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Edge Intelligence Taxonomy

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Agenda

- Introduction
- Literature Research Process
- Taxonomy Development
- Analysis & Research Agenda

The “edge” of the internet is NOT where the world ends...

... the edge is the centre of research nowadays

TRENDS

- IoT and mobile computing
- Edge Computing/Cloud Computing and Fog Computing
- Expansion of the 5G network
- Proliferation and progress in AI
- Edge Intelligence
- …

STATISTICS

2020: Over 750 million AI-chips for edge devices will be sold *(Deloitte)*

2020: 50 billion devices will be connected to the internet *(Cisco)*

2019: data produced people/machines and things amounts to 507 ZB/year *(Cisco)*

2019: data traffic to, from and within data centres only accounts for 10.4 ZBs *(Cisco)*

The edge is an IT buzzword and lacks a clear definition

1

Edge nodes are ...

…. heterogenous platforms

- IEC (2017)

2

Edge is ...

… the counterpart to the cloud

- Yu et al. (2017)

3

Edge is ...

… decentralised

- HP (2020)

4

Edge is ...

… close to the data creation point

- Hassan et al. (2018)

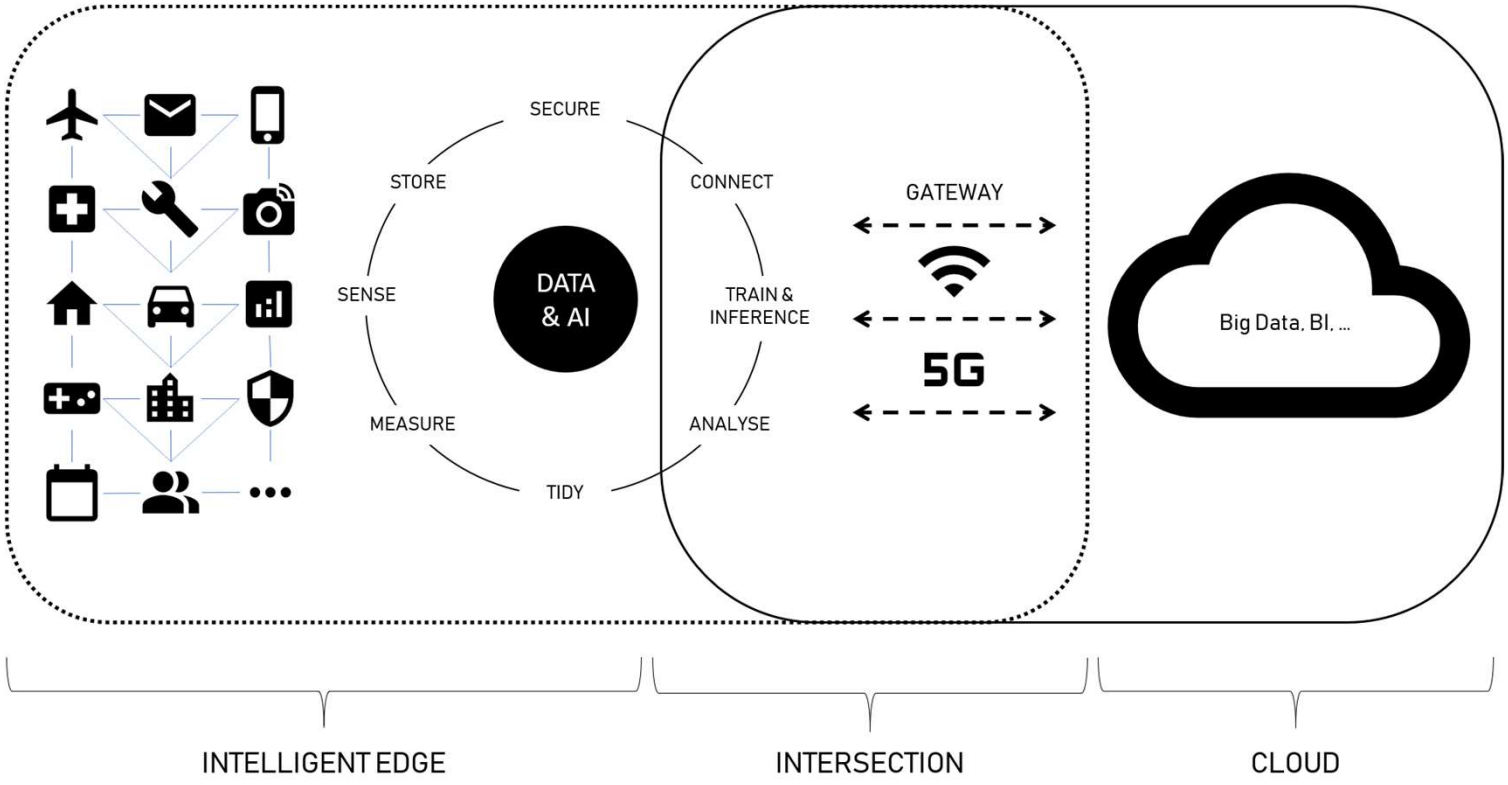
5

Edge nodes are ...

…. computer endpoints

- Dahad (2020)

My working definition for Edge Intelligence (EI)



Edge Intelligence:

- Approach to increase the data analysis and processing capacities of the edge.
- By sensing, storing, measuring, transforming, connecting and securing data
- Filter information close to the data source
- EI involves utilising the AI on edge nodes
- Training and inferencing on edge in cooperation with cloud

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Defining the scope

Inclusion criteria:

- Academic Journal Papers
- Conference Papers
- Papers in English
- Papers published between 2010-2020
- Enabling theories & technologies for training and inferencing
- Edge DNN models and architectures
- Applications of EI

Exclusion criteria:

- No citations, patents & presentations (*Google Scholar*)
- No prefaces or guest editorials
- Published papers without access
- Applications, architectures and research outcomes focused on edge-cloud synergy.
- Computation and storage offloading to the cloud
- Edge computing vs. cloud computing focus

CHARACTERISTIC		CATEGORIES			
(1)	focus	research outcomes	research methods	theories	applications
(2)	goal	integration	criticism	central issues	
(3)	organisation	historical	conceptual	methodological	
(4)	perspective	neutral representation		espousal of position	
(5)	audience	specialised scholars	general scholars	practitioners/ politicians	general public
(6)	coverage	exhaustive	exhaustive and selective	representative	central/pivotal

Taxonomy of literature reviews adapted from Cooper (1988) in Brocke et al. (2009)

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Search string development

Google Scholar	*allintitle: "Intelligent Edge" OR "Edge Intelligence" OR "Edge AI" OR "Edge Artificial Intelligence" OR "Edge ML" OR "Edge Machine Learning" OR "Artificial Intelligence on the edge" OR "Artificial Intelligence at the edge" OR "AI at the edge" OR "AI on the edge" OR "Edge Learning"*
EBSCOhost	*(TI "Intelligent Edge" OR TI "Edge Intelligence" OR TI "Edge AI" OR TI "Edge Artificial Intelligence" OR TI "Edge ML" OR TI(Edge AND Machine AND Learning) OR TI "Artificial Intelligence on the edge" OR TI "Artificial Intelligenceat the edge" OR TI "AI at the edge" OR TI "AI on the edge" OR TI "Edge Learning") AND (DT > 20100101 AND DT < 20201231)*
Web of Science	*(TI=("Intelligent Edge" OR "Edge Intelligence" OR "Edge AI" OR "Edge Artificial Intelligence" OR "Edge ML" OR "Edge Machine Learning" OR "Artificial Intelligence on the edge" OR "Artificial Intelligence at the edge" OR "AI at the edge" OR "AI on the edge" OR "Edge Learning")) AND LANGUAGE: (English) Indexes=SCI-EXPANDED, SSCI Timespan=2010-2020*

Title & synonym search

- „Intelligent Edge“
- „Edge Intelligence“
- „Edge AI“
- „Edge Artificial Intelligence“
- „Edge Machine Learning“
- „Edge Learning“
- „Artificial Intelligence on the edge“
- …

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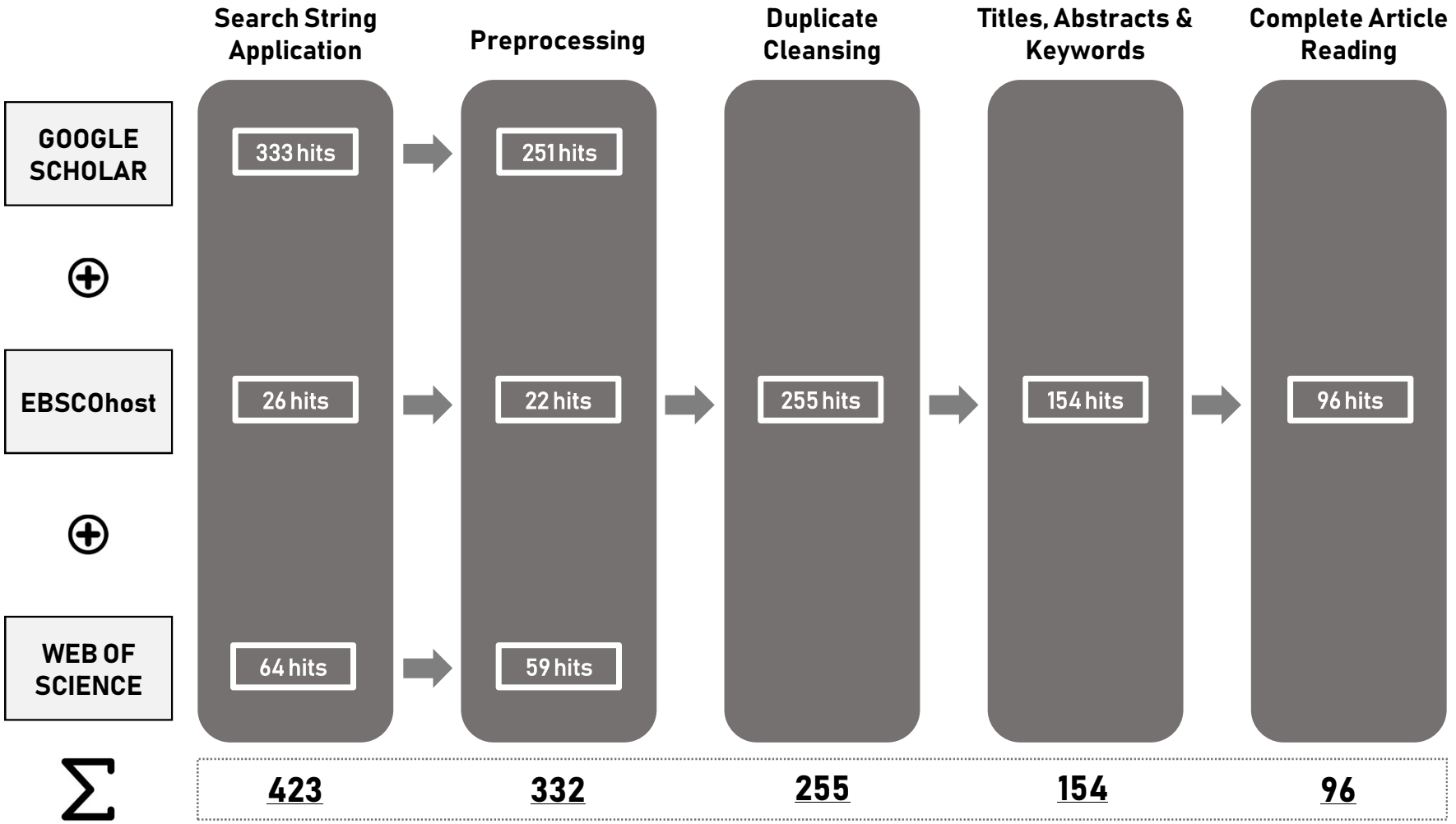
Literature review and relevance filtering process



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High-level concept matrix sneak peak

Article (Author)	CONCEPTS			
	Algorithms & DNN design for EI	Distributed EI architectures, frameworks and systems	Other EI enabling technologies & theories	EI application scenarios
Zhou et al. (2019)	✓	✓	✓	
Wang et al. (2019)	✓	✓		
Yi Liu et al. (2019)	✓			✓
G. Zhu, D. Liu, et al. (2020)		✓		
E. Li et al. (2019)	✓			
Azar et al. (2019)			✓	
Zhang et al. (2019)			✓	
Jun Zhang and Letaief (2019)				✓
Yin Zhang et al. (2019)				✓
Yushu Zhang et al. (2019)			✓	
Muhammad et al. (2019)	✓			✓
Yazici, Basurra, and Gaber (2018)	✓			
Y. Shi et al. (2020)	✓	✓	✓	
L. Li, Ota, and M. Dong (2018)	✓		✓	
Rausch, Hummer, et al. (2019)	✓			
Mills, J. Hu, and Min (2019)		✓	✓	
F. Wang et al. (2019)	✓	✓	✓	
Alonso et al. (2020)				✓
S. Xu, Qian, and R. Q. Hu (2019)				✓
Plastiras et al. (2018)			✓	
Z. Huang, Lin, Tsai, et al. (2018)				✓
D. Liu et al. (2020)	✓		✓	
Yuan et al. (2019)			✓	
Zeng et al. (2019)	✓		✓	
J Pena Queralta et al. (2019)				✓
D. Xu et al. (2020)	✓	✓	✓	
T. Zhang et al. (2020)	✓			

1

...

Article (Author)	CONCEPTS			
	Algorithms & DNN design for EI	Distributed EI architectures, frameworks and systems	Other EI enabling technologies & theories	EI application scenarios
S. Xu, Qian, and R. Q. Hu (2020)				✓
Rausch and Dustdar (2019)		✓		✓
Mazzia et al. (2020)	✓			✓
Keshavarzi and Hoek (2019)			✓	
S. Zhang et al. (2018)				✓
Lv, D. Chen, and Qingjun Wang (2020)			✓	✓
Wen et al. (2019)	✓		✓	
Qureshi et al. (2020)				✓
Yiwen Zhang et al. (2020)	✓			✓
Qianlong Wang et al. (2020)		✓		
Yaqiong Liu et al. (2020)			✓	
Shuai Wang, R. Wang, et al. (2020)				✓
Tang et al. (2020)	✓		✓	
Libri, Bartolini, and Benini (2020)		✓		✓
Chakraborty et al. (2020)	✓		✓	
Z. Huang, Lin, and Shih (2016)		✓		
Lan et al. (2019)			✓	
Xiao et al. (2020)				✓
T. Wang et al. (2020)		✓		
X. Yang et al. (2020)			✓	
Skatchkovsky, Jang, and Simeone (2020)	✓	✓		
Gamanayake et al. (2020)	✓		✓	
Xia et al. (2020)				✓
Romaszkan, T. Li, and Gupta (2020)	✓			
Hung et al. (2020)			✓	
Jie Zhang et al. (2020)			✓	
Wolf (2019)		✓	✓	

2

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Input, meta-characteristic and ending conditions

1. Input:

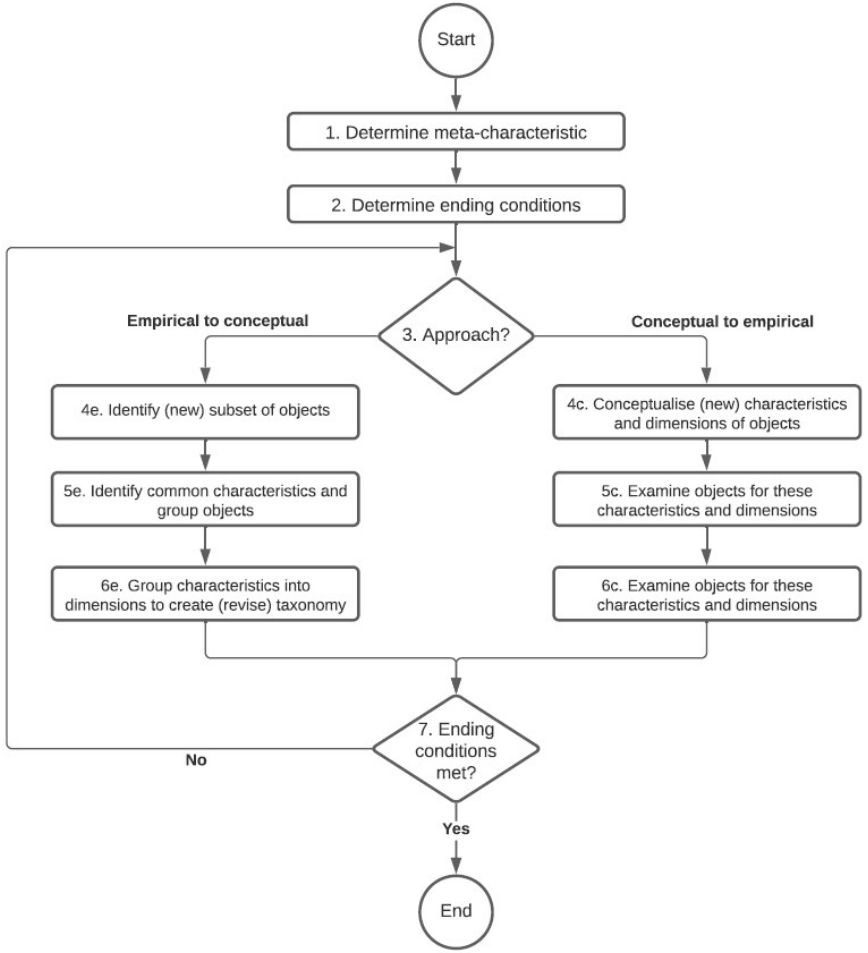
- 96 papers from literature review process

2. Meta-characteristic:

- *„design options for EI to run merely on edge nodes"*

3. Ending conditions

- **Process finishes, when the taxonomy has meaningful direction for future work on the topic of EI.**
  1. All objects need to be analysed
  2. Min. **1** object allocated to each characteristics of each dimension.
  3. There are no new dimensions added in the final iteration.
  4. Dimensions and characteristics stay the same in final iteration.
  5. Dimensions are distinct and not replicated.
  6. The characteristics of the dimensions are distinct.
  7. No cells are duplicates.
  8. Explanatory, comprehensive, robust, concise, and extendable



Iterating

1

Hoshino et al., 2019;
Jun Zhang et al. 2019;
Keshavarzi et.al, 2019;
Tang et al., 2020

29 objects

Added dimensions:

- EI Operating Edge Nodes (*EIOEN*)
  - Cameras
  - Connected Vehicle Systems
  - Other IoT devices
  - Edge servers, gateways
  - Edge-device synergy

2

Rausch, Hummer,et al., 2019;
Mills, J. Hu, and Min, 2019;
Hung et al., 2020;
Yazici et al. 2018

44 Objects

Added dimensions:

- EI Training Scheme (*EITS*)
  - On-Device training
  - Federated learning
  - computation offloading for training
  - Centralised or pre-trained modelling
  - pipeline training in sequence

3

Doku and Rawat, 2020;
C. Dong et al., 2020;
Chakraborty et al., 2020;
L. Li, et al. 2018;
Xia et al., 2020;
Wang et al.,2019

23 Objects

Added dimensions:

- Predominant EI Enabling Theory or Technology (PEETT)
  - EI Data & cyber security
  - Data filtering & model compression
  - Energy-efficiency
  - Edge Caching
  - MEC
  - Virtualisation
  - Resource Allocation

4

0 Objects

No added dimensions:

- Meaningful taxonomy!
- Ending conditions met!

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Taxonomy sneak peak

Paper	EIOEN					EITS					PEETT						
	C	V	OID	ES/G	EDS	OD	FL	DEPC	C/PT	PL	D&CS	DF&C	EEC	EC	MEC	V	ERA
Yi Liu et al. (2019)				X				X				X	X		X		X
Jun Zhang and Letaief (2019)		X					X							X			
Yin Zhang et al. (2019)					X			X			X				X		
Muhammad et al. (2019)	X								X				X				
Alonso et al. (2020)			X					X				X					
S. Xu, Qian, and R. Q. Hu (2019)	X								X		X				X		
Z. Huang, Lin, Tsai, et al. (2018)			X							X							X
J Pena Queralta et al. (2019)			X					X				X					
S. Xu, Qian, and R. Q. Hu (2020)					X		X				X						
Rausch and Dustdar (2019)				X			X	X	X	X		X			X		
Mazzia et al. (2020)	X					X							X				
S. Zhang et al. (2018)				X				X							X		
Lv, D. Chen, and Qingjun Wang (2020)		X						X					X	X			
Qureshi et al. (2020)				X							X						
Yiwen Zhang et al. (2020)				X	X		X					X		X			
Shuai Wang, R. Wang, et al. (2020)				X						X							X
Libri, Bartolini, and Benini (2020)				X					X		X				X		
Xiao et al. (2020)			X					X									X
Xia et al. (2020)				X					X								
Alaslani and Shihada (2018)				X				X			X						
Pan et al. (2020)			X			X							X				
S. Chen et al. (2019)			X						X		X						
Z. Zhu et al. (2020)				X				X	X			X					
C. Dong et al. (2020)			X				X							X	X		
Mittal, Tyagi, and Bhushan (2020)	X				X				X			X					
Vatti, Vinoth, and Sneha (2020)			X						X						X		
Corcoran et al. (2019)	X							X					X				
Jorge Peña Queralta et al. (2020)					X										X		
Guleng et al. (2020)	X							X						X	X		
Zhou et al. (2019)					X		X				X	X		X			

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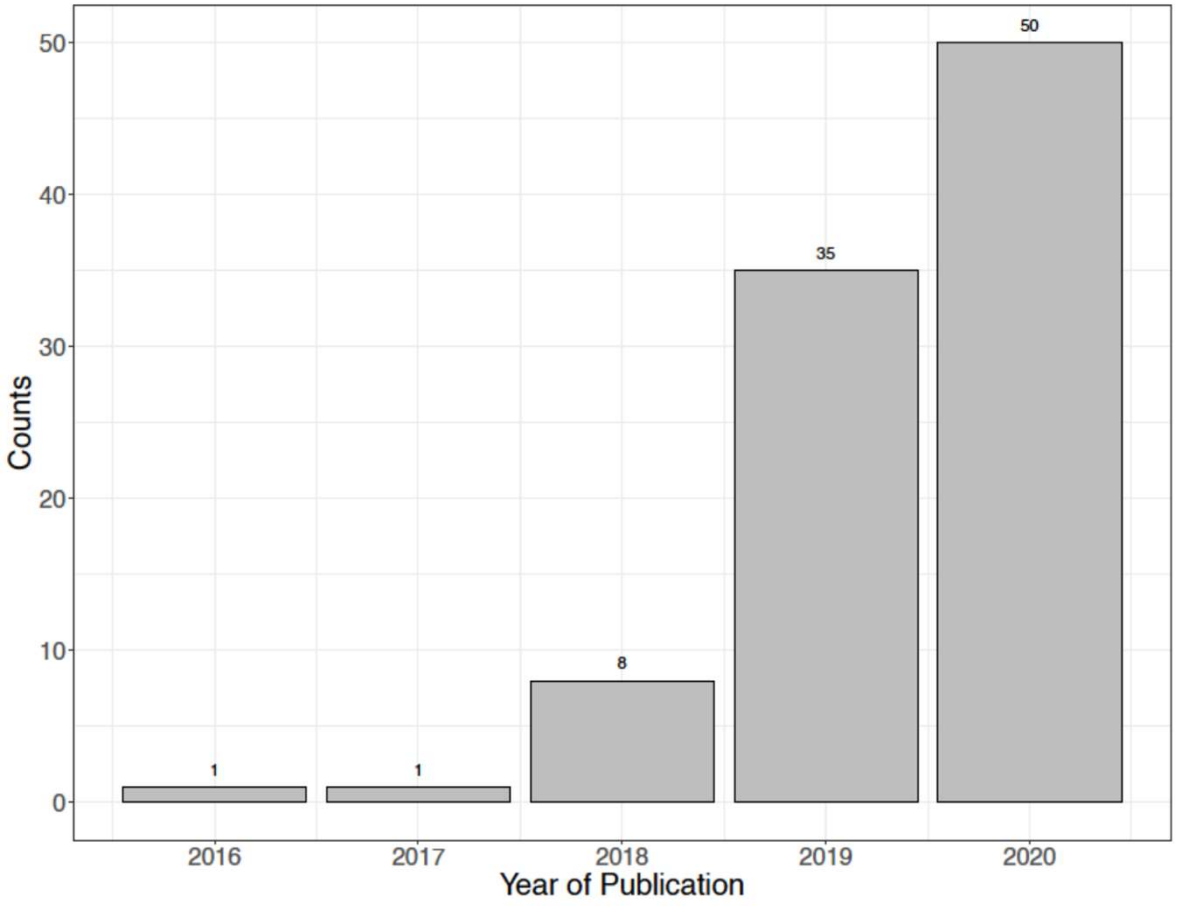
Findings & Research Agenda



Findings

- „Edge“ lacks a clear definition
- Focusing entirely on the edge environment to train, operate and process AI-models is often neglected
- 88% of this reviewed literature is published in the years 2019 and 2020
- Operating EI models is most frequently accomplished in an edge-device synergy (42)
- Models are trained edge-device collaboration scheme (45)
- Data filtering & compression, as well as energy-efficient computation are most important
- **Future work:** on-device EI