional event logs (e.g. XES) realizing that there are may be convergence and divergence problems.

Extracting one object-centric event log and creating conventional event logs (e.g. XES) on demand.



Extracting one object-centric event log and using process mining techniques directly working on object-centric event logs.





Object-Centric Process Mining



and Data Science



991213,991206}



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Merge the different models using the original frequencies.



Chair of Process and Data Science

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Example for the object type item.





W.M.P. van der Aalst and A. Berti. Discovering Object-Centric Petri Nets. Fundamenta Informaticae, vol. 175, no. 1-4, pp. 1-40, 2020

88 automatically extract from Each row corresponds to an event which discovered objectdata sources refers to one activity and any number of objects of (possibly many) different types. centric Petri net m items (884994.884995.884996.884997.884998 2019-12-24 17:27:18 (991269) 0451 van der Aalsti Fire Stick 4K.Echo Show S.Echo Plus.iPad mini.Echo Show 8 913,96 1501 place order 3502 pick item 2019-12-24 17:33:55 [991261] (Christine Dobbert (Kindle Paperwhite) 129,00 13503 pick item 2019-12-24 17-5 Wil van der Aalst) (Fire Stick 4K) \$9,99 13504 pick item 2019-12-24 17 object-centric event log (Kefang Ding) (Fire Stick 4K) 89,99 0,28 13505 pay orde Mahaa Bafroni Echo Studio, Kindle, MacBook Pro, MacBook Air 4.984,98 4583,00 2019-12-24 18: 13505 pick item 2019.12.24 18-1 (Mahnez Qafari) (Kindle Panerashita) 179.00 0.50 13507 nick item 2010-12-24 10-10-52 (051102) (004672) (Chainting Dobber (Cebo Show 9) 170.00 0,98 0,78 5184,00 13508 pick item 2019-12-24 18:33:59 (991258) (884940) (Tobias Brockhoff) (inim beq) 449,00 (884956 884957 884958 884959 884960 884961 884962 (Kindle Paperwhite, Pad Xindle, Echo Show 5, Echo Show 5, Echo Studio, Ki, € 13509 pay order 2019-12-24 18:47:07 (991261) **Christine Dobberti** 1.168.95 13510 place order 2019-12-24 19:14:23 (991220) 454,00 0,28 {Junxiong Gao} (IPad mini) 3511 item out of s 2019-12-24 20:39:01 (991224) (884803 Wil van der Aalst) (IPhone 8) 529,00 2019-12-24 20:46:47 (991119,991030,991209,991254,991 IPad Air, Echo Dot, MacBook Pro, IPad Air, Kindle Pag 4719,00 3512 package de 9 (884886 884020 884749 884930 884926 88493 (Kefang Ding) 6.829,95 Mohammadreza Fani San 2019-12-24 22-08-21 (961271) (##5000 ##5001 ##5007 ##5002) (Fire Stick 4K, IPad, Kindle Paperwhite, IPad Air) 1.194.99 1698.00 2019-12-24 22-12-24 (981229) COMANYAL Tobia: Readbaff. 30.00 0.20 0,67 2019-12-25 08-08-00 (991272) (885004.885005 Mohammadreza Fani Sani liPhone 11 Pro. Pad Pro 2.253.00 0,67 1516 cor arm ord 2019-12-25 08:12:59 89912721 0885004.8850053 (Mohammadreza Fani Sani) **APhone 11 Pro. Pad Pro!** 2.253.00 2019-12-25 09:13:08 (991244) 324,97 2043,00 517 by order (884890,884891,88489) (Jurwing Gao) Kindle, Fire Stick 4K, Echo Plu 019-12-25 09:17:36 (991229) object-centric Petri net One of the 21887 events: activity: package delivered • time: 2019-12-24 20:46:47 magobj=6368 ba=255 nigobie1546 uniqobj=425 orders involved: {991119,991030,991209,991254, 991213.991206} items involved: {884386.884020.884749.884930. p=1296 r=0 p=7914 r=0 p=2165 r=0 c=2165 m=0 c=1296 m=0 c=7914 m=0 884926,884925,884766,884927,884736} packages involved: {660784} customers involved: {Kefang Ding} median=6 mean=6.1 1296 uniqobj=7914 uniqobj=1296 median=10h mean= products involved: {iPad Air.Echo Dot.MacBook median=1h mean=10h Pro, iPad Air, Kindle Paperwhite, iPad Air, iPad Pro, package delivered iPad, iPhone 11 Pro} total price: € 6.829,99 1296 total weight: 4,719 KG freq median=6 mean=6.11 niqobj=1296 296 uniqob = 7914 -7914 ---0

We got one step closer to data & reality!

and Data Science
Conclusion



Concurrency and Objects Matter to Realize the Dream of DTO





Process Mining Offers Many Scientific Challenges (that also matter in the real world)



- Finding, extracting, and transforming event data is still taking up to 80% of the time.
- 2 Most techniques focus on a single case notion (i.e., a single process), whereas problems may be caused by interacting or competing processes.
- Process discovery is not a solved problem despite powerful techniques like inductive mining. Concurrency is hard to discover from event data that provide only a sample.
 - There is a need to better integrate mining and modeling (e.g., user-guided discovery).
 - Conformance checking is time-consuming and diagnostics tend to be non-deterministic.
- 6 There is a need for techniques recommending process changes (i.e., moving beyond diagnostics).
 - Machine Learning (ML) techniques tend to perform poorly because essential aspects are missed (e.g., system load).
- 8 Process mining results need to trigger automated actions (e.g., start a corrective workflow).



