SAPIENZA
UNIVERSITÀ DI ROMA

UNITRENTO

FONDAZIONE
BRUNO KESSLER

Runtime Integration of Machine Learning and Simulation for Business Processes

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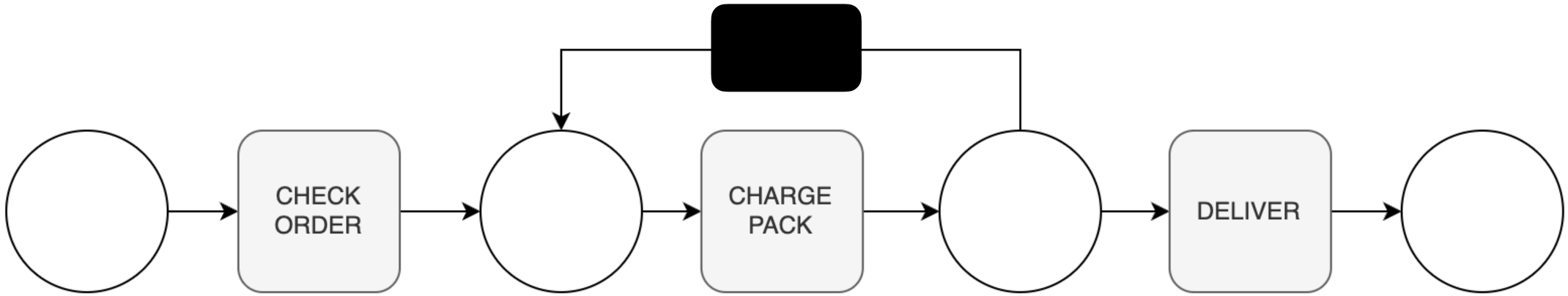
Chiara Ghidini, Fondazione Bruno Kessler, Trento, Italy

Context: Business Process Simulation

- Optimization
- What-if scenarios
- Analysis

- Monitoring
- Process improvement
- Redesign process

Typical Approach: BPSimulation model



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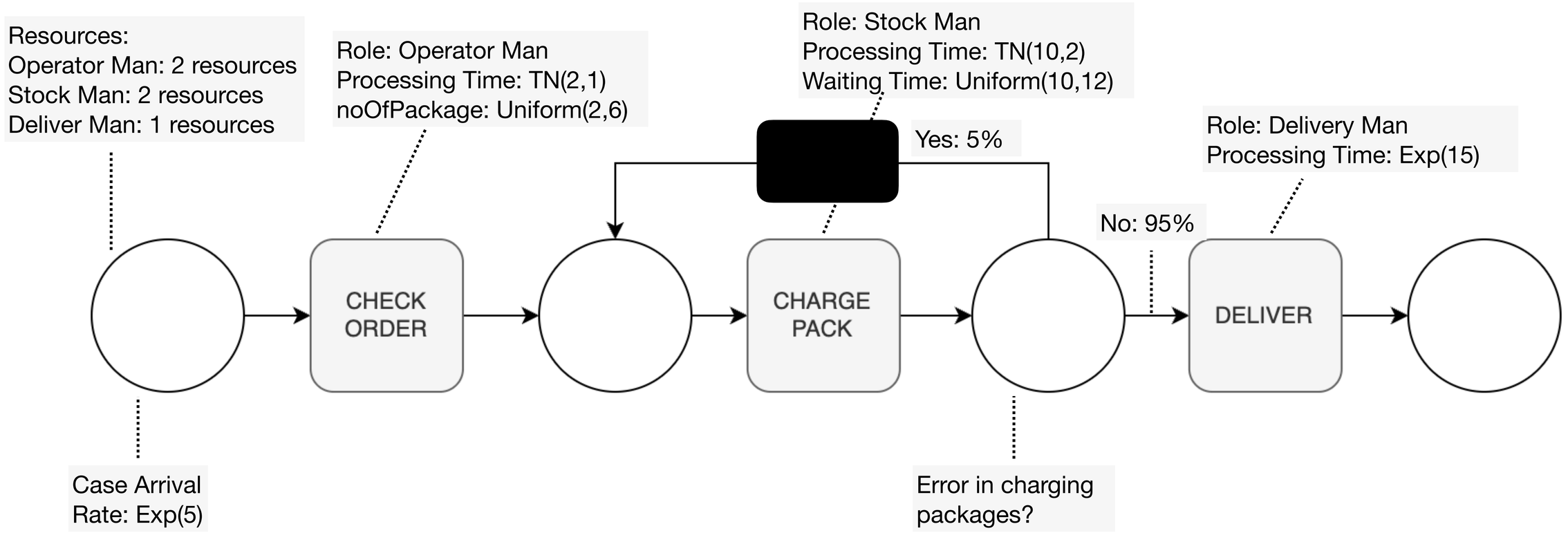

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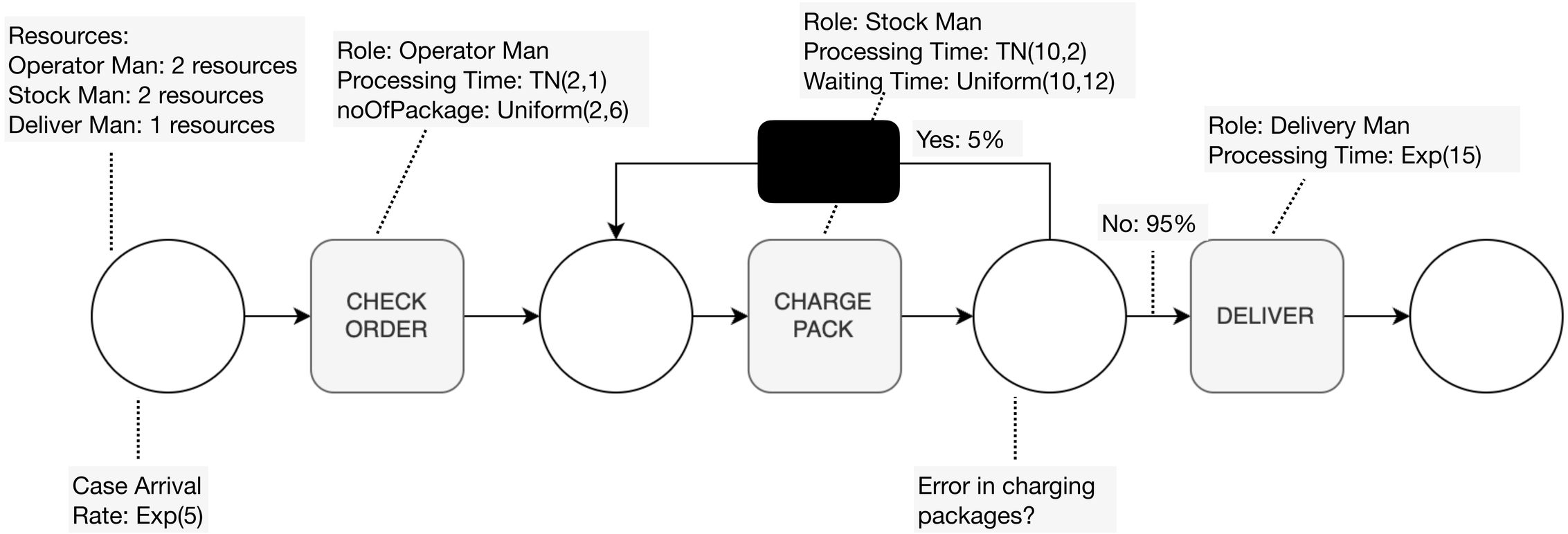
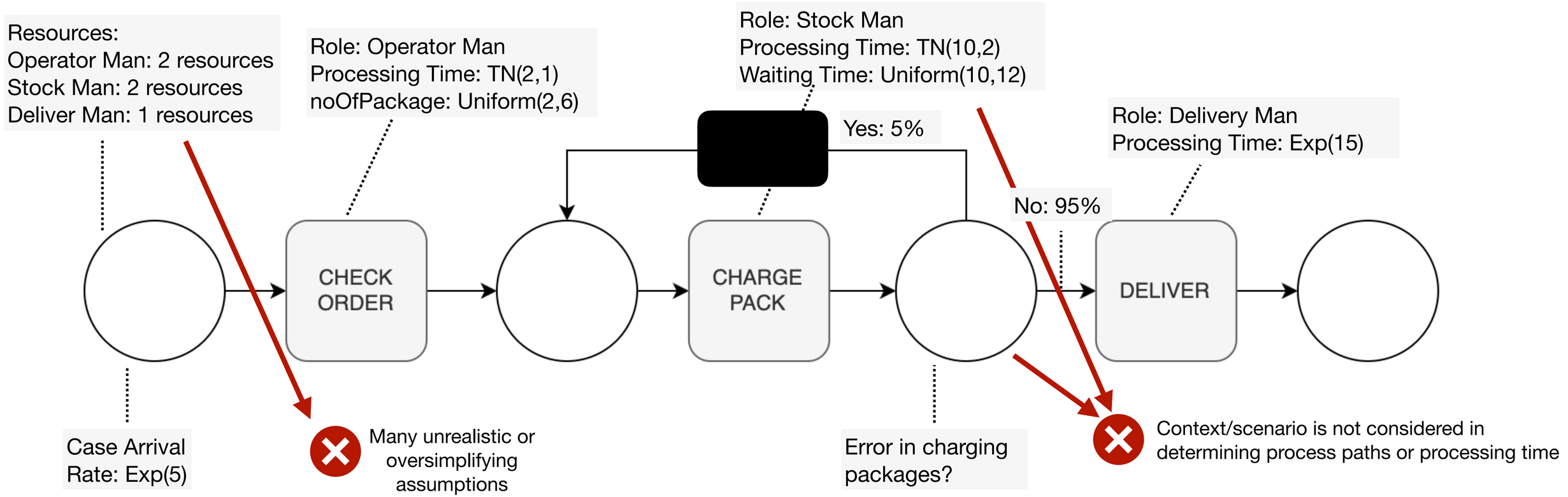


- Easy and intuitive for implementing what-if scenarios
- Leveraging Process Mining Techniques
- Monitoring the simulation

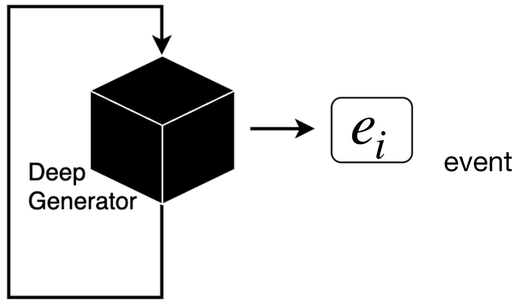
Typical Approach: BPSimulation model

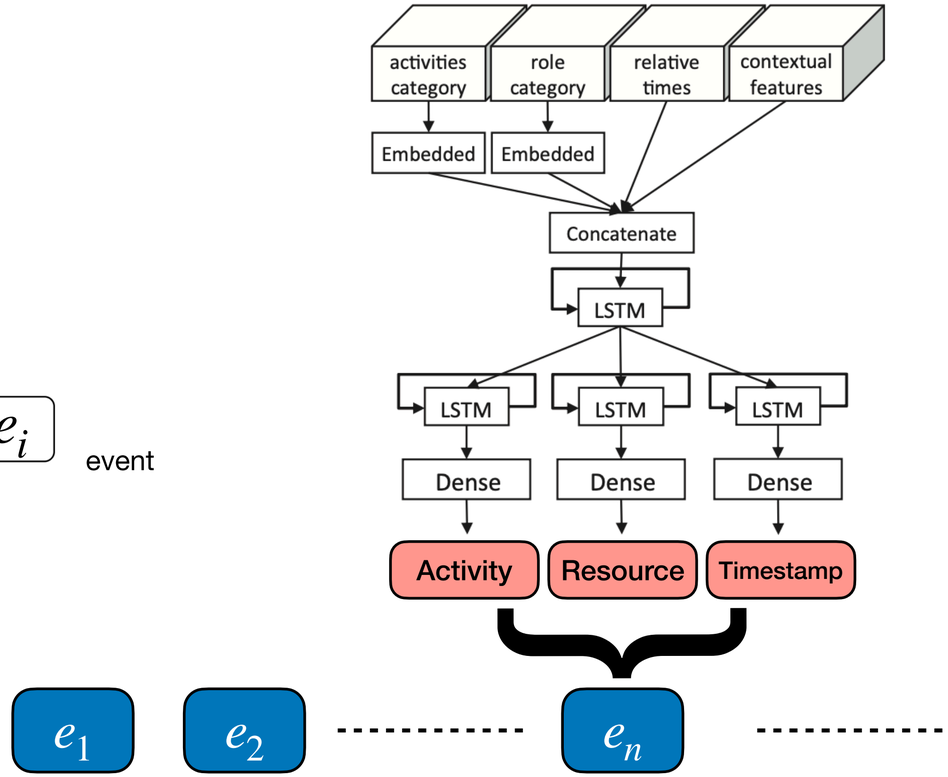


- Easy and intuitive for implementing what-if scenarios
- Leveraging Process Mining Techniques
- Monitoring the simulation

Alternative approach: Generative models

- LSTM networks used to predict the activity of the next event in a case, its timestamp, and the resource/role associated to the event
- The approach has the ability to generate complete sequences from scratch by repeatedly predicting the subsequent event.





1 Discovering generative models from event logs: data-driven simulation vs deep learning, Manuel Camargo, Marlon Dumas, Oscar González-Rojas. (PeerJ Computer Science 2021)

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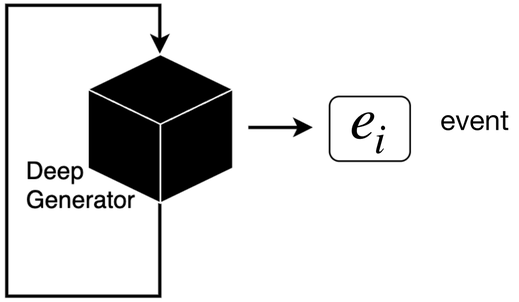

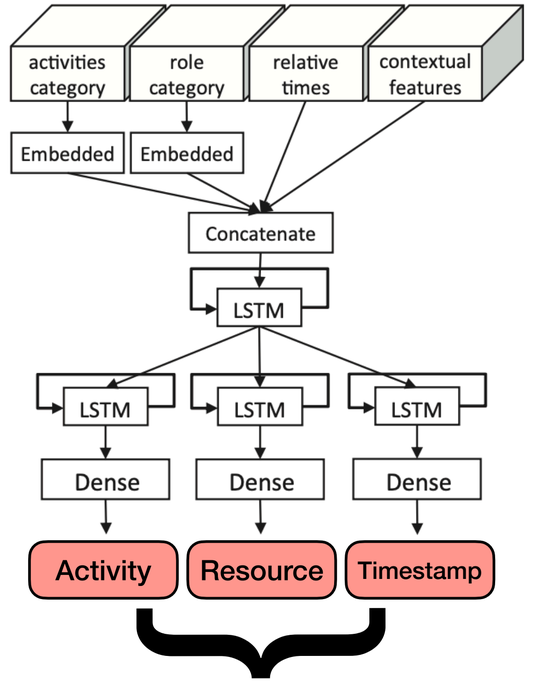

Able to consider the features of the context/ scenario for prediction

Not suitable for what-if scenarios

Not global view, only on the single trace

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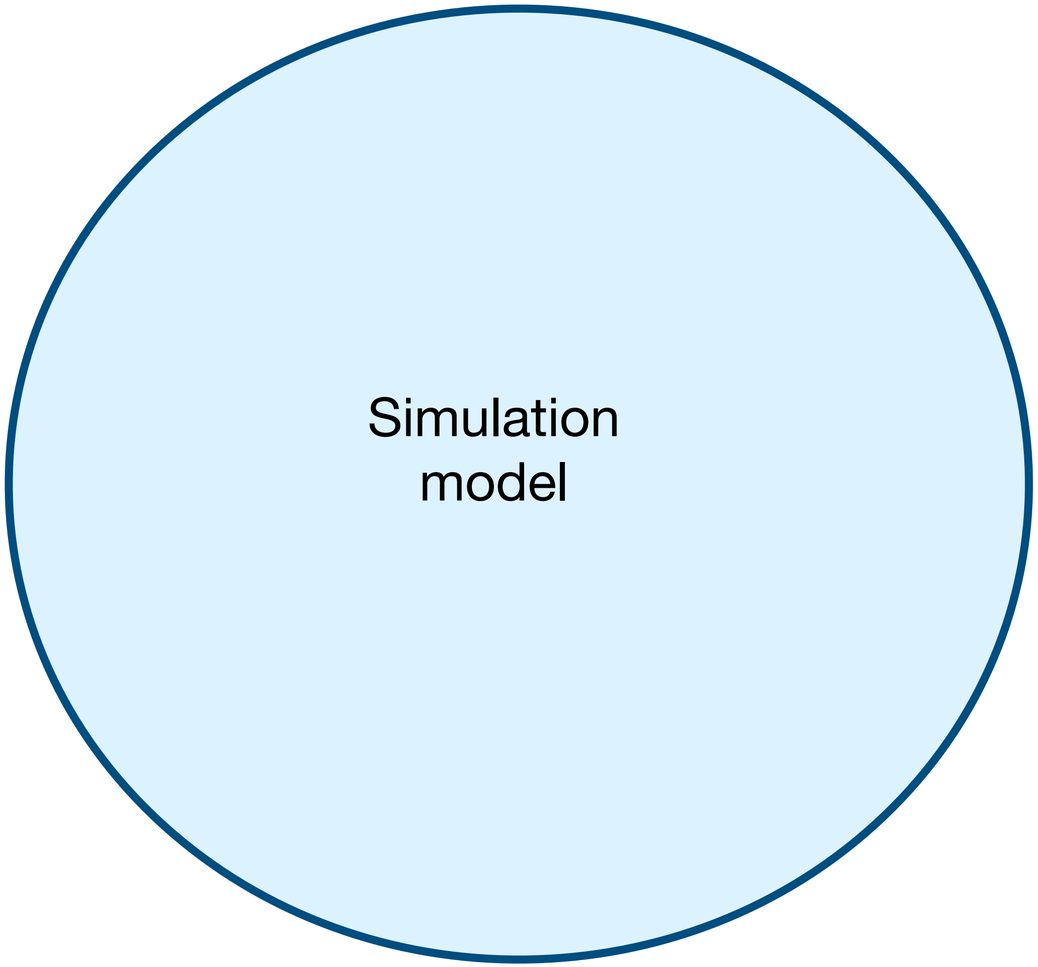
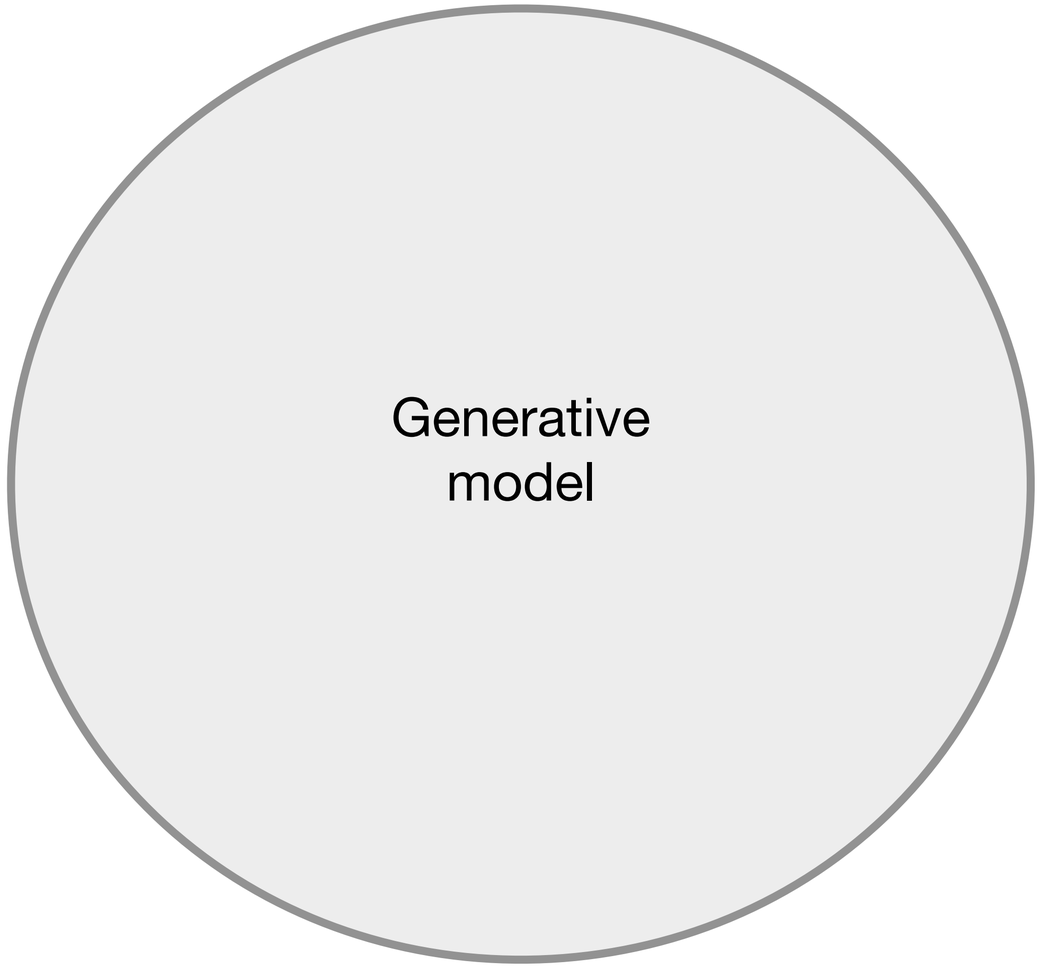
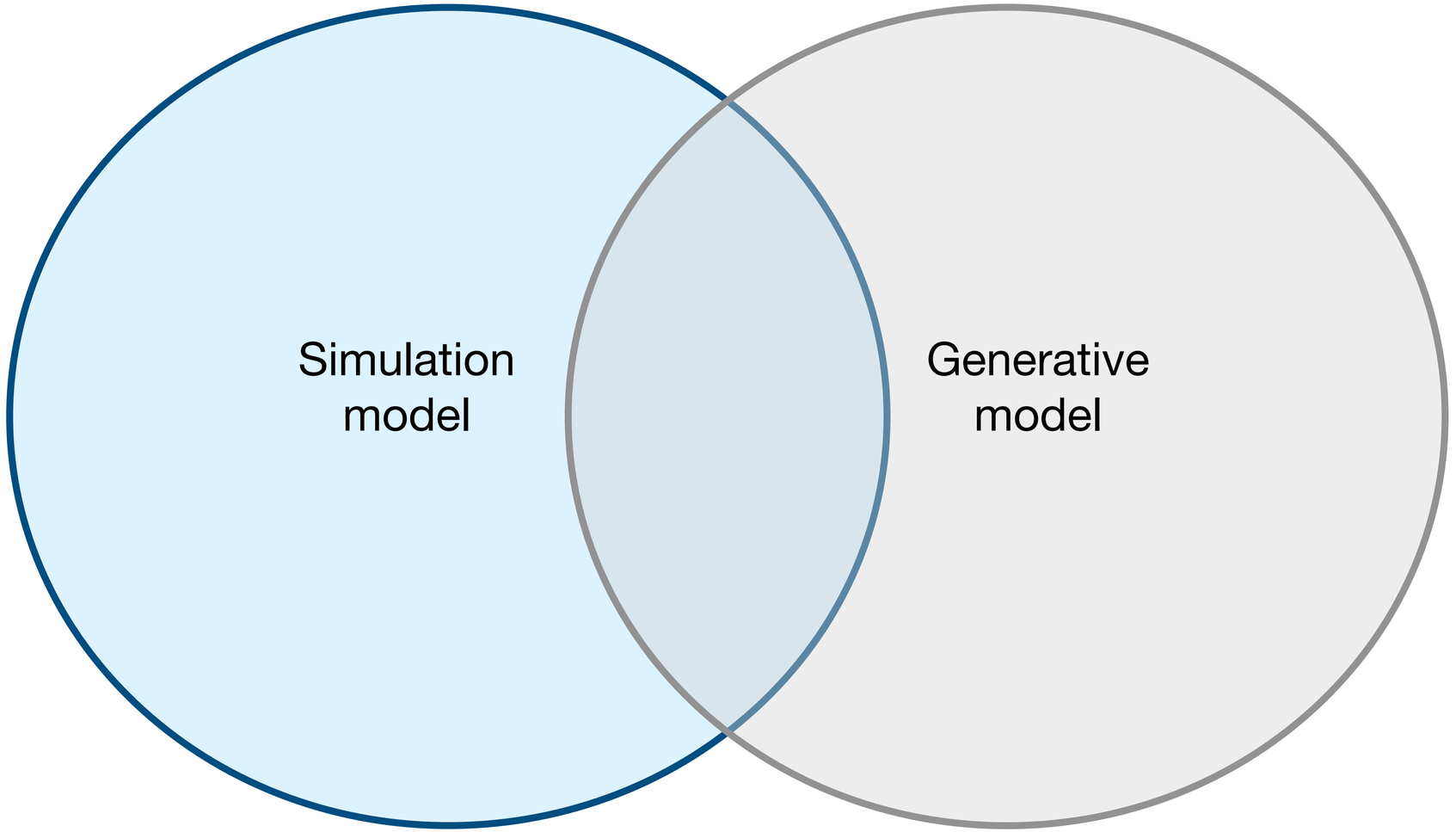
Hybrid Simulation: the Idea





Hybrid Simulation: the Idea



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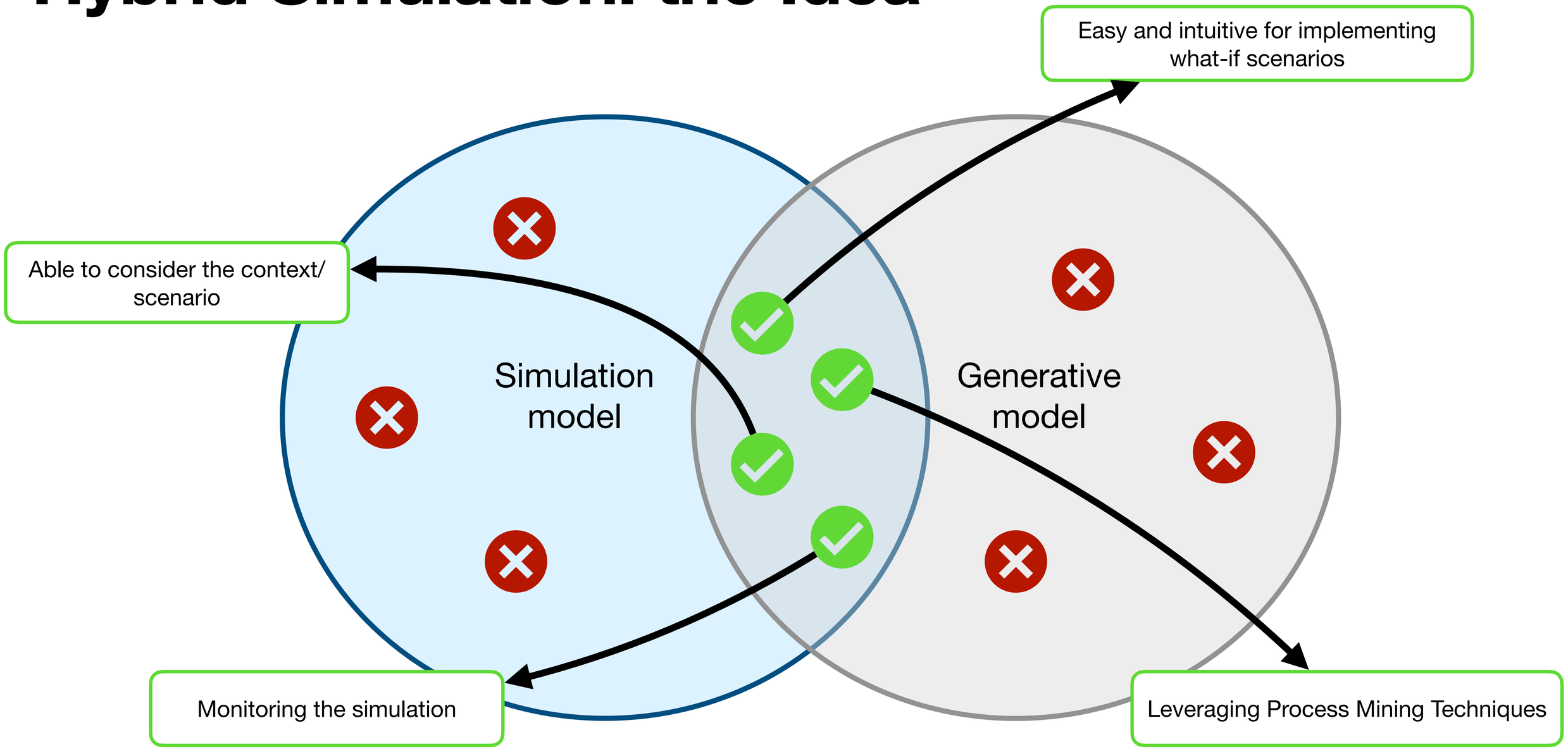
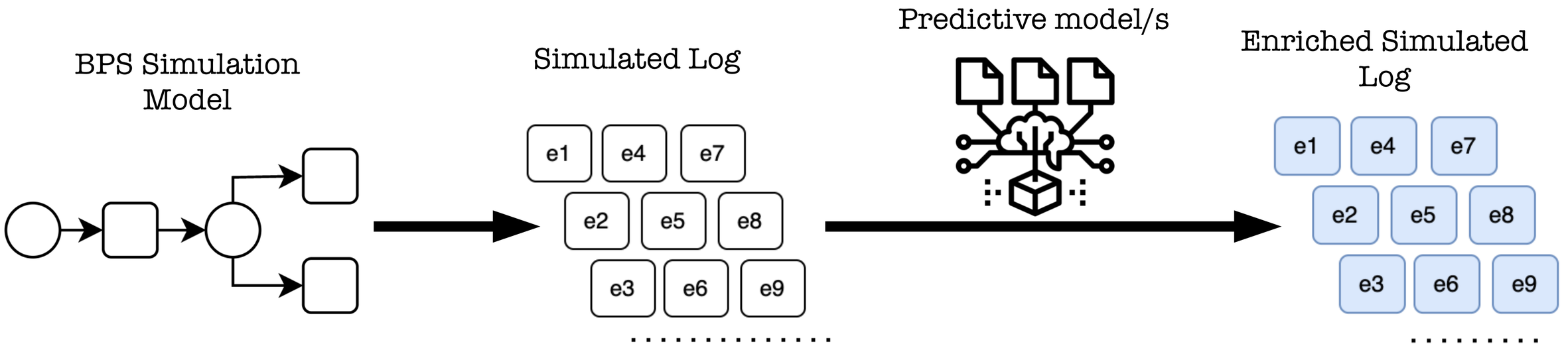


Hybrid Simulation: State of the Art



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Example of Post-integration

Example of Post-integration

Simulated Log

CHECK ORDER	CHARGE PACK	DELIVER	ID_Order: 1
CHECK ORDER	CHARGE PACK	DELIVER	ID_Order: 2

Example of Post-integration

Enriched Simulated Log

Simulated Log

CHECK ORDER	CHARGE PACK	DELIVER	ID_Order: 1
CHECK ORDER	CHARGE PACK	DELIVER	ID_Order: 2

Example of Post-integration

Simulated Log

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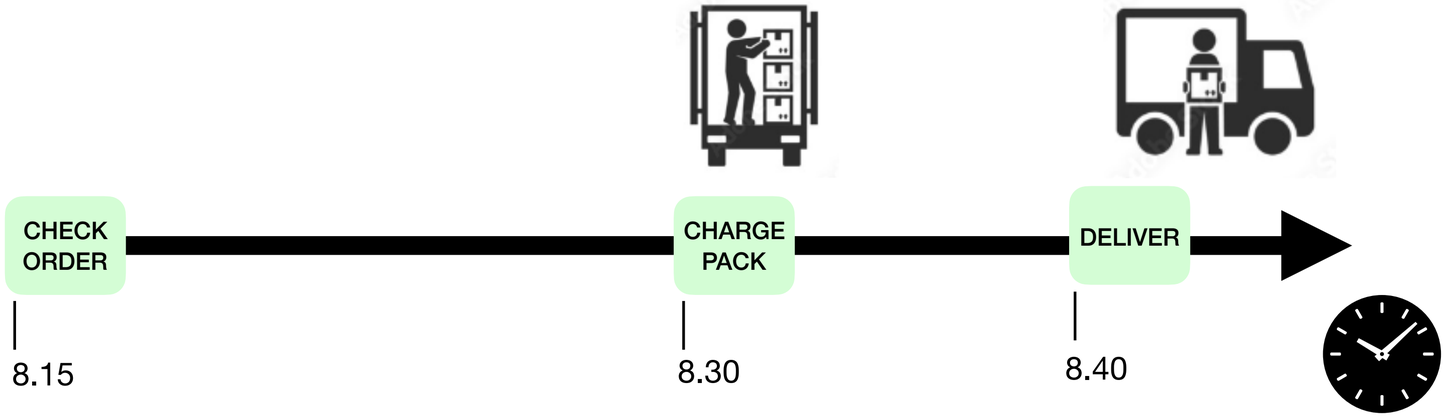

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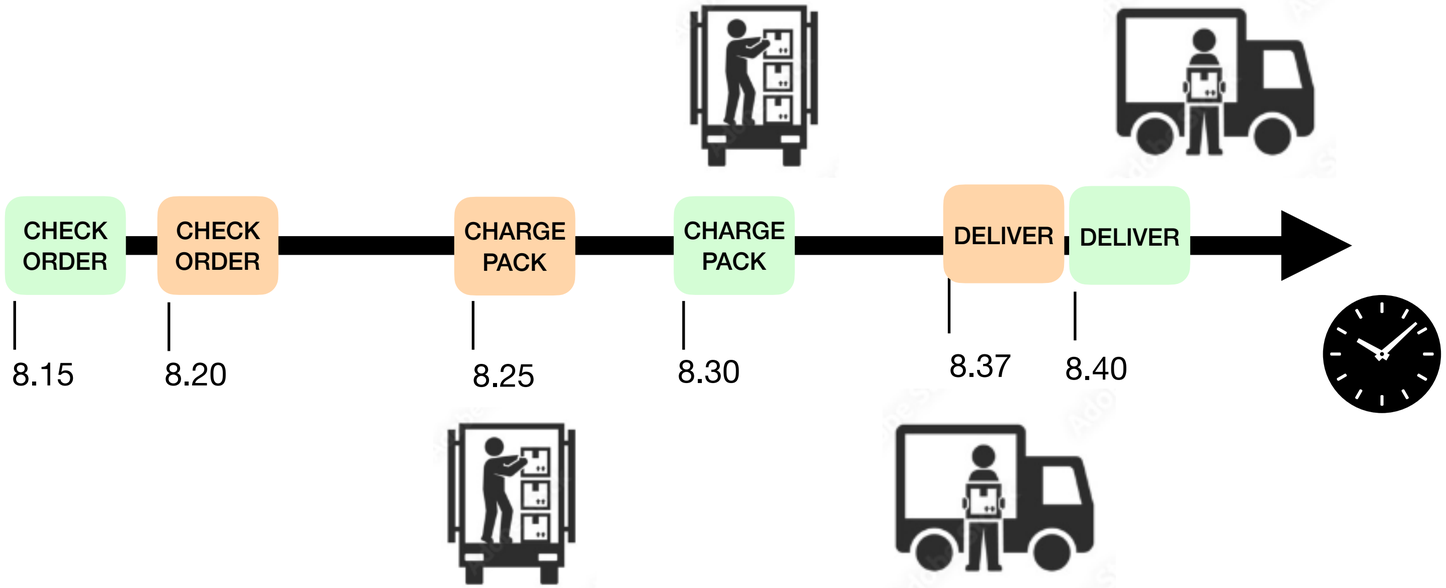

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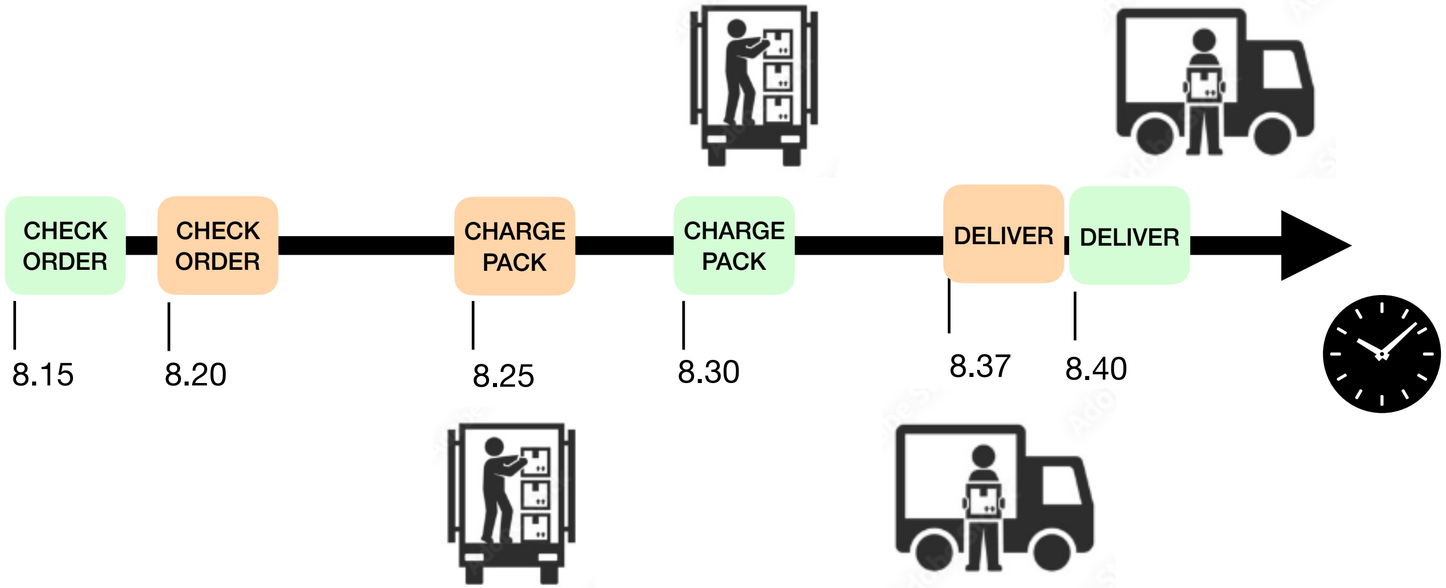
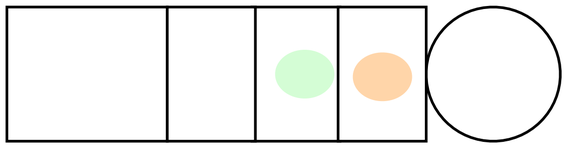


Resource Queue



1 Delivery Man

Problems with Post-integration

Simulated Log

CHECK ORDER | CHARGE PACK | DELIVER — ID_Order: 1

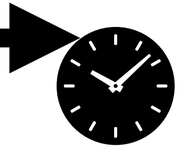
CHECK ORDER | CHARGE PACK | DELIVER — ID_Order: 2

Enriched Simulated Log

CHECK ORDER — 8.15

CHARGE PACK — 8.30

DELIVER — 8.40



Problems with Post-integration

Simulated Log

CHECK ORDER | CHARGE PACK | DELIVER — ID_Order: 1

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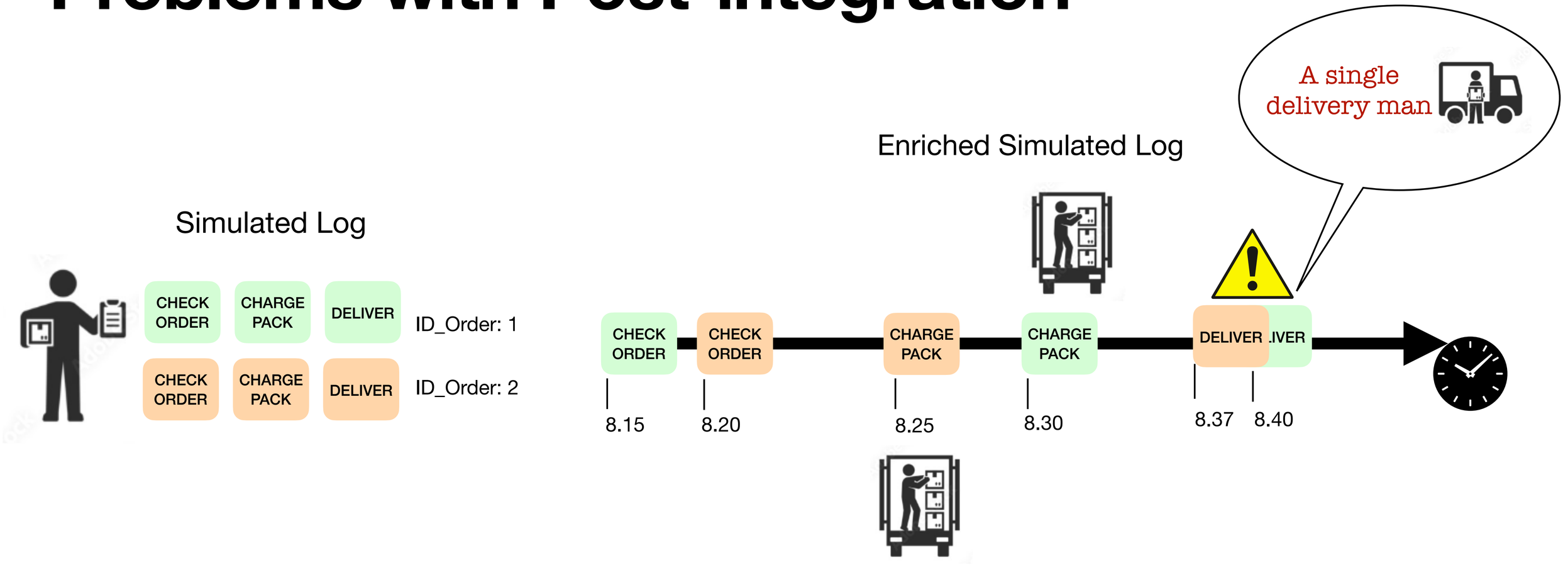
Enriched Simulated Log

CHECK ORDER (8.15) | CHECK ORDER (8.20) | CHARGE PACK (8.25) | CHARGE PACK (8.30) | DELIVER (8.37) | IVER (8.40)

Problems with Post-integration



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A single delivery man

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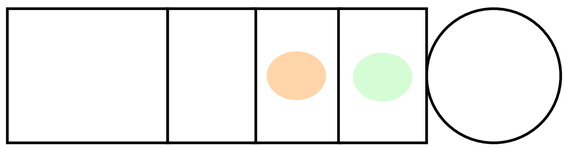
A single delivery man

Adapted Resource Queue



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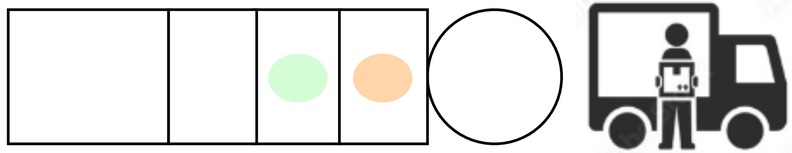
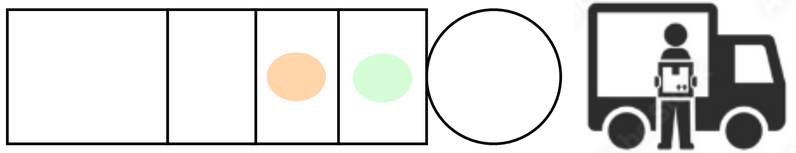
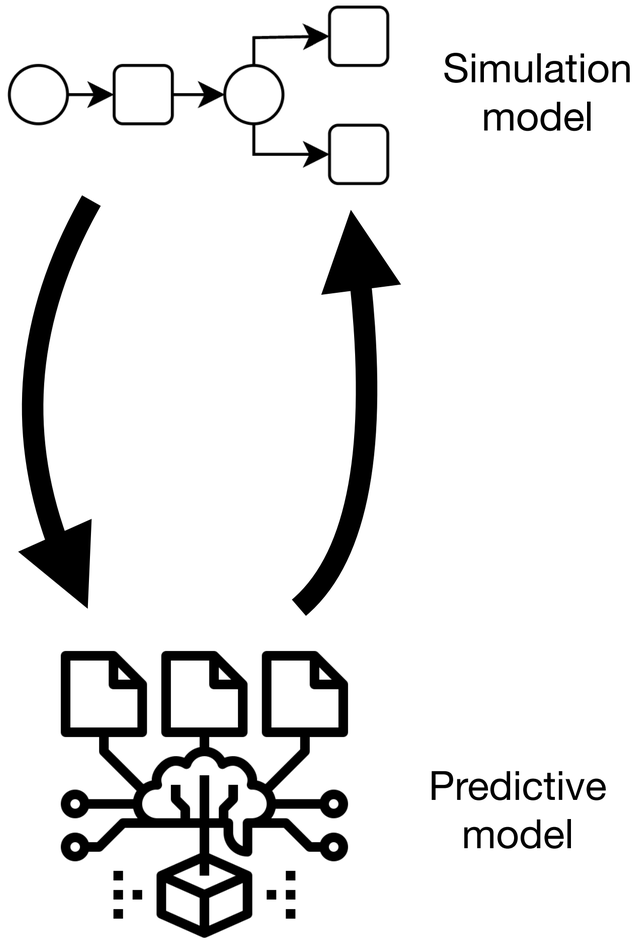
Predicted Resource Queue



Adapted Resource Queue



Our solution: Runtime-Integration



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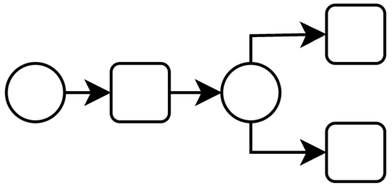
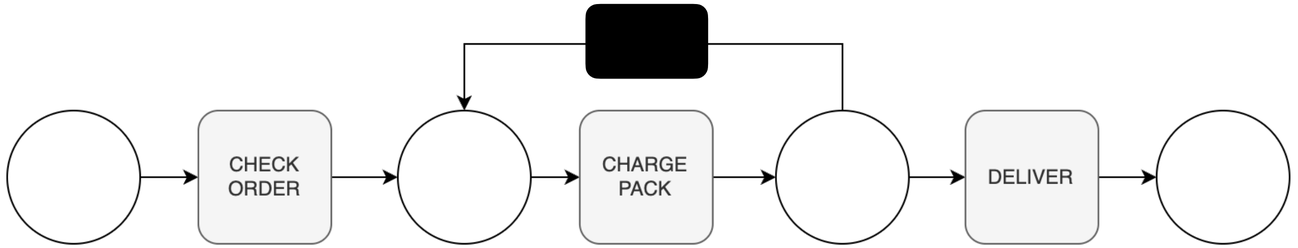
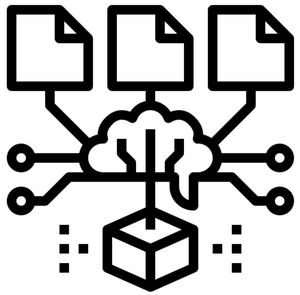


Simulation model





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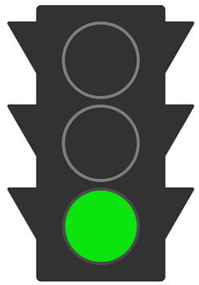
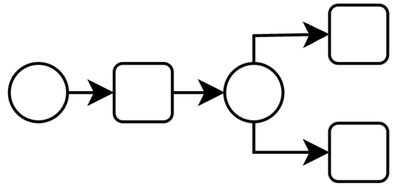
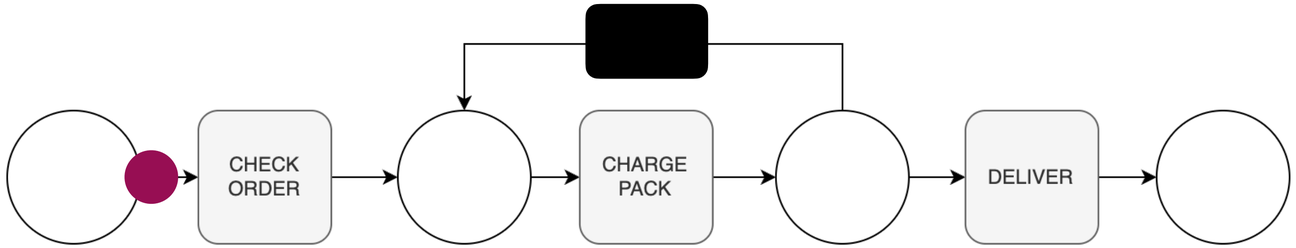
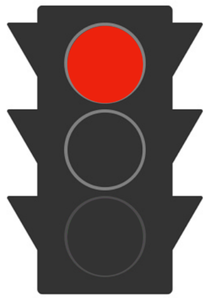
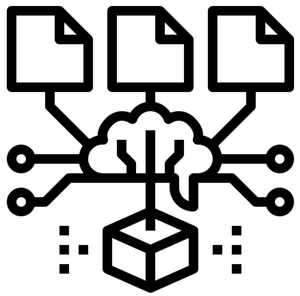




Simulation model







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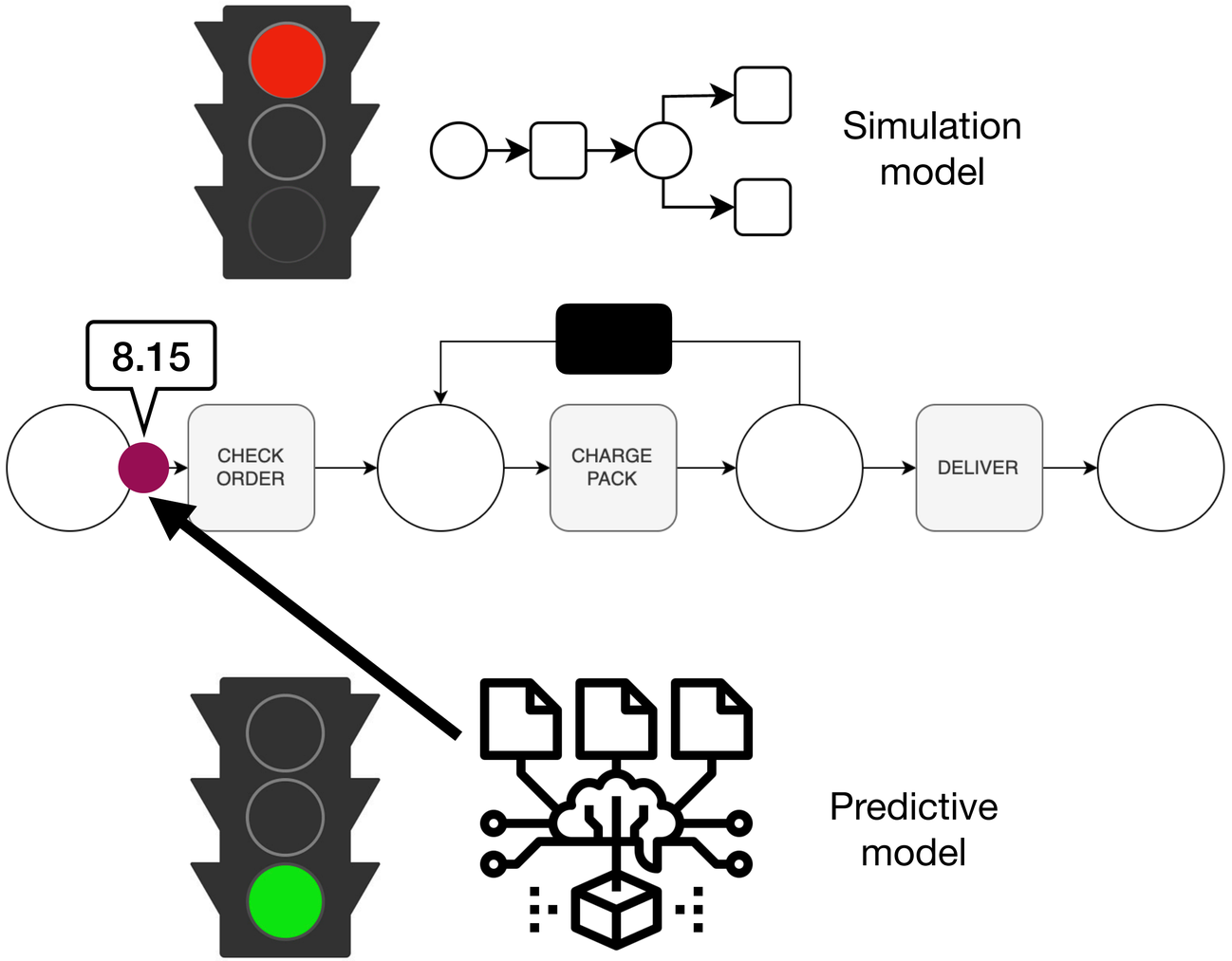

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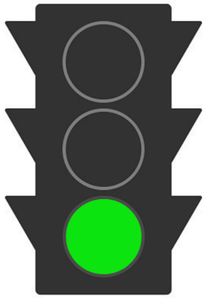

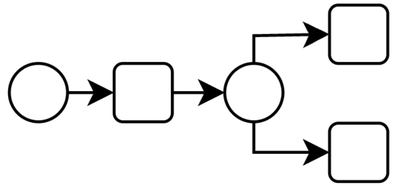

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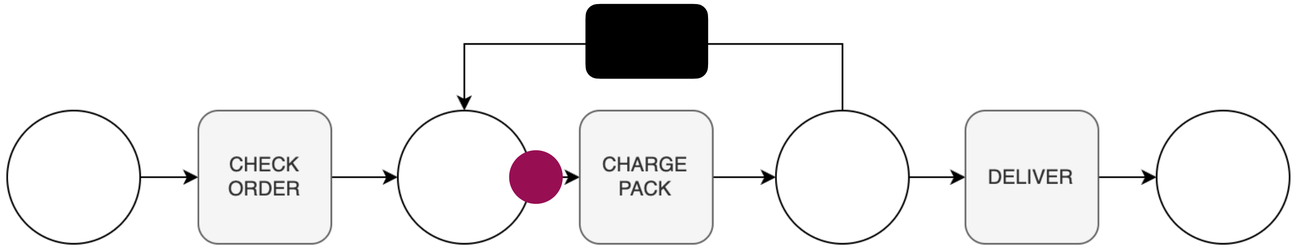

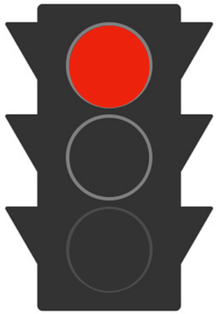

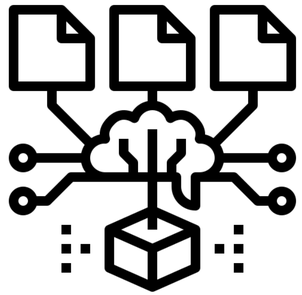

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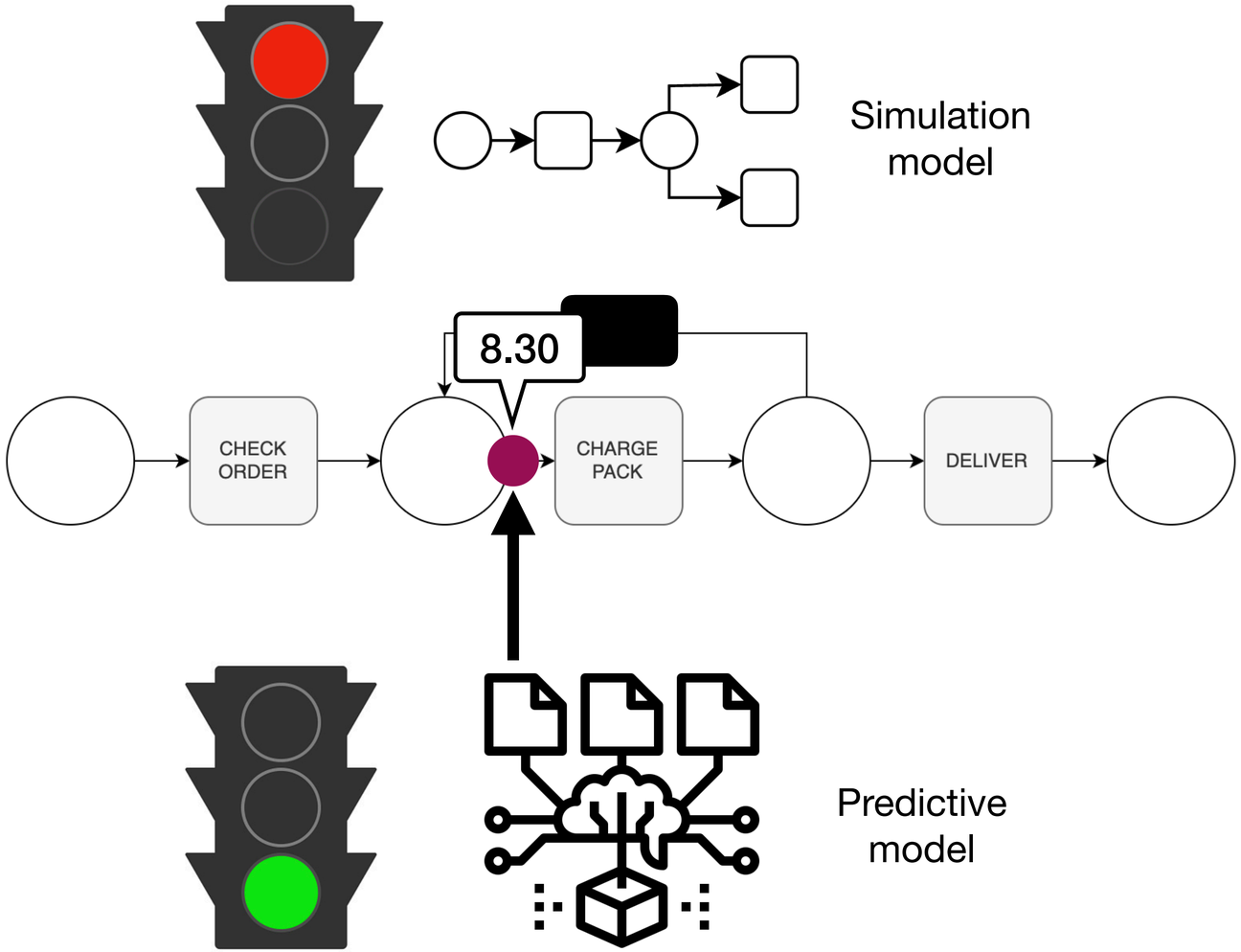
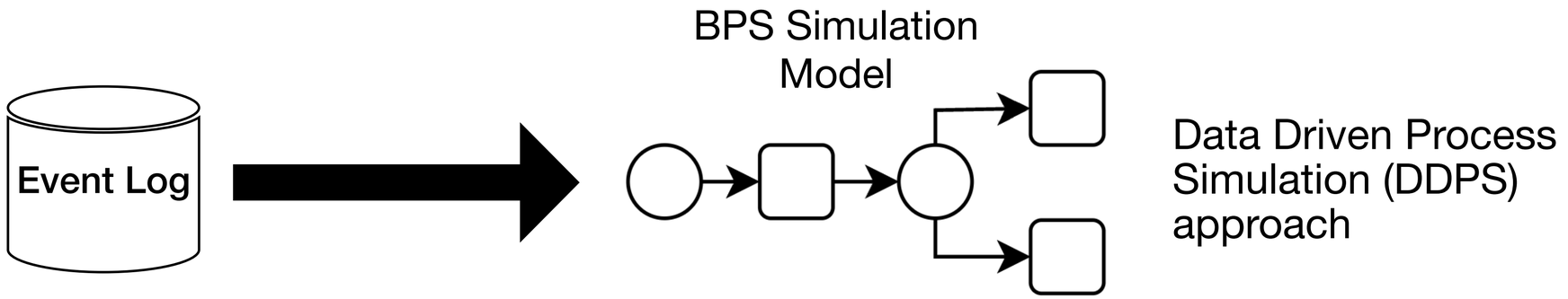
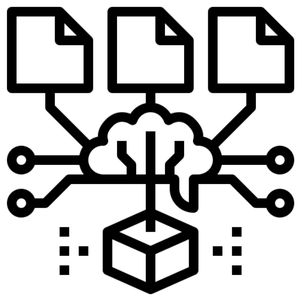


RIMS: Runtime Integration of Machine Learning and Simulation for Business Processes

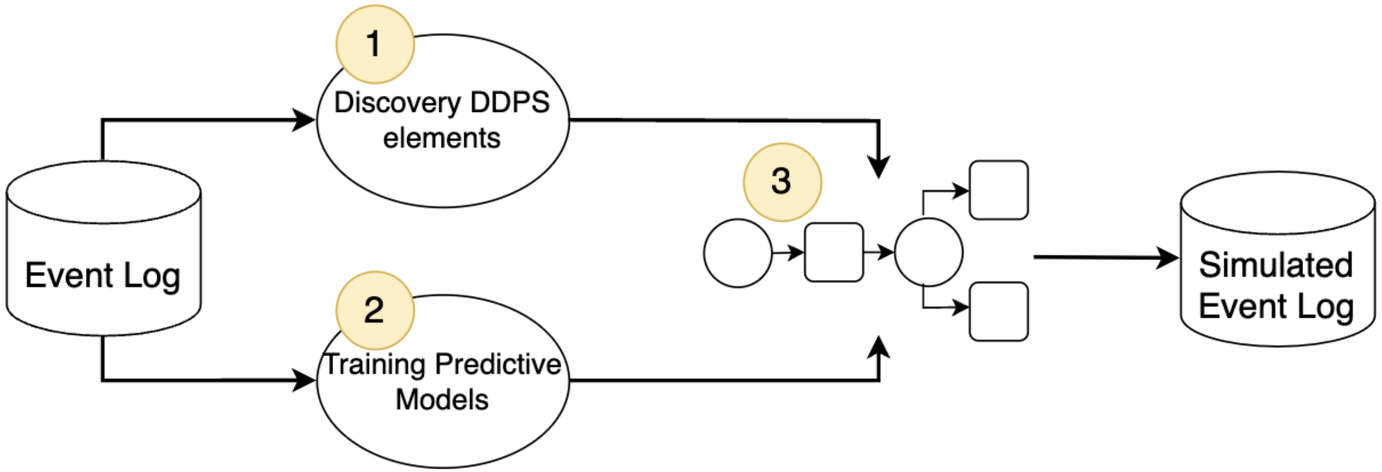


Data Driven Process Simulation (DDPS) approach



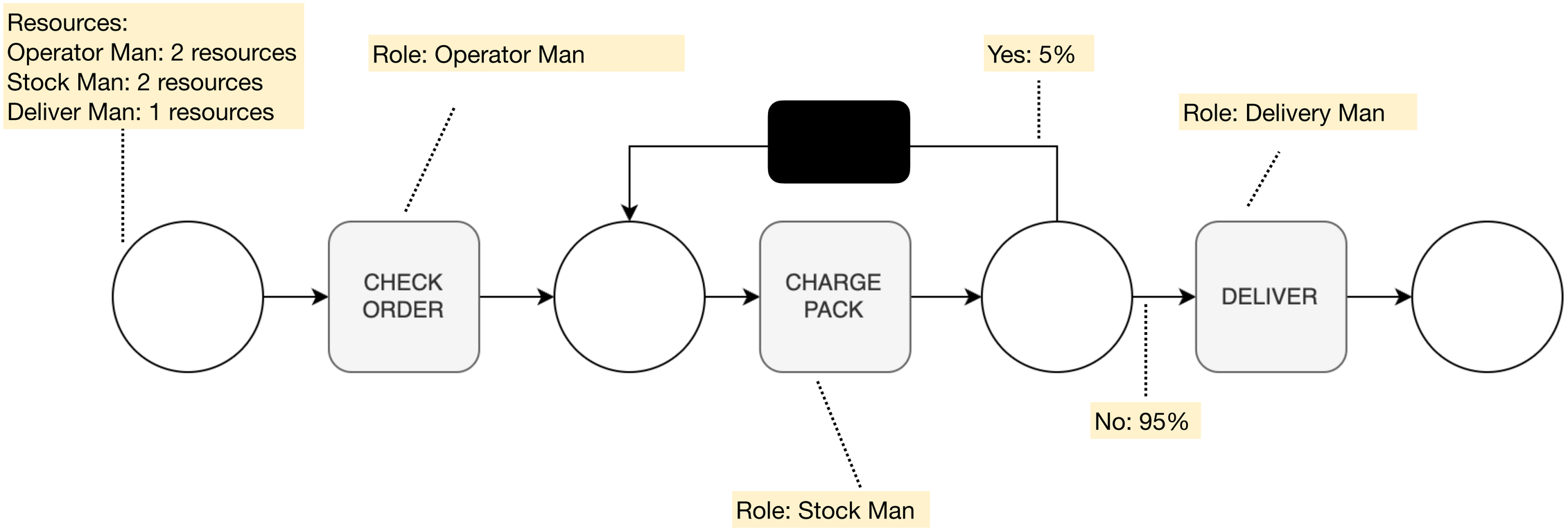
Predictive models for time perspective

RIMS receipt



1. Definition of the DDPS elements
2. Training of the predictive models
3. Integration and run simulation

1 Definition of the DDPS elements



2 Training predictive models

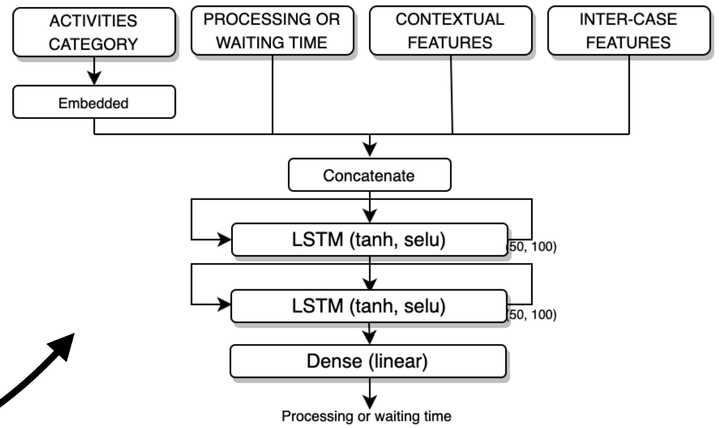
1 Time series to predict the trace start times

2 Predictive model for Waiting time:

1) Next activity
2) End timestamp of the current activity
3) Intercase features: WIP(work-in-progress) and resources' occupation

3 Predictive model for Processing Time:

1) Current activity
2) Start timestamp of the current activity
3) Intercase features: WIP(work-in-progress) and resources' occupation



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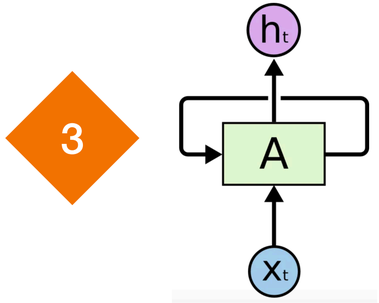
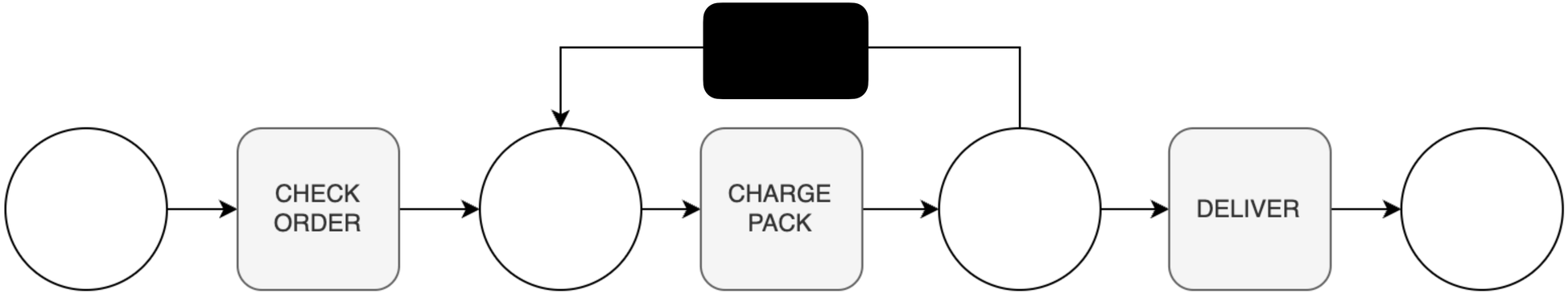
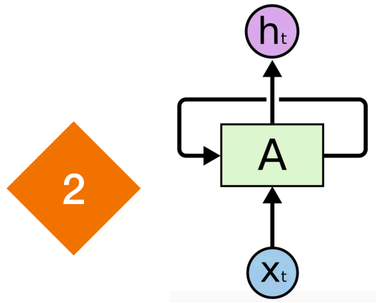
3 Integration and run simulation



Predict Processing time

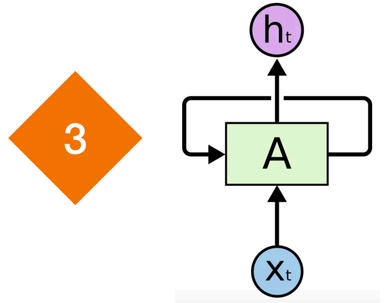


Predict new arrival



Predict Waiting time

3 Integration and run simulation



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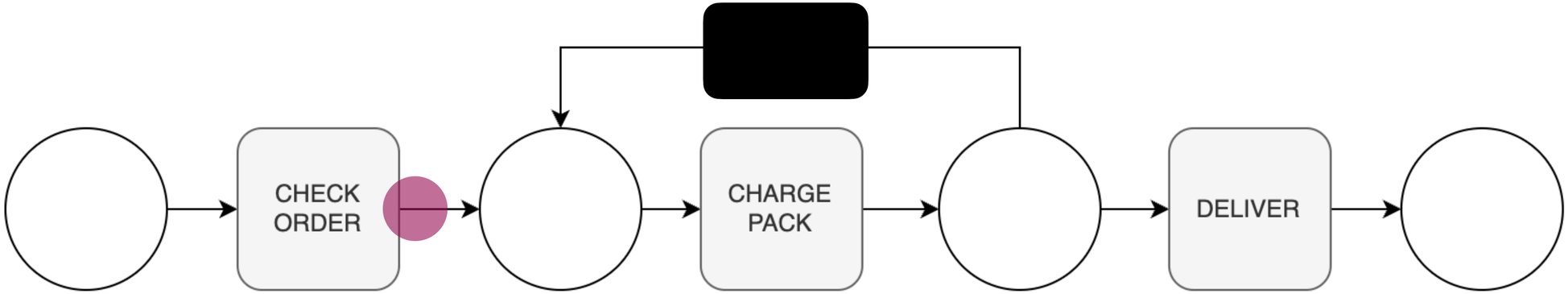

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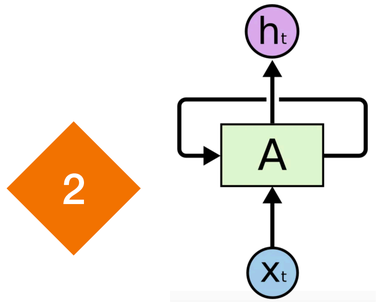
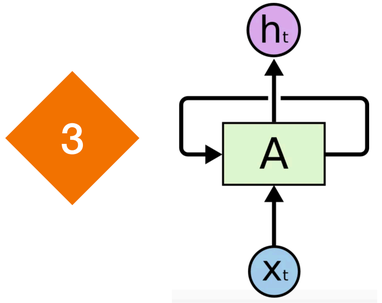
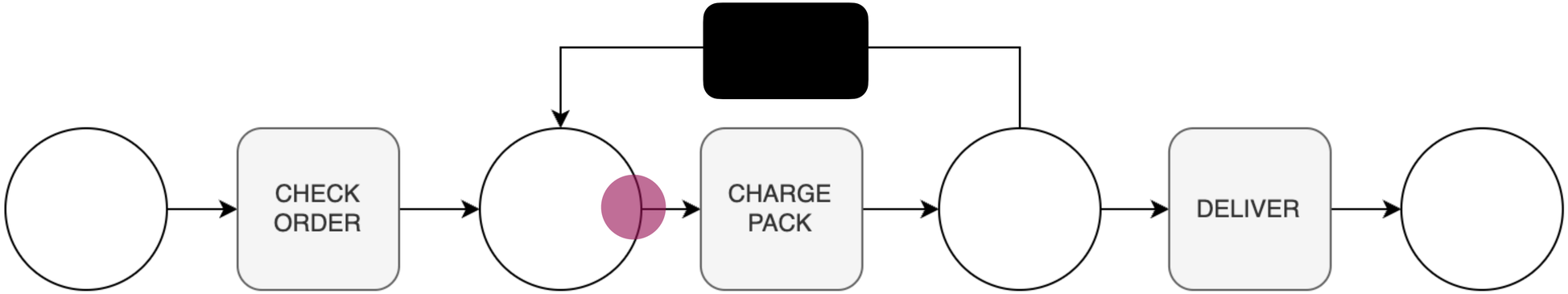


Predict Waiting time

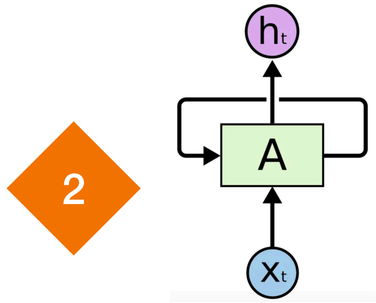
3 Integration and run simulation



Predict Processing time

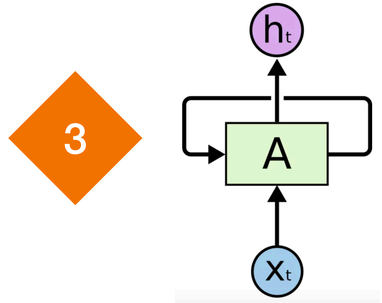


Predict new arrival

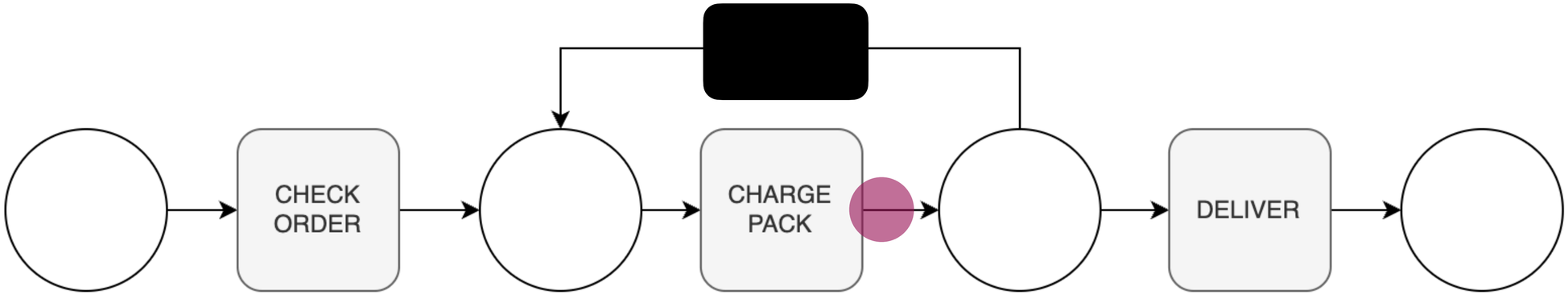


Predict Waiting time

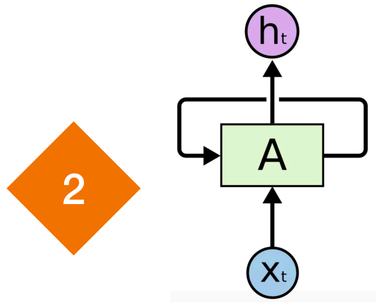
3 Integration and run simulation



Predict Processing time

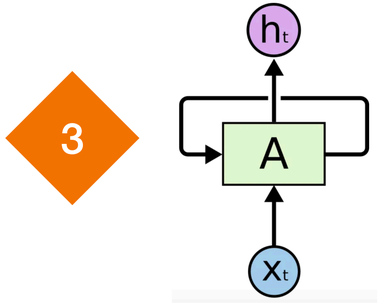


Predict new arrival

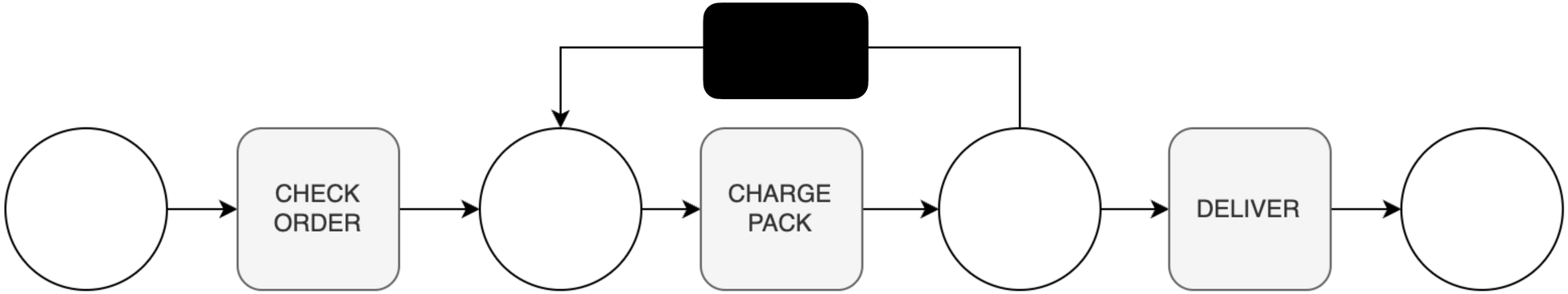


Predict Waiting time

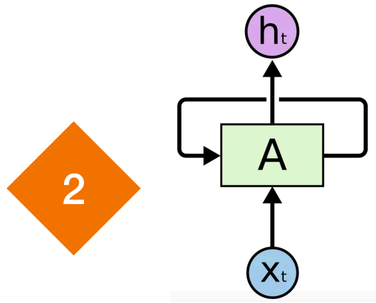
3 Integration and run simulation



Predict Processing time



Predict new arrival



Predict Waiting time

How does RIMS perform in terms of simulation quality compared to other techniques?

Simulation Model

Generative Model

Post-Integration approach

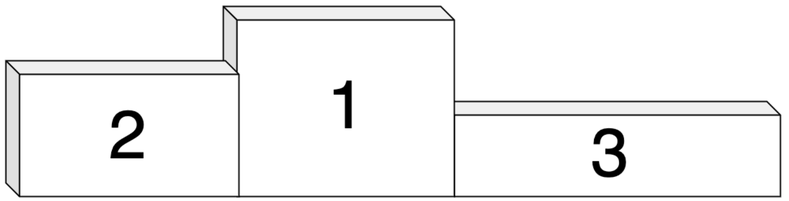
?

DDPS

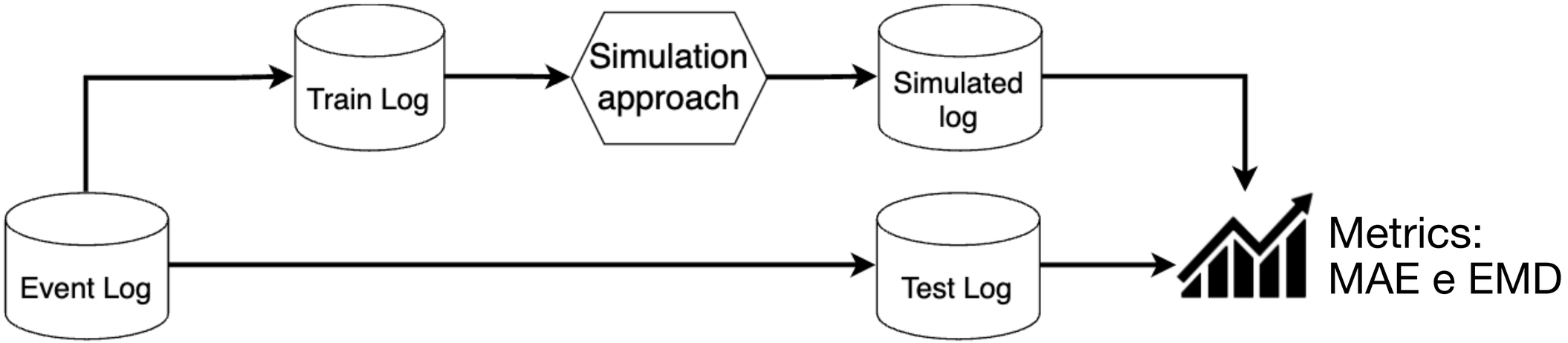
LSTM

DSim

RIMS



Evaluation: Procedure



- 25 simulations for each simulation approach
- MAE (Mean Absolute Error) of cycle times
- EMD (Earth Mover's Distance) of the normalized histograms of activity timestamps grouped by day and hour

Evaluation: Datasets

Log	Type	#Traces	#Events	#Activity	Avg. Trace length
Confidential1000	Syn	800	21221	29	26.53
Confidential2000	Syn	1670	44373	29	26.57
Cvs Pharmacy	Syn	10000	103906	15	10.39
Purchasing Example	Syn	608	9119	21	15
SynLoan	Syn	2000	43164	25	39
Production	Real	225	4503	24	20
ConsultaDataMining	Real	954	4962	16	5.2
BPI12W	Real	8616	59302	6	6.88
BPI17W	Real	30276	240854	8	7.96

Evaluation RIMS: MAE metric

	DDPS			LSTM			Dsim			RIMS		
	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u
Confidential 1000	55477	51509	59444	32754	32377	33132	36337	35796	36878	**26950**	**25683**	**28217**
Confidential 2000	234520	179570	289471	37344	37063	37625	8095	7309	8882	**7385**	6381	8390
Cvs Pharmacy	1061957	1061300	1062613	638665	637616	639714	137636	136104	139168	**102950**	**101130**	**104771**
PurchasingExample	2127361	2109665	2145058	2299619	2294319	2304919	2280717	2273954	2287481	**2104676**	2082360	2126992
SynLoan	2295797	2295579	2296015	1446177	1446177	1463812	1675036	1635297	1714775	**1278782**	**1271133**	**1286430**
Production	312153	307036	317270	128942	117516	140368	**83700**	73572	93828	105988	91713	120264
ConsultaDataMining	274786	271536	278035	343520	343422	343618	230921	228349	233494	**155994**	**141180**	**170707**
BPI12W	667139	665889	668389	**316642**	**309766**	**323517**	597090	594860	599320	555094	550135	560052
BPI17W	952502	949997	955007	757742	653898	861585	417641	416631	418650	**393749**	**391442**	**396056**

Evaluation RIMS: MAE metric

	DDPS			LSTM			Dsim			RIMS		
	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u
Confidential 1000	55477	51509	59444	32754	32377	33132	36337	35796	36878	**26950**	**25683**	**28217**
Confidential 2000	234520	179570	289471	37344	37063	37625	8095	7309	8882	**7385**	6381	8390
Cvs Pharmacy	1061957	1061300	1062613	638665	637616	639714	137636	136104	139168	**102950**	**101130**	**104771**
PurchasingExample	2127361	2109665	2145058	2299619	2294319	2304919	2280717	2273954	2287481	**2104676**	2082360	2126992
SynLoan	2295797	2295579	2296015	1446177	1446177	1463812	1675036	1635297	1714775	**1278782**	**1271133**	**1286430**
Production	312153	307036	317270	128942	117516	140368	**83700**	73572	93828	105988	91713	120264
ConsultaDataMining	274786	271536	278035	343520	343422	343618	230921	228349	233494	**155994**	**141180**	**170707**
BPI12W	667139	665889	668389	**316642**	**309766**	**323517**	597090	594860	599320	555094	550135	560052
BPI17W	952502	949997	955007	757742	653898	861585	417641	416631	418650	**393749**	**391442**	**396056**

Evaluation RIMS: MAE metric

	DDPS			LSTM			Dsim			RIMS		
	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u
Confidential 1000	55477	51509	59444	32754	32377	33132	36337	35796	36878	**26950**	**25683**	**28217**
Confidential 2000	234520	179570	289471	37344	37063	37625	8095	7309	8882	**7385**	6381	8390
Cvs Pharmacy	1061957	1061300	1062613	638665	637616	639714	137636	136104	139168	**102950**	**101130**	**104771**
PurchasingExample	2127361	2109665	2145058	2299619	2294319	2304919	2280717	2273954	2287481	**2104676**	2082360	2126992
SynLoan	2295797	2295579	2296015	1446177	1446177	1463812	1675036	1635297	1714775	**1278782**	**1271133**	**1286430**
Production	312153	307036	317270	128942	117516	140368	**83700**	73572	93828	105988	91713	120264
ConsultaDataMining	274786	271536	278035	343520	343422	343618	230921	228349	233494	**155994**	**141180**	**170707**
BPI12W	667139	665889	668389	**316642**	**309766**	**323517**	597090	594860	599320	555094	550135	560052
BPI12W*	694558	694083	695033	316642	309766	323517	**310293**	304608	315977	357940	351301	364579
BPI17W	952502	949997	955007	757742	653898	861585	417641	416631	418650	**393749**	**391442**	**396056**

Evaluation RIMS: EMD metric

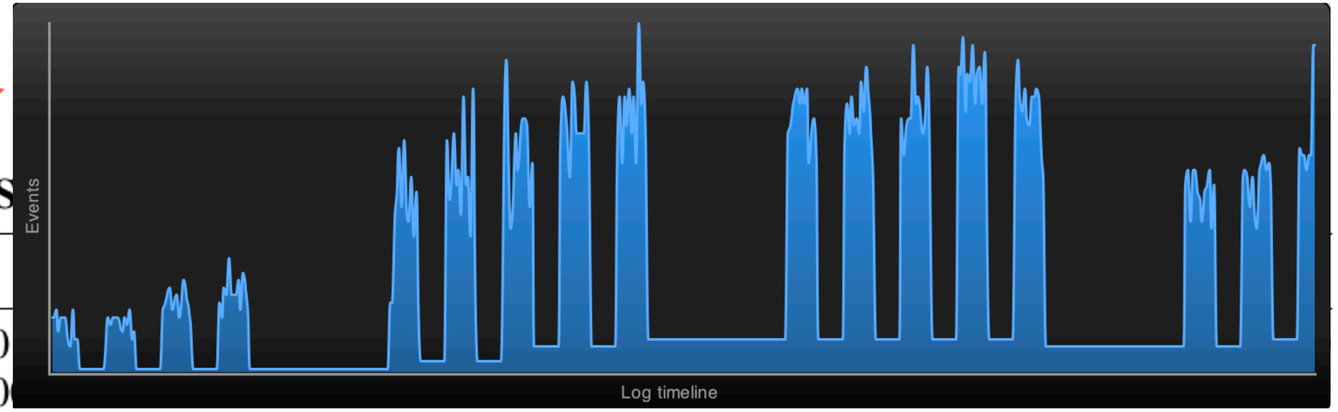
	DDPS			LSTM			Dsim			RIMS		
	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u
Confidential 1000	**0.00115**	**0.00103**	**0.00127**	0.01435	0.01434	0.01437	0.01269	0.01263	0.01274	0.01264	0.01257	0.01270
Confidential 2000	**0.00109**	**0.00105**	**0.00113**	0.00992	0.00991	0.00993	0.00897	0.00895	0.00899	0.00907	0.00905	0.00909
Cvs Pharmacy	**0.00093**	**0.00092**	**0.00094**	0.00237	0.00237	0.00237	0.00659	0.00658	0.00659	0.00672	0.00672	0.00673
PurchasingExample	0.00702	0.00699	0.00706	**0.00525**	**0.00500**	**0.00550**	0.00645	0.00634	0.00656	0.00856	0.00831	0.00880
SynLoan	0.00799	0.00798	0.00800	0.01926	0.01924	0.01928	0.00473	0.00469	0.00477	**0.00321**	**0.00317**	**0.00325**
Production	0.01486	0.01438	0.01534	0.00715	0.00647	0.00784	0.00635	0.00589	0.00680	**0.00523**	**0.00487**	**0.00559**
ConsultaDataMining	0.01573	0.01555	0.01591	0.03830	0.03820	0.03840	0.01233	0.01202	0.01265	**0.00777**	**0.00739**	**0.00816**
BPI12W	**0.00642**	**0.00640**	**0.00644**	0.00766	0.00765	0.00768	0.00807	0.00806	0.00808	0.00805	0.00804	0.00806
BPI12W*	**0.00468**	**0.00465**	**0.00470**	0.00766	0.00765	0.00768	0.00799	0.00798	0.00799	0.00798	0.00798	0.00799

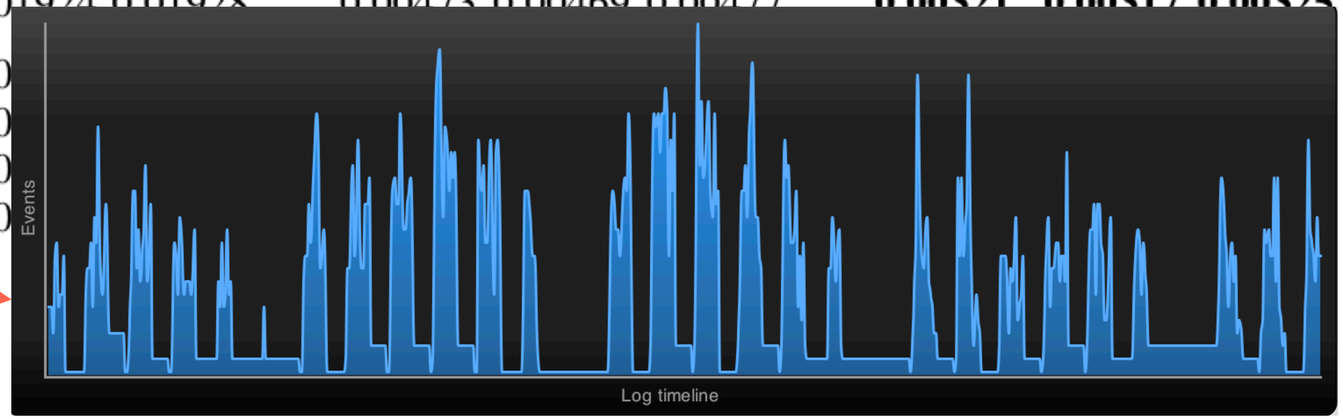
Evaluation RIMS: EMD metric

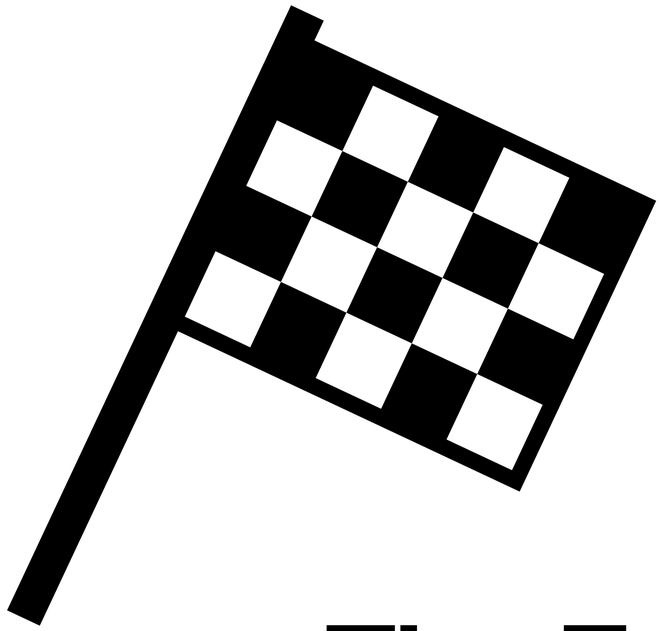
	DDPS			LSTM			Dsim			RIMS		
	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u	$Mean$	CI_l	CI_u
Confidential 1000	**0.00115**	**0.00103**	**0.00127**	0.01435	0.01434	0.01437	0.01269	0.01263	0.01274	0.01264	0.01257	0.01270
Confidential 2000	**0.00109**	**0.00105**	**0.00113**	0.00992	0.00991	0.00993	0.00897	0.00895	0.00899	0.00907	0.00905	0.00909
Cvs Pharmacy	**0.00093**	**0.00092**	**0.00094**	0.00237	0.00237	0.00237	0.00659	0.00658	0.00659	0.00672	0.00672	0.00673
PurchasingExample	0.00702	0.00699	0.00706	**0.00525**	**0.00500**	**0.00550**	0.00645	0.00634	0.00656	0.00856	0.00831	0.00880
SynLoan	0.00799	0.00798	0.00800	0.01926	0.01924	0.01928	0.00473	0.00469	0.00477	**0.00321**	**0.00317**	**0.00325**
Production	0.01486	0.01438	0.01534	0.00715	0.00647	0.00784	0.00635	0.00589	0.00680	**0.00523**	**0.00487**	**0.00559**
ConsultaDataMining	0.01573	0.01555	0.01591	0.03830	0.03820	0.03840	0.01233	0.01202	0.01265	**0.00777**	**0.00739**	**0.00816**
BPI12W	**0.00642**	**0.00640**	**0.00644**	0.00766	0.00765	0.00768	0.00807	0.00806	0.00808	0.00805	0.00804	0.00806
BPI12W*	**0.00468**	**0.00465**	**0.00470**	0.00766	0.00765	0.00768	0.00799	0.00798	0.00799	0.00798	0.00798	0.00799

Evaluation RIMS: EMD metric

	DDPS			LS								
	Mean	CI_l	CI_u	*Mean*								
Confidential 1000	**0.00115**	**0.00103**	**0.00127**	0.01435	0.0							
Confidential 2000	**0.00109**	**0.00105**	**0.00113**	0.00992	0.0							
Cvs Pharmacy	**0.00093**	**0.00092**	**0.00094**	0.00237	0.00237	0.00237	0.00659	0.00658	0.00659	0.00672	0.00672	0.00673
PurchasingExample	0.00702	0.00699	0.00706	**0.00525**	**0.00500**	**0.00550**	0.00645	0.00634	0.00656	0.00856	0.00831	0.00880
SynLoan	0.00799	0.00798	0.00800	0.01926	0.01924	0.01928	0.00473	0.00469	0.00477	**0.00321**	**0.00317**	**0.00325**
Production	0.01486	0.01438	0.01534	0.00715	0.0							
ConsultaDataMining	0.01573	0.01555	0.01591	0.03830	0.0							
BPI12W	**0.00642**	**0.00640**	**0.00644**	0.00766	0.0							
BPI12W*	**0.00468**	**0.00465**	**0.00470**	0.00766	0.0							







The End??

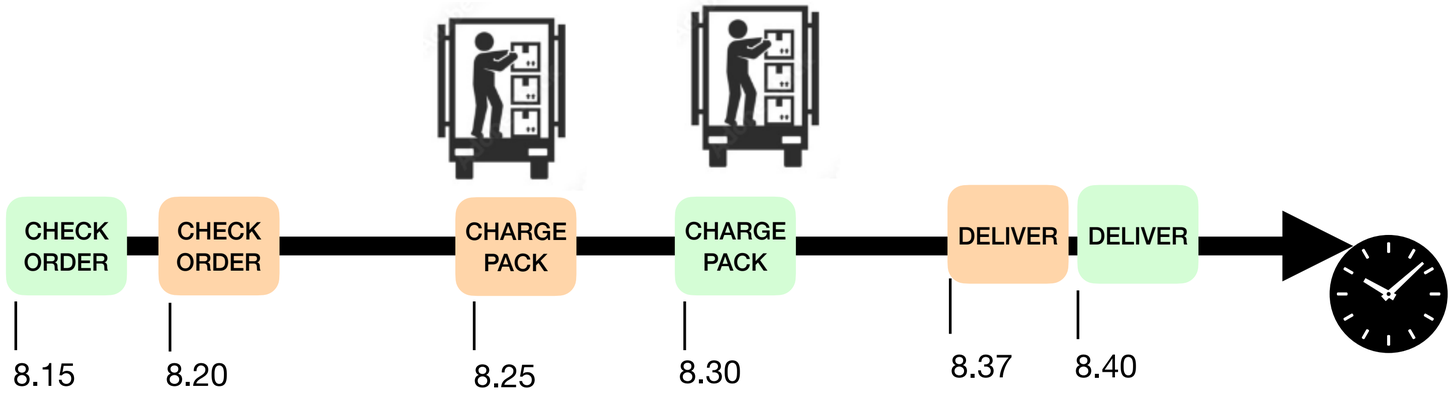
What about the queue??

Simulated Log

CHECK ORDER | CHARGE PACK | DELIVER — ID_Order: 1

CHECK ORDER | CHARGE PACK | DELIVER — ID_Order: 2

Enriched Simulated Log



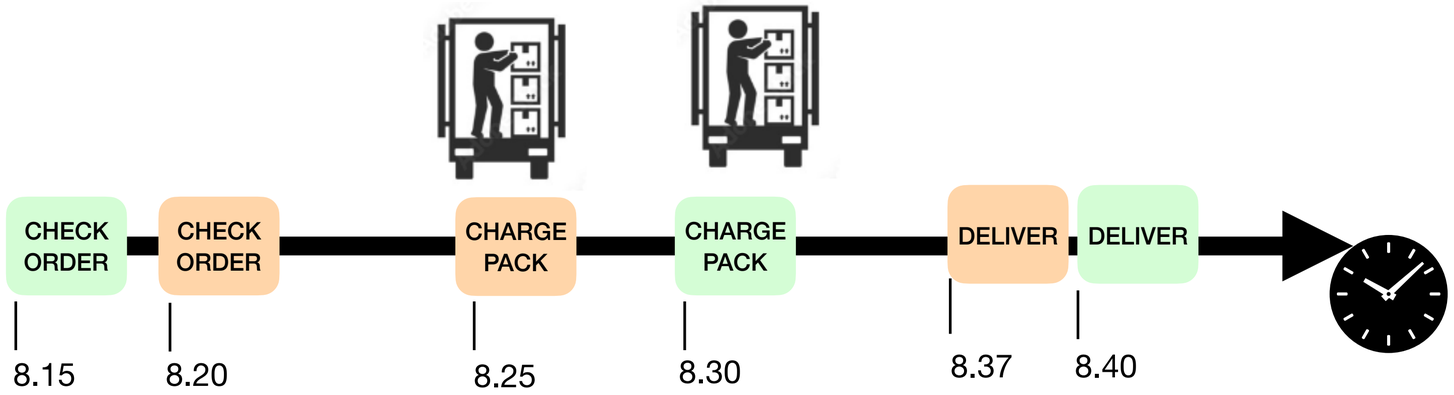
What about the queue??

Simulated Log

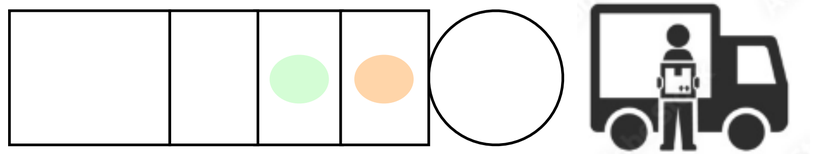
CHECK ORDER | CHARGE PACK | DELIVER — ID_Order: 1

CHECK ORDER | CHARGE PACK | DELIVER — ID_Order: 2

Enriched Simulated Log



Queue of Delivery Man Requests



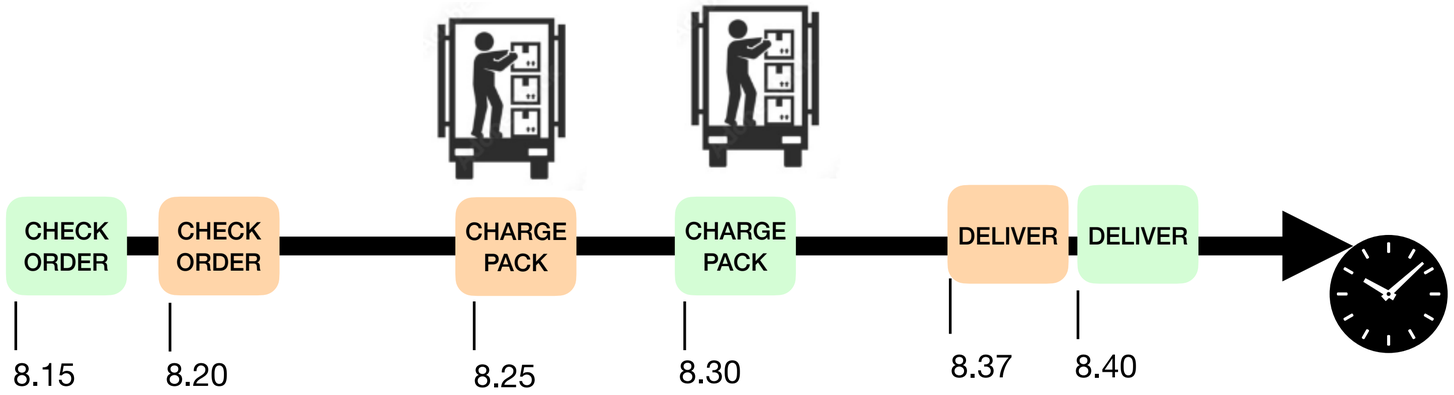
What about the queue??

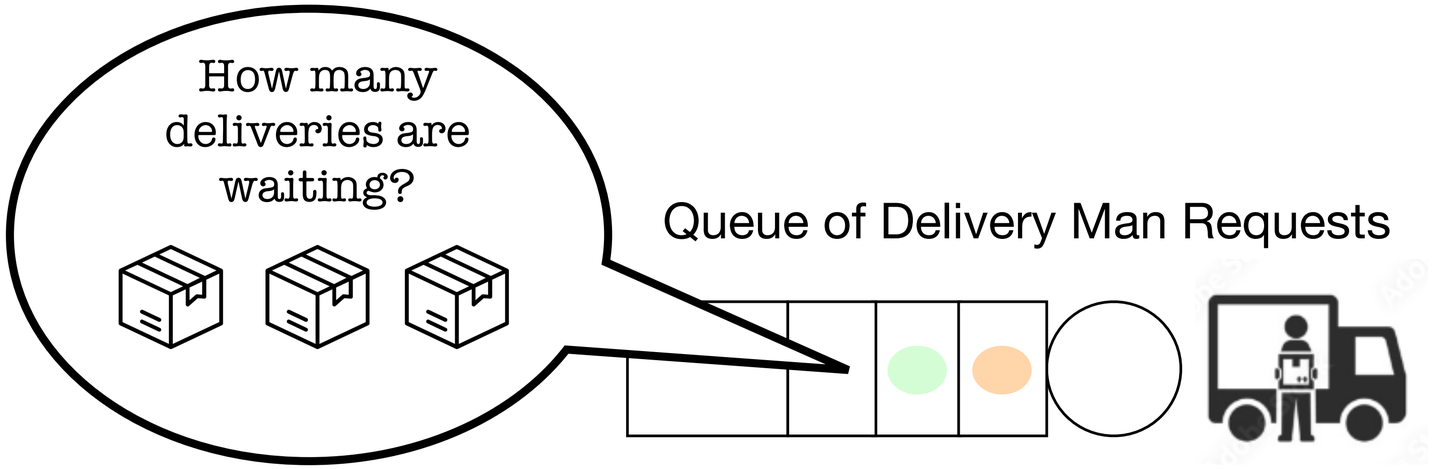
Simulated Log

CHECK ORDER | CHARGE PACK | DELIVER | ID_Order: 1

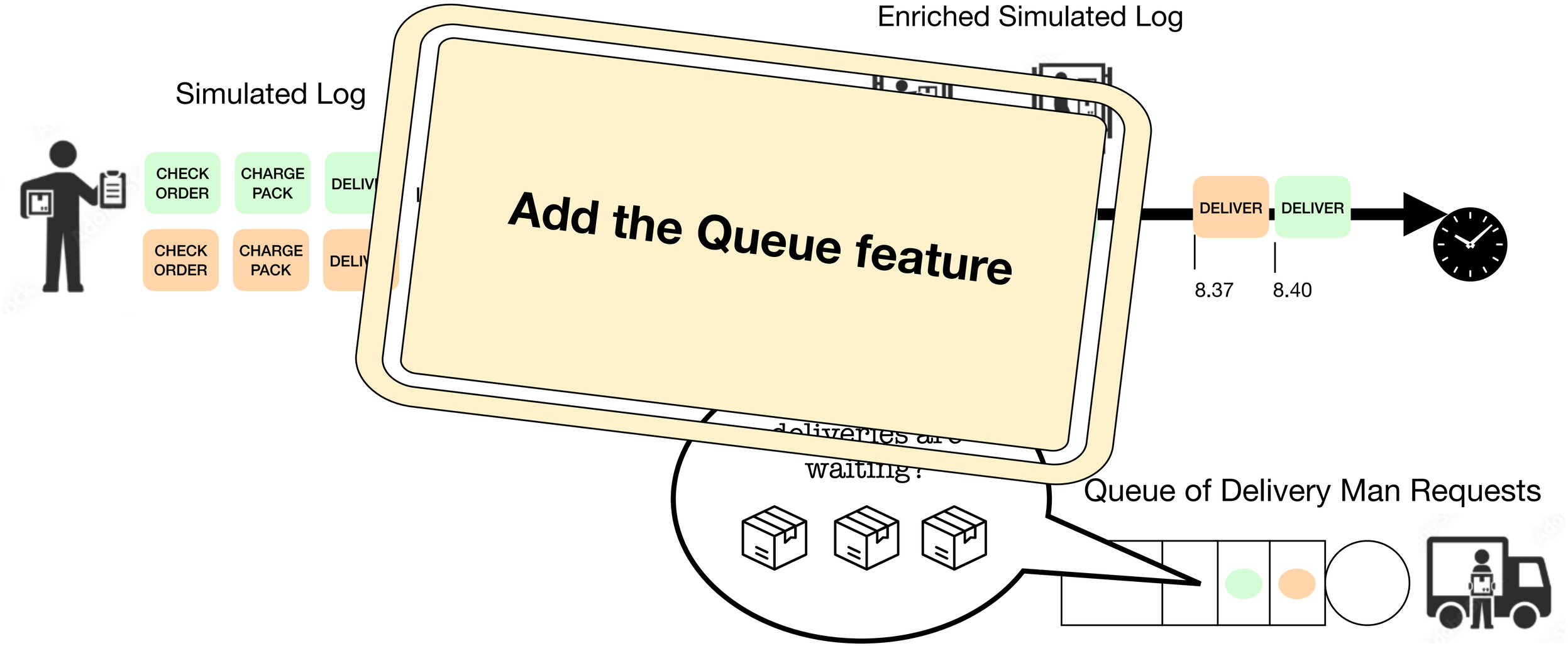
CHECK ORDER | CHARGE PACK | DELIVER | ID_Order: 2

Enriched Simulated Log

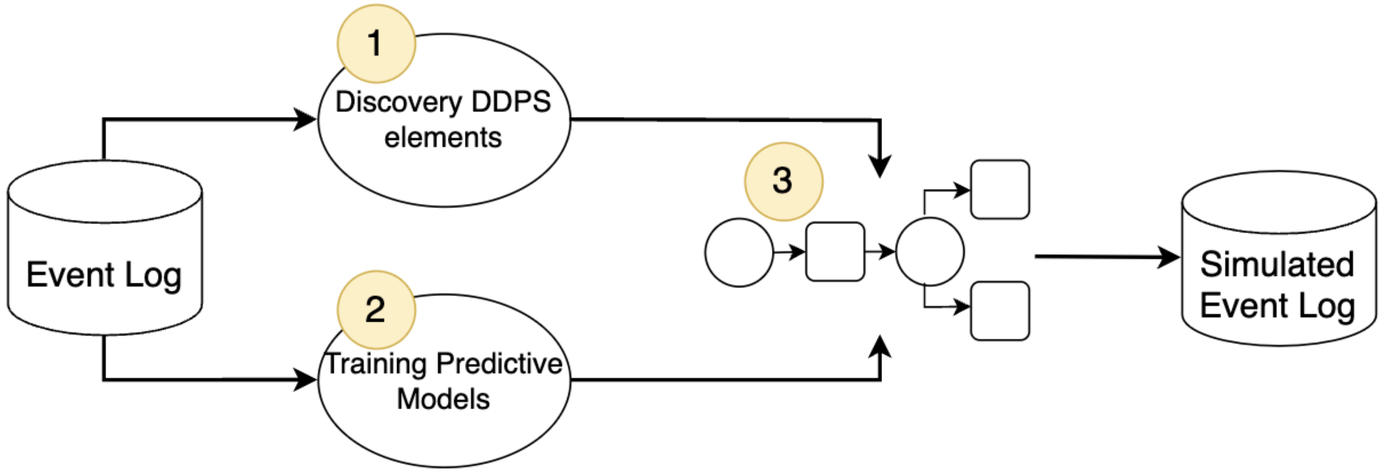




What about the queue??

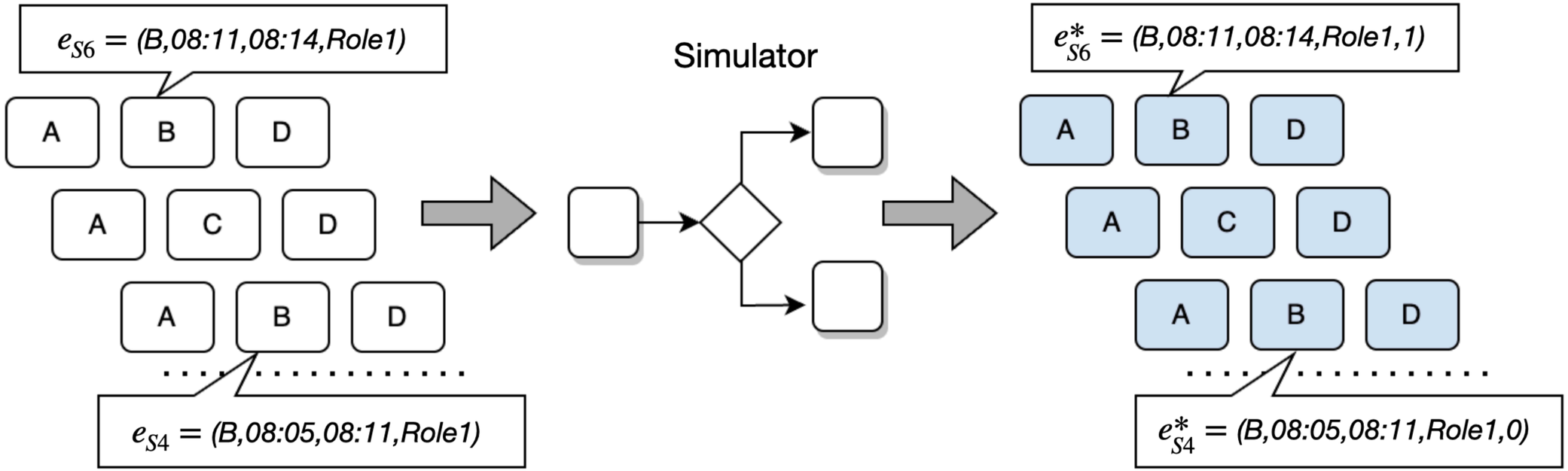


RIMS^{+} receipt

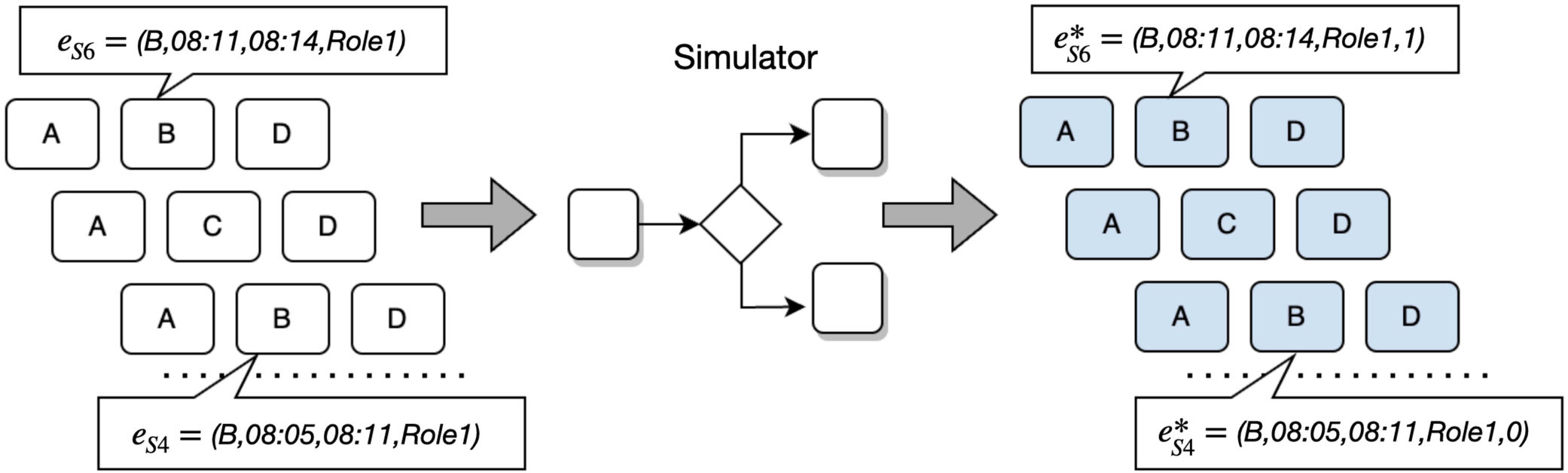


1. Definition of the DDPS elements
2. Training of the predictive models:
   - 2a Retrieve the queue feature from the log
   - 2b Train the waiting time predictive model with the queue feature
3. Integration and run simulation

2a Retrieve the queue feature from the log

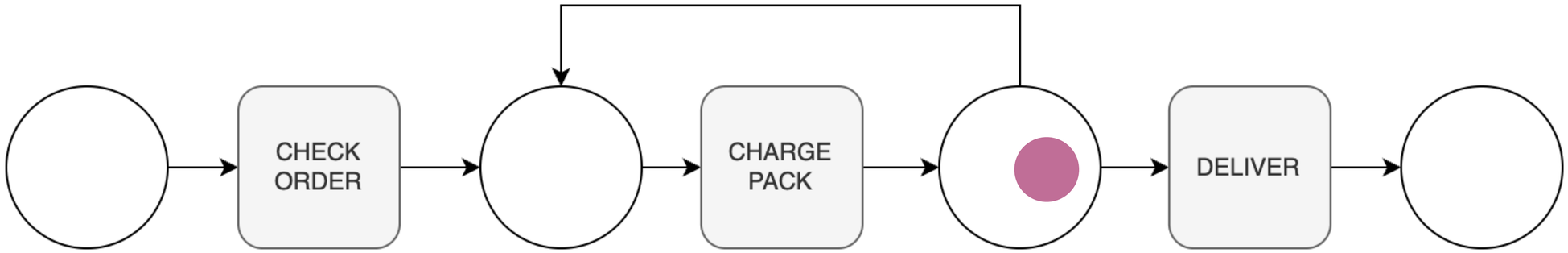


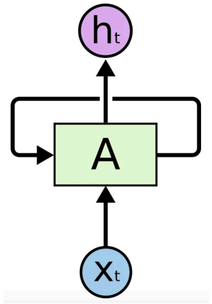
2a Retrieve the queue feature from the log



2b Train the waiting time predictive model with the queue feature

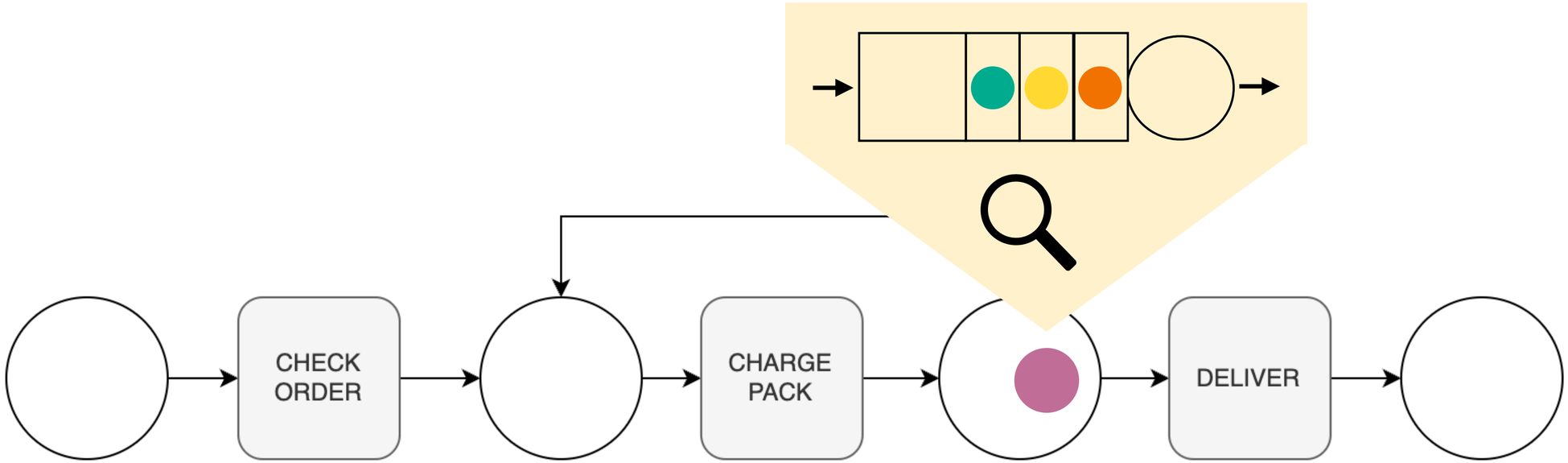
3 RIMS+: Integration and run simulation

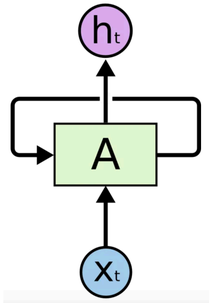




Predict
Waiting
time

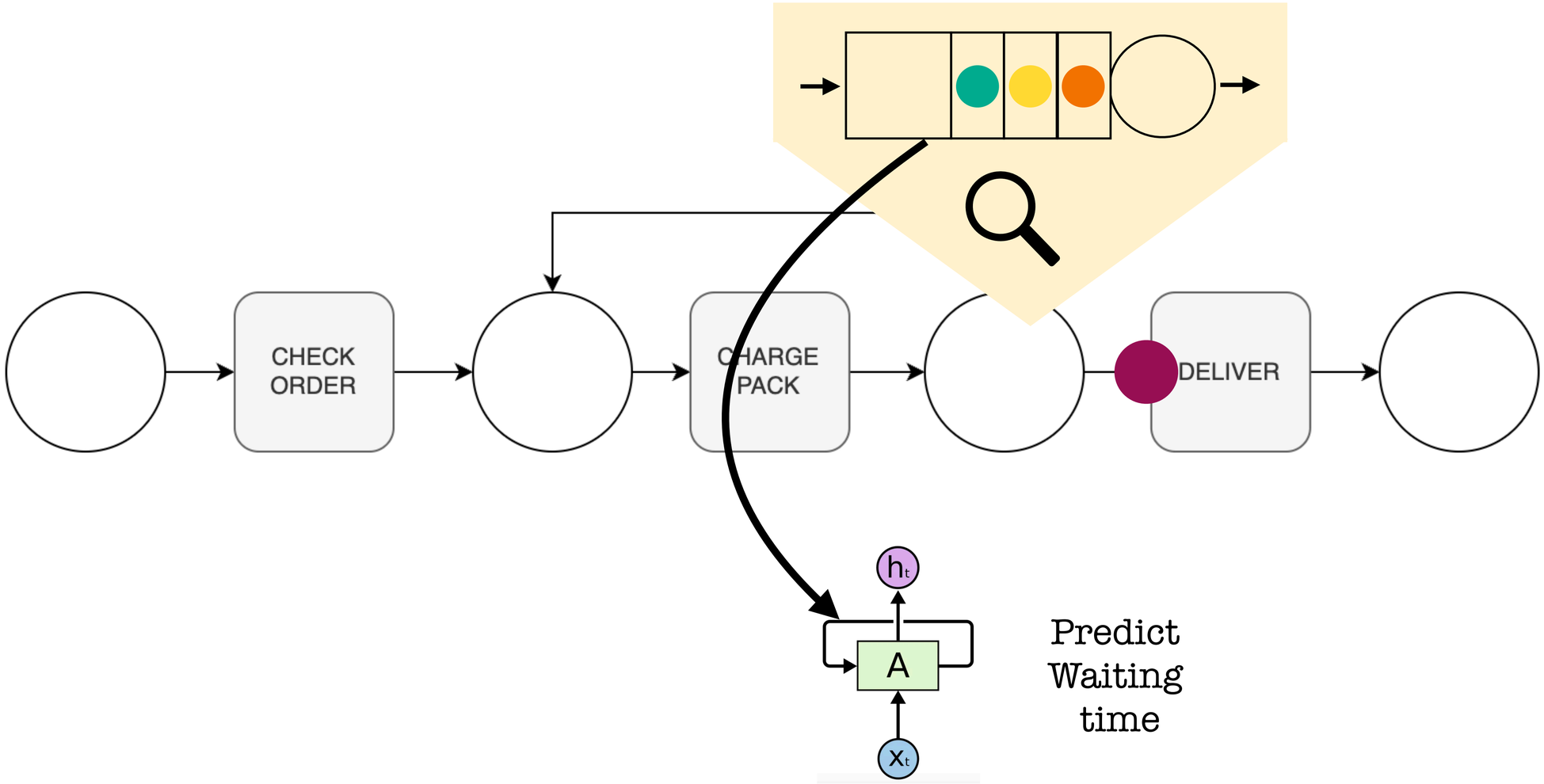
3 RIMS+: Integration and run simulation





Predict Waiting time

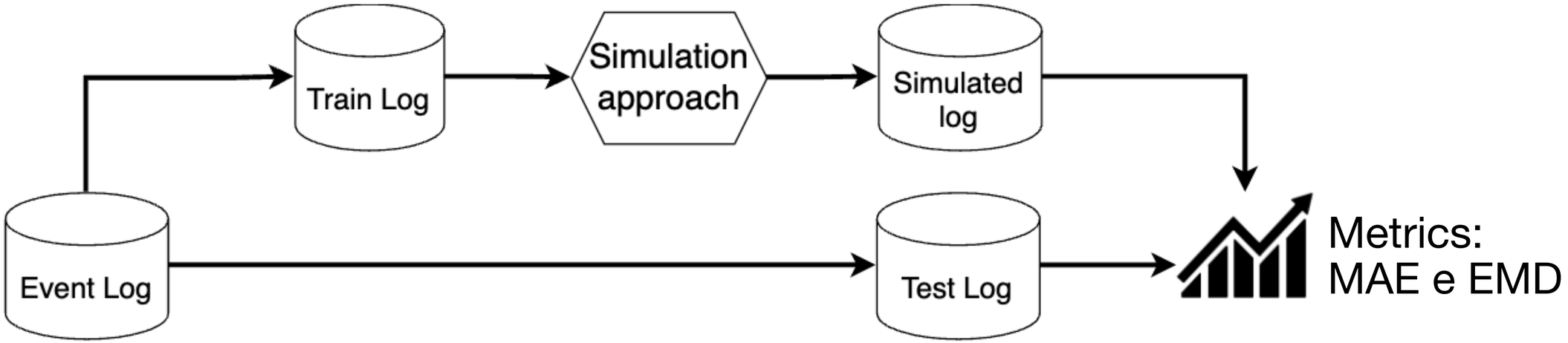
3 RIMS+: Integration and run simulation



How does RIMS+ improve the quality of simulation compared to approaches that do not use the queue feature?

RIMS+ VS 

Evaluation: Procedure



- 25 simulations for each simulation approach
- MAE (Mean Absolute Error) of cycle times
- EMD (Earth Mover's Distance) of the normalized histograms of activity timestamps grouped by day and hour

Evaluation: Datasets

Log	Type	#Traces	#Events	#Activity	Avg. Trace length	Queue mean
Confidential1000	Syn	800	21221	29	26.53	9.91
Confidential2000	Syn	1670	44373	29	26.57	2.37
Cvs Pharmacy	Syn	10000	103906	15	10.39	59
Purchasing Example	Syn	608	9119	21	15	0.30
SynLoan	Syn	2000	43164	25	39	68.89
Production	Real	225	4503	24	20	1.17
ConsultaDataMining	Real	954	4962	16	5.2	0
BPI12W	Real	8616	59302	6	6.88	1115
BPI17W	Real	30276	240854	8	7.96	1646

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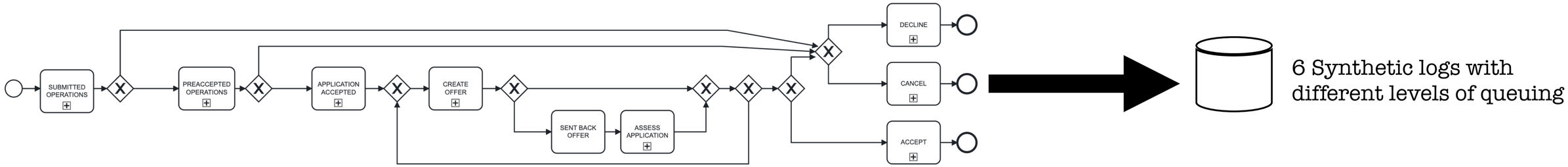
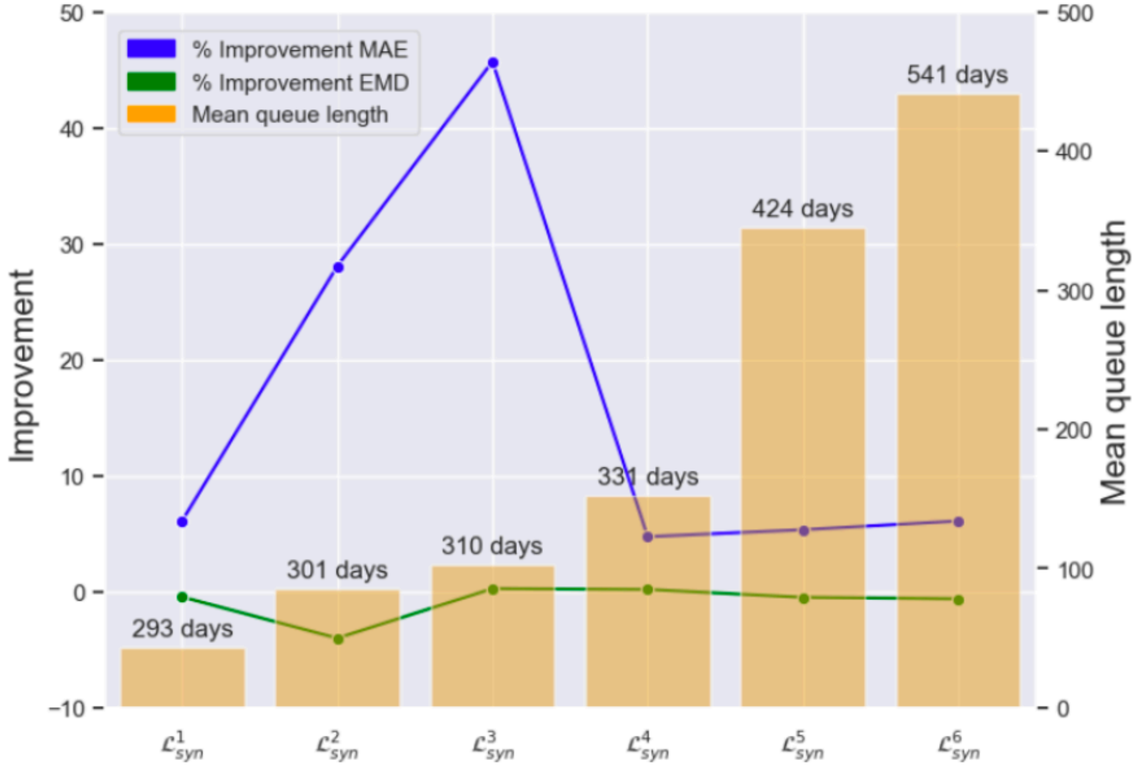
Evaluation RIMS+ vs Best

		Best			RIMS+		
		Mean	CI_l	CI_u	*Mean*	CI_l	CI_u
MAE	*Confidential 1000*	26950	25683	28217	**15489**	**14771**	**16208**
	Cvs Pharmacy	102950	101130	104771	**45756**	**37930**	**53583**
	SynLoan	1278782	1271133	1286430	**827635**	**821431**	**833839**
	BPI12W	**316642**	**309766**	**323517**	454494	452008	456980
	BPI12W*	310293	304608	315977	**301663**	292720	310606
	BPI17W	393749	391442	396056	**308038**	**299884**	**316193**
EMD	*Confidential 1000*	**0.00115**	**0.00103**	**0.00127**	0.01254	0.01247	0.01260
	Cvs Pharmacy	**0.00093**	**0.00092**	**0.00094**	0.00680	0.00679	0.00681
	SynLoan	**0.00321**	**0.00317**	**0.00325**	0.00576	0.00571	0.00582
	BPI12W	**0.00642**	**0.00640**	**0.00644**	0.00813	0.00812	0.00814
	BPI12W*	**0.00468**	**0.00465**	**0.00470**	0.00799	0.00797	0.00801
	BPI17W	**0.00448**	**0.00446**	**0.00449**	0.00847	0.00798	0.00895

- RIMS^{+}outperforms the best approach in MAE
- RIMS^{+} worsens slightly in EMD

RIMS vs RIMS+: the impact of queue





Conclusions

- New hybrid simulation approach
- **RIMS** and **RIMS**$^{+}$ outperform state of the art

Future work:

- Add the remaining perspectives
- Consider Resource Calendar
- Consider queue policies

THANK YOU!

Questions, doubts, thoughts?

Contact me: fmeneghello@fbk.eu
Process & Data Intelligence group website: https://pdi.fbk.eu/

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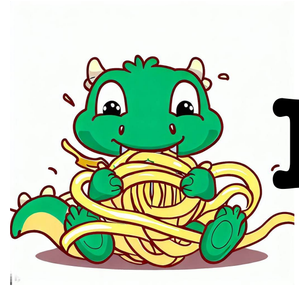

RIMS Tool