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Artificial General Intelligence vs. Industry 4.0: Do They Need Each Other?

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Abstract

Artificial Intelligence (AI) is known to be a driving force behind the Industry 4.0. Nowadays the current hype on development and industrial adoption of the AI systems is mostly associated with the deep learning, i.e., with the abilities of the AI to perform various specific cognitive activities better than humans do. However, what about the Artificial General Intelligence (AGI), associated with the generic ability of a machine to perform consciously any task that a human can? Do we have many samples of the AGI research adopted by Industry 4.0 and used for smart manufacturing? In this paper, we report the systematic mapping study regarding the AGI-related papers (published during the five-year period) to find out whether AGI is giving up its positions within AI as an attractive tool to address the industry needs. We show what the major concerns of the AGI academic community are nowadays and how the AGI findings have been already or could be potentially applied within the Industry 4.0. We have discovered that the gap between the AGI studies and the industrial needs is still high and even has some indications to grow. However, some AGI-related findings have potential to make real value in smart manufacturing.

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Keywords: Artificial general intelligence; Industry 4.0; systematic mapping study; google distance

1. Introduction

Current success of Artificial Intelligence (AI) is associated with modelling of particular cognitive capabilities of smart systems for very specific problems and it is based on Machine Learning (ML) from focused sets of training data. It is admitted that the problem of generalizing particular AI implementations to be used within a wider context is still a limitation of current ML tools. Actually, a more generic use of AI has been studied by the Artificial General Intelligence (AGI) for a long time. AGI concerns a generic ability of a machine to perform consciously any task that a human can. Is there any demand from the current industry towards such objectives of AGI? What is the current

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status of AGI as an academic discipline and as a potential application domain? Addressing these questions may be useful for the practitioners representing smart manufacturing and particularly Industry 4.0 (and beyond).

In this paper, we report the systematic mapping study regarding the AGI-related papers (published during the five-year period) to identify the themes and topics researched in the AGI field in recent years, discover the types of the research gaps that exist in the field, and measure the gap between the AGI studies and the industrial needs.

More details of the mapping study that do not fit the size of this article have been archived in [1]. The data used in the study is available online in [2], along with the full-sized illustrations. This paper summarizes and extends the results of the mapping, and the further details can be found in the archived texts.

We have chosen a provocative title for this paper due to the following reason. Yes, AI (in general) and Industry 4.0 are naturally related. However, some subfields of AI are related more and some less. Current trends show the success and industrial adoption of the ML-driven computational intelligence. The point of this paper, however, is to discover current level of relatedness between Industry 4.0 and AGI, which is a special dimension in AI, often called a "strong AI", and which is supposed to have (to some extend) certain sentience, self-awareness, consciousness, etc. Definitely, AGI is a popular subject within futurology and science fiction, however, our concern was: are there any indicators (within the recent academic publications) that current discoveries in AGI are being adopted already or going to be adopted soon within Industry 4.0.

The significance of such objective has two dimensions. On the one hand, we want to inform the Industry 4.0 practitioners that there might be recent results within the AGI domain that can be adopted and will potentially create a new important value. On the other hand, we aim to warn the AGI philosophers to find connections of their abstract AGI concepts within Industry 4.0. And, finally, we want to roughly measure the gap (and trends regarding such gap) between the AGI research and modern industry needs, taking for analysis available data from chosen academic publication sources. We believe that such study may give certain optimism in the roadmap of AGI development towards Industry 4.0 needs.

This article is structured as follows: Section 2 presents the literature mapping and the results, and Sections 3 and 4 discuss the bad and the good news regarding the relationship of AGI and industry 4.0. Key findings of the study are concluded in Section 5.

2. Literature mapping

2.1. Conducting the mapping study

The goal of the mapping study was to create an overview of the scientific research performed on the field of AGI. It aimed to discover what kind of research is done in the field, where the studies are mainly published, what the major research topics in AGI are, and how they have changed in recent years. The mapping process guidelines are suggested by Petersen et al. [3-4]. We also utilized the scientific paper classification presented by Wieringa et al. [5]. In the mapping, 92 articles from three scientific journals and two conferences were inspected as follows:

- Artificial Intelligence (AIJ);
- International Conference on Artificial General Intelligence (ICAGI);
- International Joint Conference on Artificial Intelligence (IJCAI);
- Journal of Artificial General Intelligence (JAGI);
- Journal of Artificial Intelligence Research (JAIR).

According to Petersen et al. [3-4], the search for the evidence needed for the mapping study can also be conducted manually on specific journals and conference proceedings that cover the target area. This approach has been used also in this study, as it enables targeting specific reputable and well-known publication venues. The inspected publications were selected based on their relatedness to AGI, as well as their perceived popularity and quality. One basis for the selection of publications was the Finnish Publication Forum (Publication Forum, JUFO, https://www.tsv.fi/julkaisufoorumi) ranking. The search terms that were derived from the goal of the study were broad and non-restricting. The search phrase used in the automatic search was: 'artificial general intelligence' OR AGI OR 'human-level AI' OR HLAI OR superintelligence.

The reasoning behind such venue choices were as follows: Journal of Artificial general intelligence (JAGI) and International Conference on Artificial General Intelligence (ICAGI) are very topic specific, and, therefore, should provide the most relevant information within the field. These main forums are likely to contain most of the research articles relevant for this study. Artificial Intelligence journal (AIJ) and Journal of Artificial Intelligence Research (JAIR) were chosen because they are considered the leading publications of the AI field by Finnish experts, having the highest JUFO ranking. Both also have high CiteScore considering they do not focus on any specific subfield of AI. International Joint Conference on Artificial Intelligence (IJCAI) was included because it is a popular conference that produces a large amount of articles, and it is also ranked high by JUFO (rank 2). These more general sources may not contain as many papers as the topic-specific publications, but can show the relative popularity of the field within the AI research

2.2. Mapping results

2.2.1. Publication years and venues

The field of AGI is focused on specific publication forums. This can be seen from the sample papers' publication venues. Figure 1a shows that almost 86% of the 92 articles were published as the proceedings of the International Conference on Artificial General Intelligence. The second largest set of articles was from the Journal of Artificial General Intelligence, as was expected it being the only non-conference publication on the topic. Even though Artificial Intelligence Journal and Journal of Artificial Intelligence Research are esteemed journals that contribute dozens of AI articles every year, these articles only constituted to less than four percent of this study's papers. IJCAI, that published 3923 papers as proceedings during the inspected period, only produced 4 accepted papers about the topic. The publication of AGI research on the most popular forums is clearly very marginal.

In Figure 1b the amount of yearly published articles and their venues are visualized in a bar plot. As the inspected time period on the mapping was short, only five years, predicting temporal trends accurately is not possible. However, every year there is a steady publication pace of at least 13 articles, with the average being 18.4 a year. This indicates a small but active research community. In year 2018 25 different articles were published, which was the highest number during the inspection period. ICAGI is the *"only major conference series devoted wholly and specifically to the creation of AI systems possessing general intelligence at the human level and ultimately beyond"* [6]. It has been organized yearly since 2008.

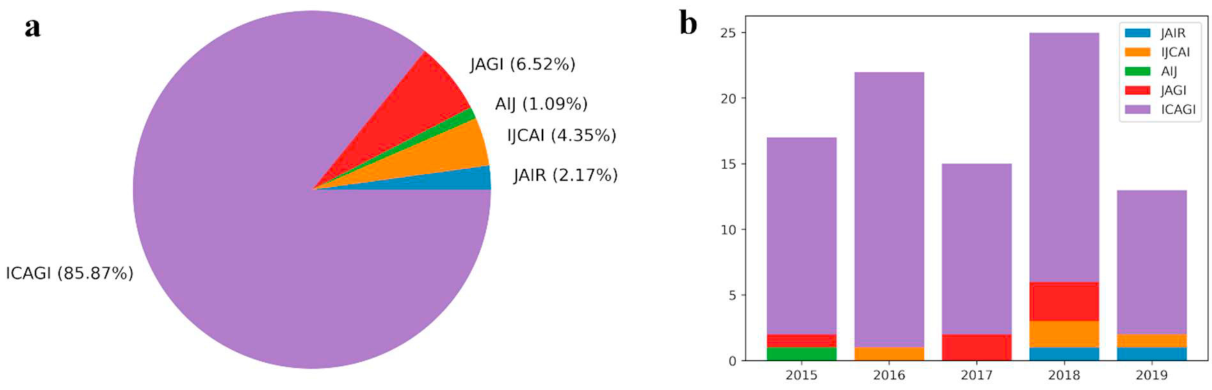

Figure 1. (a) Article distribution between publication forums; (b) Yearly distribution of articles by forums

2.2.2. Common research topics

Through the mapping process, 22 different topic categories were found, and they are presented in Table 1. The order of topics is based on the themes, with similar topics close to each other. A single paper can relate to multiple topics. These topics show how the AGI research is focused on the top level. From the amount of different topics, it can be seen that the research area is broad and is not focused on only a few different approaches. Major themes in the categories and papers were naturally AGI system development, different learning approaches, interactions between agents and environments, as well as the more philosophical questions like AI ethics.

Table 1. Emergent topic categories

#	Topic	Topic description
1	Cognitive architectures	Cognitive architectures and their descriptions.
2	AGI Design	General ideas on how AGI or its components could be designed and implemented.
3	Reasoning and Inference	Approaches on temporal and causal reasoning and inference techniques.
4	Planning and decision making	Utilizing existing knowledge in planning and making decisions.
5	Probabilistic approaches	Probabilistic approaches e.g., Bayesian techniques and uncertainty handling.
6	Category theory	Approaches relating to category theory.
7	Universal AI	Concepts relating to Universal AI: universal induction, AIXI, compression.
8	Physical robots	Physical robots and interaction with physical environment.
9	Computer vision and perception	Topics concerning vision and perception systems of an agent.
10	Nature-inspired approaches	Artificial animals, homeostatic agents and other nature-inspired ideas.
11	Reinforcement learning	Topics directly relating to reinforcement learning, e.g., Q-learning, rewarding techniques.
12	Recursive self-Improvement	Relating to fast self-improvement of an agent and intelligence explosion.
13	Experiential learning	Topics related to how agent builds on existing knowledge, like cumulative learning and artificial pedagogy.
14	Agent environment	Descriptions of environments and how agents interact within them.
15	Multi-agent systems	Topics relating to agent-to-agent interaction and cooperation.
16	Human-computer interaction	How human and agent interact and communicate and their relation to each other.
17	AI safety	Approaches on how to safely create and interact with AGI, and what safety issues arise alongside general intelligence.
18	Philosophical aspects	Philosophical questions relating to AI, e.g., AI ethics and morality.
19	Human-like qualities	Approaches with basis on human qualities like emotion and empathy.
20	AGI research	Secondary studies about AGI research.
21	AI evaluation	How to evaluate and measure AI intelligence and performance.
22	Game playing	Game playing as a tool in development and evaluation of general agents.

In Figure 2, the frequencies of research topics are presented over the years. The most researched topic is **Cognitive architectures,** which are the abstract models of cognition as well as its software implementation that aims to be a system showing intelligent behavior through AI [7]. In AGI research there are few cognitive architectures that are standing out in the field. Goertzel's OpenCog framework was seen in 8 different papers, e.g. Goertzel's idea of bridging the gap between theory and practice in AGI design [8] and Potapov's attempt to create semantic vision system by combining OpenCog with YOLOv2 object detection system [9]. In addition to OpenCog, Non-Axiomatic Reasoning System (NARS), developed by Pei Wang, was part of many articles. For example, besides the introduction of its implementation [10], there were papers describing its approach to emotion [11] and inferential learning [12]. While many of these cognitive architecture articles were mainly focused on presenting authors' system's implementation, some were offering ideas that could be used in any other approaches to AGI.

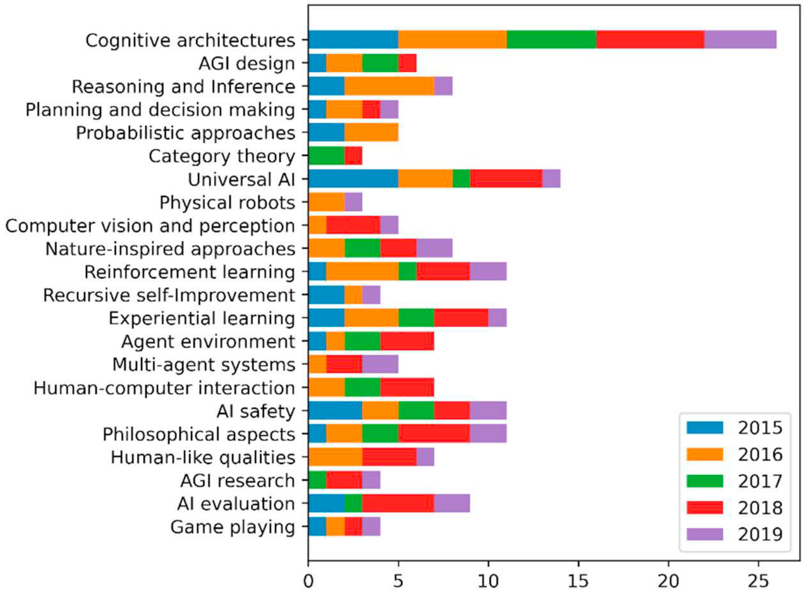

Figure 2. Topic frequencies by year

The second largest topic category was **Universal AI**. The theory of universal AI was created by Marcus Hutter [13] and it describes a complete mathematical model for general AI, named AIXI. Although incomputable, this theory is a target of vigorous research. There are 14 articles concerning AIXI and its related topics, Solomonoff's universal induction, functional programming and compression. In 2019 paper by Franz, Gogulya and Löffler [14], a monolithic inductive approach to AGI was presented, taking advantage of AIXI and the incremental compression techniques.

Reinforcement learning (RL) was the third largest category with 11 articles relating directly to it. As can be seen from the topic heatmap [2, fig. 4a], it is technique associated with wide range of other topics. In 2016 paper Susumu Katayama presents a new RL algorithm idea with similarity to AIXI [15]. RL is one of the main paradigms of ML, and widely used in narrow AI approaches, but it is also a very important part of many approaches to AGI.

Experiential learning means that an agent utilizes its previous experiences through its actions, incrementally increasing its knowledge [16]. This type of learning enables agent to generalize its abilities continuously, making it one of the necessary requirements of AGI. 11 articles with this topic were found, with some defining new concepts such as cumulative learning [16], some researching novel techniques like imitation learning [17], and some focusing on how to teach cumulatively learning agents systematically via artificial pedagogy [18].

Many papers with less technical topics such as **AI safety** and **Philosophical aspects** could be found in the study, both prevalent in 11 papers. An especially targeted topic was AI safety, which concerns problems like how can we make sure AGI has the same desirable ethical values as its creators, how can a superintelligent agent be contained safely, and how we can be sure that the AGI accomplishes its goals without the possibility of using harmful unintended shortcuts. These questions are generally referred respectively as the alignment problem, the containment problem, and the problem of perverse instantiation. In [19], necessary requirements are identified for AGI containers to solve the containment problem. In 2019 paper, Aliman and Kester present a novel ethical framework called Augmented Utilitarianism to alleviate the problem of perverse instantiation [20]. As can be seen from the quantity of papers relating to AI safety, it is one of the main issues that needs to be solved in the creation of AGI.

2.2.3. Temporal trends

Due to the limited time span of the study, it is difficult to observe long term trends in AGI research. However, some short-term observations can be made from the yearly publications presented in Figures 1b and 2.

The last year included in the study, 2019, had a major drop in published articles in comparison with the previous year, from 25 to 13. In 2019, many topics that were prominent on the previous years, e.g., universal AI, agent environment, and human-computer interaction, dropped to only one or zero articles published. Surprisingly, there are some topics that do not have any relating papers published in recent years, but each have one on 2019. This is the case of recursive self-improvement, physical robots, and reasoning and inference, each area has only had one paper published since 2016. Few of the most common topics like AI safety, philosophical aspects, and cognitive architectures have a regular publication pace, with approximately the same number of articles published every year, even in the slower years of 2017 and 2019. Other popular topics such as experiential learning and universal AI show much more fluctuation in the yearly number of articles published. Interestingly articles about probabilistic approaches have not been published since 2016, which suggests that the interest towards that approach is decreasing.

2.2.4. Connections between topics

The relations between the topic categories were also visualized [2, fig. 4a]. As could be expected, cognitive architectures can be associated with as many as 15 other categories. As the aim of cognitive architecture is often to create a versatile general agent, it is reflected on the way the research is done. Interestingly nature-inspired approaches are often associated with agent environment and reinforcement learning topics. One explaining factor is the subject of artificial animals, also known as animats that were discussed in three articles. Animats are homeostatic reinforcement learning agents that interact with their environment. The relation between AI evaluation and universal AI can also be observed, with three related articles. As universal AI deals with computability and similar subjects, their mathematical evaluation might be more viable than other approaches. Two of the three articles focused on the Algorithmic Intelligence Quotient test, designed for intelligent agent evaluation by Legg and Veness [21]. A clearly visible focus area on the topic relations is the area with topics 15-20. The heatmap shows close connections between less technical topics such as human-computer interaction, AI safety, philosophical aspects, and human-like qualities, and also multi-agent systems and AGI research. This shows how discussing AI safety also requires discussing how humans and computers interact, and how abstract and difficult concepts like ethics, values and emotions can be represented and conveyed to the machine. Two out of three of the found secondary research articles were targeting this focus area, so there is an undeniable interest in these topics.

2.2.5. Types of AGI research

The figure [2, fig. 5] shows us the relation of the articles' topics and their Wieringa classification. Here we can observe the specific foci of the field in two different facets. It can be clearly seen that most of the research in the field is solution proposals. This means that the research consists predominantly of new approaches to different problems. This focus on the new ideas combined with the almost complete lack of evaluation research shows that the field is still very young, as there are not much practical applications to investigate. It is also possible that often this kind of evaluation research could be very valuable and therefore kept private and unpublished, but as the sample articles are mostly from academia, that should not be the case here.

There is some validation research, which means investigation of not-yet-implemented solution proposals. Often solution proposal articles provided some proof in form of methodological analysis, prototype or experiments, which makes them also validation research papers.

Also common were philosophical papers, meaning papers that sketch a new way of looking at the subject, or that present a conceptual framework to be used in future research. Especially on the topics of philosophical aspects and AI safety this was a dominating research type, with multiple ethical frameworks and safety guidelines presented in the articles. Especially on these topics the lack of practical applications makes evaluation and validation research difficult, as there is currently no competent AGI.

The research gap in evaluation research could be target for future research. Finding examples of AGI solutions used in practice and investigating their effectiveness against traditional approaches or more narrow AI solutions would be an interesting way to survey the state of the field in more detail. Especially the usage of popular cognitive architectures in real-world situations could be a good subject for a more focused systematic literature review. Topicwise, category theory and physical robots are the least researched. This is interesting especially when considering the wide usage of robots in manufacturing and other industries. There are also recent suggestions that AGI will never be realized as it cannot experience the world as humans can, attaining tacit knowledge [22]. Considering this, it would make sense to invest in future research that would aim to enable AIs to experience the physical world through robotics. This was also suggested by David Kremelberg in one of the studied articles [23], where he argues that embodiment is a necessity for general intelligence.

2.2.6. Research locations

As even the leaders of many countries have voiced their opinions about the prospects of AI research and utilizing AI in society, the affiliations of studied articles were also mapped geographically [2, fig. 6]. The figure shows how the research of AGI is focused between different countries. With 59 papers published, most of the articles are affiliated with researchers in European countries, although the largest single country in AGI research is the USA, with 36 published articles. Surprisingly, Iceland and Netherlands are the runner-ups with 10 articles each. Economic powers like China, Russia and Japan are still in the 10 largest countries in the field, with 7, 6, and 5 papers respectively. However, their number of published articles when compared to that of the USA is relatively low. These numbers do not necessarily reflect the total amount of AI research done, as AGI was the focus of the mapping. Some countries collaborate more than others, especially Iceland, Switzerland, Netherlands and the USA, which often have articles involving other nationalities. There are some authors whose contribution to AGI research is quite noticeable, based on the number of papers published. In Iceland, there's Kristinn R. Thórisson, in China there is Ben Goertzel, in the USA there's Pei Wang and Patrick Hammer, and many others. Naturally, authors' work is often relating to same subjects, in this case, cumulative learning, OpenCog, and NARS, respectively.

3. The "Bad news" for AGI

According to our initial attitude, we suspected (assumed) that the needs and interest of Industry 4.0 towards the ML studies are evolving over time faster than towards the AGI, and that the AGI as a target area gradually degrades in the eyes of industry experts. We, however, were interested to get some evidence for this assumption. In this section we study what are the correlation trends over the last few years regarding the (AGI - Industry 4.0) vs. (ML – Industry 4.0) and how these trends can be seen from the academic publications. To address our concern, we used academic publications portal Google Scholar (scholar.google.com) as a tool. To measure the gap between our terms we used the Google Scholar Distance (GSD) function, which is a modified (i.e., adopted to the Google Scholar context) Normalized Google Distance (dissimilarity) measure [24]. GSD function is defined as follows:

$$GSD(x,y) = \frac{max\{log\,F(x), log\,F(y)\} - log\,F(x,y)}{log\,F\big(Domain(x,y)\big) - min\{log\,F(x), log\,F(y)\}} \quad (1)$$

$F(x)$ is the number of Google Scholar hits regarding the search term x;
$F(y)$ is the number of Google Scholar hits regarding the search term y;
$F(x,y)$ is the number of Google Scholar hits regarding the search term (x AND y);
$F(Domain(x,y))$ is the number of Google Scholar hits regarding the search term (X OR Y), where $x \subset X$ and $y \subset Y$. The maximal possible value here is the number of academic items indexed by Google Scholar (currently about 13 000 000 indexed items).

Such function is definitely an approximate and heuristic measure for concept matching (or, to be precise, it is a mismatch or distance or the gap between the concepts measure) and it is usually applied when the concepts x and y are expected to have different definitions in different sources (articles) and the set of such sources is huge (big data) and it is not feasible to process it all manually. In many realistic domains like Industry 4.0, it is difficult to give precise concept definitions, and consequently any equivalence measure will be a fuzzy one.

Intuitively, GSD function (1) is a measure for the symmetric conditional probability of co-occurrence of the terms x and y: given a Scholar article containing one of the terms x or y, $GSD(x,y)$ measures the probability of that the article contains also the other term.

The inputs (search terms used) and the results (search results and computed distances) of that gap analysis study (made for the period 2015-2020) are collected within the Table 2 and visualized in the Figure 3.

Table 2. Gap analysis using Google Scholar and related dissimilarity measure.

F(Domain(A, B,C))	F(A)	F(B)	F(C)	F(A, B)	F(C, B)	GSD(A, B)	GSD(C, B)
			YEAR: 2015				
1 630 000	1 160	20 000	17 100	106	5 030	0.723	0.303
			YEAR: 2016				
1 570 000	1 360	18 700	16 900	170	8930	0.667	0.163
			YEAR: 2017				
1 190 000	2 050	18 100	16 900	418	15 900	0.592	0.03
			YEAR: 2018				
1 050 000	2 990	17 800	15 400	646	17 100	0.566	0.009
			YEAR: 2019				
652 000	3 790	17 500	15 000	993	17 500	0.557	≈ + 0.0
			YEAR: 2020				
366 000	4 850	17 700	16 400	1 230	17 700	0.617	≈ + 0.0

GOOGLE SCHOLAR SEARCH TERMS USED

A (or "AGI"): ("Artificial General Intelligence" OR "Strong AI" OR Superintelligence);

B (or "Industry 4.0"): ("Industry 4.0" OR "smart manufacturing" OR "smart factory" OR "fourth industrial revolution" OR "Cyber-Physical Systems" OR "Internet of Things");

C (or "ML"): ("Machine learning" OR "deep learning");

Domain (A,B,C): ("Artificial Intelligence" OR Industry OR Manufacturing)

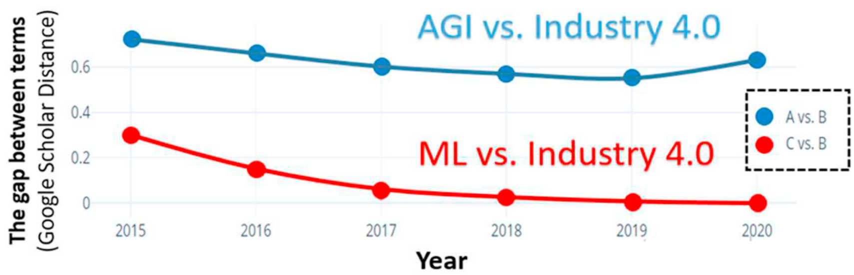

Figure 3: Gap trends visualized. One can see that (according to the academic publications during 2015-2020) Industry 4.0 is much closer related to ML than to AGI. Even more – from 2019 the gap (Industry 4.0 – AGI) began to widen, while the gap (Industry 4.0 – ML) has almost vanished.

Therefore, now one may see that the published studies related to the ML-for-Industry-4.0 steadily displace from the academic agenda the studies related to the AGI-for-Industry-4.0.

4. The "Good news" for AGI

Despite the seemingly low interest towards AGI, there is still hope for its common future with Industry 4.0. Among the articles inspected for the mapping study, there were few presenting the possible applications of AGI systems in practical problems. We chose to present the most prominent ones here.

Tősér and Lőrincz [25] suggest the cyber-physical system approach towards AGI aiming at a variety of tasks related to the workflow management using special reinforcement learning technique. The AGI view to this problem is possible because the modern time-critical cyber-physical systems are largely autonomous and goal-oriented. Therefore, workflow management in such systems becomes a process of planning and plan adaptation in real time to changing contexts. The decision-making capability about the changes needed in the workflow can be trained by reinforcement learning. Observing the workflow with various sensors, using controllers as actuators to make real time changes to the process, planning, real time plan verification and autonomous decision-making on plan adaptation, learning capabilities to plan and make decisions, - all these makes a good case (aka self-managed smart workflows) for AGI application in Industry 4.0.

Planning in general and plan recovery in particular applied to the robots within the Industry 4.0 environments are also a critical part of any capable AGI. Potapov et al. [26] developed a corresponding AGI framework for these tasks, a generative model for plans and a probabilistic programming approach for optimizing an objective function calculated via plan simulation. Their experiment with NAO robot showed that re-planning and plan recovery could be done by continuous optimization of the dynamically varying special objective functions, enabling the real-time robot self-control in a changing environment.

Bieger and Thórisson [27] argue that a generally intelligent machine (one of the main AGI concerns) should be capable to learn a wide range of tasks (aka cumulative learning). To have capable autonomous agents for a variety of tasks ("jobs") in smart manufacturing, one needs to arrange special training programs driven by special curricula. The study suggests such curricula-for-AI design methods aiming facilitation of learning and the trustworthy behavior of the trained agents within the industrial processes.

One of the most important application domains where cognitive architectures driven by computational intelligence meet AGI are related to the model generalization problem and generalized diagnostics in particular. Power et al. [28] study these issues in the smart manufacturing contexts regarding complex artifacts such as cars and circuit designs. They utilize the Non-Axiomatic Reasoning System (NARS) for model-based diagnostics, which demonstrates certain features of the generalized diagnostics. NARS is capable of diagnosing the abnormal states of different, previously unknown industrial systems or artifacts without having prior knowledge on it. Another example of generalized cognitive architectures applied to generally different asynchronously running sets of mutually competing processes is presented in Ng et al. [29]. This approach that takes advantage of the global workspace theory and the attention mechanism is applied to an urban traffic control problem, showing again a practical use case for AGI. Actually, to be able to achieve the pervasive manufacturing one need to consider seriously the general collective intelligence as a stronger version of AGI to be used as a tool to manage multiple processes in smart manufacturing as suggested by Williams [30].

Even though all the presented experiments are simplified and not at the level of real world cyber-physical systems, they display that there are interesting possibilities in the future interplay of AGI and industry 4.0.

In one of the most recent articles [31], the AGI concept "singularity" has been discussed in the Industry 4.0 context as a "manufacturing singularity". In contrast to the existing fears about the dominance of machines after the singularity point, the study provides the arguments that the manufacturing singularity will lead to a growing human role in smart manufacturing and that an intelligent machine will always be human dependent. The practitioners and industry experts can be very optimistic regarding the future potential of AGI for smart manufacturing, but they must take into account that the evolution of AGI systems will directly depend on the evolution of human role in such systems that include collaborative (human + AGI) intelligence.

The Collective Intelligence research group has recently published several studies regarding the added value of the collaborative AGI architectures for Industry 4.0. These include: general schema of bridging (mixing) human and ML processes to train heterogeneous decision-making teams for smart manufacturing [32]; general mechanisms for digital cloning of individual [33] and group [34] cognitive experiences aiming to make industrial processes more efficient and ubiquitous; and, finally, the general cognitive self-protection mechanism for the industrial AI systems as a kind of digital immunity facilitated by digital vaccination [35].

5. Conclusion

In this paper, a systematic literature mapping study was reported on the field of AGI, aiming to create a general overview of the complex AGI research field and to uncover its current state and opportunities within the industry.

92 peer-reviewed articles from scientific journals and conference proceedings were inspected. With three journals and two conferences examined, it was discovered that a majority of AGI research is published as the proceedings of the International Conference on Artificial General Intelligence and in the Journal of Artificial General Intelligence, with shares of 85.87% and 6.52%, respectively. The AGI research is focused on these two venues, as the three more general forums constitute only 7.61% of the publications.

Due to time limitations for this particular study, we have stopped analysis at the year 2019. Anyway, similar analysis could be continued beyond 2019, which will be within a focus of our further research. Please notice that the study (gap analysis) reported in Section 3 used the facts from 2020 already. During the inspected years 2015-2019, an average of 18.4 articles were published yearly, with some fluctuation in particular years. While popular topics remain relatively well represented each year, there are topics like probabilistic approaches that have not been seen in the articles since 2016.

Through the mapping process, 22 distinct topical categories were found. Major themes in the research were development of AGI systems, different types of learning, interaction of agents, and philosophical questions about AI. Topics that stood out the most were cognitive architectures, universal AI, reinforcement learning, experiential learning, and AI safety and ethics. Cognitive architecture frameworks and implementations like OpenCog and NARS are heavily researched, with 26 articles directly relating to them. Universal AI, which comprises subjects like universal induction and AIXI, is the second most researched topic with 14 relating papers. It is also interesting to see that as the dangers of AI and "intelligence explosion" are subjects often discussed in the media, AI safety is also one of the most researched topics in the field of AGI. When viewed through scientific paper classification by Wieringa et al. [5], the current AGI research is mostly solution proposals, presenting new ideas and approaches to problems. The lack of evaluation research shows that there are not yet many practical industry applications to evaluate, which is a concerning sign of slow progress.

When placing the AGI research on the geographic map, it is apparent that most of the explorations in the field is performed by researchers in Europe and the United States of America. In Europe, nations standing out are Iceland and Netherlands, both publishing more articles on the subject than Russia, China and Japan. However, this may not reflect the amount of other AI research besides AGI.

When concerning future AGI research, the gaps observed through the mapping would suggest that there is a need for more research on the practical applications of AGI, if there are any. This would truly show the current state of progress and could help the growth of interest in the area. It is also seen that there are only few studies combining robotics with AGI, and as there are suggestions that having a physical body is required for human-like intelligence, it would make sense to further investigate this subject as well. In this mapping study, it was observed that while AGI research is definitely not the most popular subfield of AI at the moment, there is steady number of articles being published on the topics regularly in its main publication forums, with wide variety of different issues. It is obvious that even though there have been major breakthroughs in AI in recent years, the ultimate goal of general intelligence is not yet close to realization.

We have also used the Google Scholar Distance metric to assess the dynamics of the AGI-Industry 4.0 gap using bigger set of articles (all indexed by Google Scholar). We admit that the gap is still big and even have tendency to grow, however we discovered some indicators of potential application areas of AGI suitable to the Industry 4.0 needs (e.g., adaptive planning, cumulative learning, general collective intelligence, digital cloning, etc.).

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