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Bachelorarbeit

A Systematic Mapping Study on Development and Use of AI Planning Tools

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Abstract

Artificial intelligence (AI) planning is a big area in the AI field with many needs and special problems. Therefore, it needs tools to suit these special problems and request, as well as for trends in the AI planning community. Since 1971 there has been an influx of many tools that assist in solving planning problems and making plans. To give a better overview of the available landscape of AI planning tools this systematic mapping study was conducted and try also to shows what software engineering principles are used in creating the tools. We also try to depict in which industry domains the AI planning tools are used and how many papers mention the tools being used in the industry. In the end, we conclude that there are at least 106 different tools out there, with only a fraction being used in the industry. While only a small part of the tools are talked about being used in the industry, this small part is covering a wide array of industry domains.

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Acronyms

AAAI Association for the Advancement of Artificial Intelligence. 33

ACM Association for Computing Machinery. 17

AI Artificial intelligence. 3

DBLP Digital Bibliography Library Project. 17

Elsevier ScienceDirect. 17

HTN Hierarchical Task Network. 13

ICAPS International Conference on Automated Planning and Scheduling. 33

IEEE Xplore Institute of Electrical and Electronics Engineers Xplore Digital Library. 17

IJCAI International Joint Conference on Artificial Intelligence. 33

IoT Internet of Things. 33

IPC International Planning Competition. 33

KE Knowledge Engineering. 15

PDDL Planning Domain Definition Language. 15

RQ Research question. 13

SMS Systematic mapping study. 13

STRIPS STanford Research Institute Problem Solver. 15

WSC Web service composition. 21

1 Introduction

AI planning or automated planning, is an important area of research and development due to the usage of AI planning in many domains like space mission control [RRCB01] or crisis management [des94], but also narrative generation and analysis [GEM16], ubiquitous computing [GA16], cloud deployment [GNLA17] or robotics [MRB16].
But what is AI planning exactly? AI planning tries to solve a planning problem through computational techniques. A planning problem consists of a starting state, a goal state and a set of actions that should help with the transformation from the start state to the goal state. For these actions, there are many different types of actions. And because there are many type of actions there are also many different forms of planning, for example temporal planning [MBKY04] or Hierarchical Task Network (HTN) planning [GA15]. The solution to a planning problem is a plan, "if the plan is applicable in the problem's initial state, and if after the execution of the plan, the goal is satisfied" [GA16]. So a plan is a structure of actions to solve a planning problem. And for all the distinct planning types we need distinct tools to generate the mentioned plans. In all the time AI planning is researched and worked on, many tools and languages have been developed to achieve and tackle a variety of planning problems [SY01]. There are even so many tools, that one might lose sight over some of the distinct tools that are used in the industry and in research for many different reasons. So this thesis has the intention to give an overview of the current state of the field in the aspect of tools used in AI planning, be it a planner [KWD15] or a tool to support existing planners [JCKV15] or even an architecture for planners [CT91]. To achieve this, we look at the following research questions:

1. Which AI planning tools have been developed and are available for use?
2. Which software engineering principles, techniques or methods are used for the development, evolution and application of AI planning tools?
3. Which AI planning tools have been used in industry and which in research only (or what is the connection between the research on AI planning tools and industry)?
4. In which real-world domains are AI planning tools used or integrated?

To answer these questions, we conduct a Systematic mapping study (SMS). Systematic mapping studies have the purpose of giving an overview of a certain research area through "classification and counting contributions in relation to the categories of that classification" [PVK15]. For that reason, we searched the literature to see what topics are covered and where are they published. With the first Research question (RQ) we try to get an understanding of the available AI planning tools and frameworks. The second RQ has the objective to give an overview what principles are the ones most desirable for producing AI planning tools and what techniques have to be used. To aid in knowing what to look for, the books "Software engineering principles" [VVV08] and "Software engineering" [LL13] are taken, to help define the wanted principles, techniques and methods. The purpose of the third RQ is to see how many of the AI planning tools are used in the industry and

how many are used in the research and development area. We also try to answer the question of what qualities are wanted in AI planning tools to be used in the industry (if there are any quirks that can be determined). Lastly, the forth RQ has the purpose of showing us for what industry the tools are being developed or where they are already in use.
The next chapter looks at all the related or similar work and summarizes them in a short manner. Chapter 3 shows the workflow and path taken throughout the SMS. In Chapter 4 we will present the graphs that were created from the collected data and describe what can be seen. Chapter 5 goes into detail with the results and discusses the product of the SMS, as well as explains shortcomings in the study. Lastly, Chapter 6 concludes the thesis as a whole.

2 Related Work

AI is a broad research field and long-standing at that. AI planning is just one of the many sub-fields. As can be seen in chapter 4 one of the first AI planning tools, that are being used in this thesis, is presented in 1991, which was the O-Plan tool [CT91]. Since then there was a steady influx of new AI planning tools to tackle different tasks and achieve diverse objectives. To not lose the sight of all the new and upcoming AI planning tools and techniques, there were many papers with a similar task as this thesis: to give an overview of all available AI planning tools that are currently available. Some of these papers will be presented in the following paragraphs.

One such paper describes many tools and languages of the time that were used up until the year 2001 [SY01] to created planning domains like Planning Domain Definition Language (PDDL) [AHK+98] or the all well known STanford Research Institute Problem Solver (STRIPS) [FN71], which is around since 1971. Also, other planners, tools and learning sites are called out in the paper from 2001 [SY01] but on closer inspection of the cited papers and listed links, some have shifted to other sites or are not accessible or outdated. That is an unfortunate fate, but this paper did nonetheless help in listing some tools and planners that are used in this thesis as well.

Another even older paper with the title 'AI planning: Systems and techniques' was published in 1990 [HTD90], so even before PDDL was invented. This paper lists besides STRIPS, also other planners like NONLIN [Tat77] and SIPE [Wil83] which we used for this study, but it used planners like HACKER [Sus73] or FORBIN [DFM87] which were not included in the collected papers. The reason for that is simple, the paper did not come up in one of the used databases mention in 3. But the fact that planners like STRIPS, NONLIN or SIPE were mentioned in more recent papers and were included in the collected papers tells, which planners are more relevant nowadays and which might be not.

Another paper that was initially not used in the thesis, but help in classifying some tools, bears the title 'A Brief Review of Tools and Methods for Knowledge Engineering for Planning Scheduling' [VSB11] and was published in the year 2011. As the title suggests, the paper talks about different planners, as well as tools used for Knowledge Engineering (KE). KE tools can be used to help in gathering knowledge and in constructing domain models, which are used in AI planning [VK20].

3 Research Method

This chapter is dedicated to explain how the study was conducted and describing every step that was taken. Firstly, we talk how the search was guided, showing which libraries were used and what search strings were created for the use of the different database libraries. Secondly, we take a look at the Inclusion and Exclusion step, naming the criteria for including a paper or excluding it, the different steps taken to reduce and refine the papers taken for the study. Thirdly, we discuss the data extraction step and following after that the classification of the extracted data.
We follow the guidelines of Kai Petersen [PVK15] [PFMM08] as a reference and inspiration for the structure of the whole thesis and the course of actions that had to be taken.

3.1 Paper search

To search for papers 5 databases were used: Association for Computing Machinery (ACM) Digital Library, Digital Bibliography Library Project (DBLP), Institute of Electrical and Electronics Engineers Xplore Digital Library (IEEE Xplore), ScienceDirect (Elsevier), Springer Link and lastly Web of Science.
Every database had a different search engine algorithm, so there were multiple search strings used. See Table 3.1 for the search strings used in the different databases to filter for papers with the theme of AI planning.

After using the search strings on all the different databases a total of 1808 papers were collected for the Inclusion/Exclusion step.

3.2 Inclusion and Exclusion of Papers

The Inclusion/Exclusion step of the systematic mapping study is one of the most important parts. The researchers are determining which papers will be included for further examination and which papers will be excluded from the mapping study, because they are irrelevant.
For this systematic mapping study in this thesis the Inclusion/Exclusion step is divided in two parts:

1. A quick search with only a few inclusion and exclusion criteria.
2. A thorough search with a more detailed look at the papers and more factors.

Database	Search string	Filter
ACM	’AI planning’ AND (’tools’ OR ’development’ OR ’methods’ OR ’instruments’)	None
DBLP	’AI planning tools’ OR ’AI planning method’ OR ’AI planning development’	None
IEEE	(’AI planning’ AND (’tools’ OR ’development’ OR ’methods’ OR ’instruments’))	Conferences AND Journals
Elsevier	’AI planning’ AND (’tools’ OR ’development’ OR ’methods’ OR ’instruments’)	’Subject areas = Computer Science’ AND ’Article type = Review articles, Research articles, Conference abstracts AND info, Data articles’
Springer	’AI planning’ AND (’tools’ OR ’development’ OR ’methods’ OR ’instruments’)	’Discipline = Computer Science’ AND ’Subdiscipline = Artifical Intelligence’ AND ’Language = English’
WebOfScience	(TS = (AI planning AND (tools OR development OR methods OR instruments))) AND LANGUAGE: (English)	WEB OF SCIENCE CATEGORIES: (COMPUTER SCIENCE ARTIFICIAL INTELLIGENCE OR COMPUTER SCIENCE INFORMATION SYSTEMS OR COMPUTER SCIENCE INTERDISCIPLINARY APPLICATIONS OR COMPUTER SCIENCE CYBERNETICS OR COMPUTER SCIENCE SOFTWARE ENGINEERING) AND DOCUMENT TYPES: (ARTICLE)

Table 3.1: Search strings used for the different libraries

The first search was conducted by looking at the title, the keywords and the abstract and scan for specific keywords. The keywords are detailed in Table 3.2. The idea behind these keywords was to cover as many tools that are meant for AI planning as possible. With that train of thought, we deliberately did use the keywords ’AI planning’ or synonyms for that. Some papers did not use words like ’AI planning’ or one of the other synonyms, so we also took papers into the set which use the keywords ’Planning’ or ’Scheduling’ or some variation of these two. If any of these keywords were used in either the title, the paper keywords or the abstract, the paper was included for a closer look and with that for the second iteration of the Inclusion/Exclusion step. Papers that mentioned a tool specifically, but they did not have one of the listed keywords, they were also included for a closer inspection to determine if it is a tool for AI planning or if it is a tool using AI planning but for another objective.

Keywords
AI planning
Automated Planning
Artificial intelligence planning
Planning and scheduling

Table 3.2: Keywords for the first inclusion/exclusion loop

In the second part of the Inclusion/Exclusion step we used more precise Inclusion/Exclusion criteria, in the traditional sense of a systematic mapping study.

Exclusion Criteria

- Paper was not written in the English language.
- Paper was not accessible.
- Paper used prior keywords only in the abstract and did not elaborate on them.
- Paper is a workshop or conference summary without further information.

The exclusion criteria are chosen through different means of reasoning. If a paper was not written in English, it would hinder the extraction of the paper through constant need of permanent translation. If a paper was not completely accessible, be it through conventional means or unconventional means, it was not possible to extract the needed data only from the abstract. Some papers use the keywords only in the abstract, but do not touch upon the topic or not in the desired way. Workshop or conference summary papers were generally excluded, but if they give any indication for papers important to this thesis these papers were also screened for the inclusion/exclusion.

Inclusion Criteria

- Paper is from journal, book or conference.
- Paper talks about tools, methods or planners in abstract, introduction or conclusion.
- Paper answers one or more RQ.

Inclusion criteria are decided by specific reasons. If a paper is not a summary, or it gives answers to at least one of the RQs, than it is included.
After the first and second inclusion and exclusion step, a full text reading was conducted with a few papers that were unclear to include or exclude, just by using the inclusion and exclusion criteria.

3.3 Data Extraction

In the data extraction step we look at all the included papers and gather as much information to answer the research questions as possible, as well as looking at data that is not related to the research question but still interesting for the systematic mapping study.
In this thesis we combined the data extraction step with the prerequisite, the quality assessment. The quality assessment has the function to check through all included papers and determine if they hold valuable information or if they do not mention anything to answer the research questions. The data that was gathered is shown in the data extraction form of Table 3.3.

Data Item	Value	RQ
Article Title	Name of the article	
Publish Year	Year of the publishing	
Publish Type	Name of the publish type	
Release Library	Name of the publishing library	
Tools	Names of all mentioned tools	RQ1
Software engineering principles	Name of used principles	RQ2
Sector	Differentiation between industry and research	RQ3
Industry domains	Name of domain tools are used	RQ4

Table 3.3: Data extraction form

3.4 Classification

To gain a deeper understanding of the matter at hand and the connection between the data, we group the collected data into self-made categories in the classification step. For that we analyse and interpret the gathered data and find similarities between the different terms. An example would be 'Disaster response' and 'Emergency planning' could be bound together with the term 'Emergencies' in RQ 4. In RQ 1 there was a need for a little different approach. In RQ 1 the different tools, structures and languages were collected and some of them could be defined and classified, but some items were explained and defined and could not be assigned to any existing category or merged into new categories. Examples are 'Attack Graph Builder' for the AGBuilder [BRT19] or 'Planning Workbench' for ModPlan [SSV20]. Facing this problem, a decision was made to use a hierarchy of classes where everything is under the pretence of 'AI planning tools and assistance'.
The classification has the following structure as seen in Figure 3.1, which was inspired by the paper "Automated Planning for Ubiquitous Computing" from 2016 [GA16]:

To see the explanation for the bigger categories look up Table 3.4.

The top-level classification is 'AI planning tools and assistance', which sums up all the classifications in the lower levels. The second level classifications (abb. classes), depicted in grey, combine more than one tool and can sometimes be even further divided into sub-classes. A darker grey combines more than one class and can be defined as a sup-class. The third level classifications (abb.

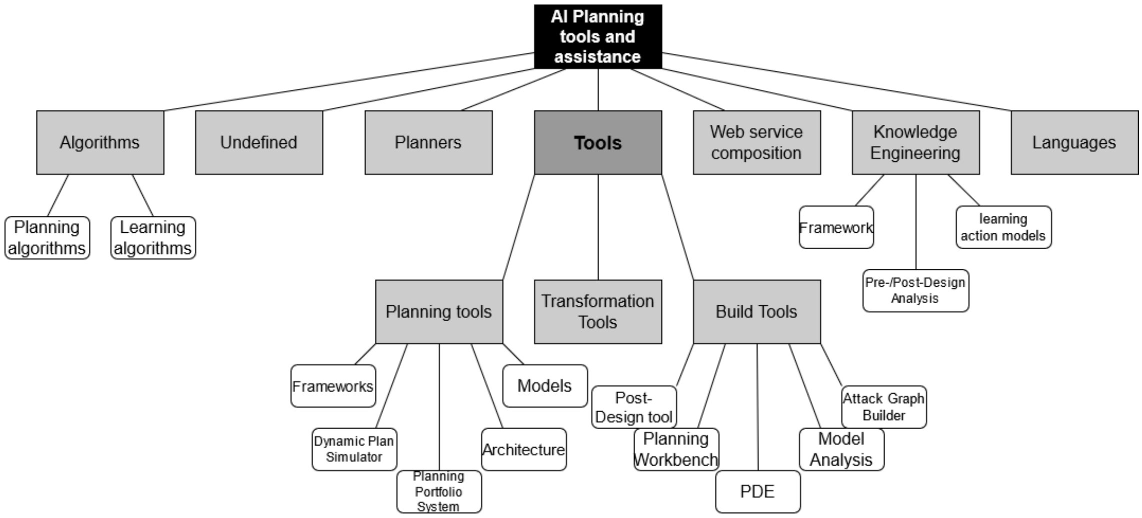

Figure 3.1: Hierarchy of Classifications in RQ1

Classification	Description
Languages	This category holds languages that are used to define or describe domains or actions.
Planners	Planners can create plans based on some input and a desired outcome.
Tools	There are 3 subcategories: *Transformation*: These tools transform either from one language to another or transform problem graphs. *Planning*: Those kind of tools, that are abstract and are more of a guide. For example Frameworks and architecture. *Build*: Build tools either help constructing a plan, verify a plan or visualize a plan.
Web service composition (WSC)	AI planning tools with the purpose of automatically composing Web services.
KE	All these tools were defined as KE tools.
Algorithms	Here are algorithms listed that are defined as 'Planning algorithm' or 'Learning algorithm' or 'AI planning related algorithm'
Undefined	Here are all the tools that were not defined in the source paper and could not be defined through a Google Search or the cited paper.

Table 3.4: Explanation of the bigger class categories

sub-classes), shown in white, does describe one or more tools as such a type of tool (e.g. 'FlowOpt' and 'VLEPpO' as PDE).
RQ 2 talks about Software engineering principles that were discussed in the source paper, if there was any at all. Table 3.5 shows the different categories that could be defined from the gathered terms.

RQ 3 counts how many papers mention tools being used in the industry and how many papers mention tools being used in research. One paper can be counted into both categories, if it mentions multiple tools and some of them are only used in the research while others a used also in the industry.

Classification	Description
Architectures	All papers that mentioned at least one system architecture which was important for the construction of the tool.
Software Life Cycle	All the papers that talked about a software life cycle (e.g. waterfall).
Software qualities	A paper mentions about achieving a certain software quality (e.g. Usability).

Table 3.5: Categories for RQ 2

Papers that present a tool that is still in the research and development phase, but it is mentioned that is made for a specific industry sector, it will be counted into the industry category. Descriptions for the categories are shown in Table 3.6.

Classification	Description
Research area	A paper mentions a one or more tools as a research tool.
Industry sector	A tool is produced for a specific industry sector or it is mentioned to be used in certain industry sectors.

Table 3.6: Categories for RQ 3

RQ 4 in Table 3.7 explains the different categories that were created in this step.

It is to mention, that papers can name multiple keywords that go into the same classification. As an example, the keywords ’Manufacturing’ and ’Logistics’ go into the ’Enterprise planning’ category but are not the same thing, so they are counted as 2 entries into the category [SSV20].

Classification	Description
Emergencies	This group sums up all papers that concern themselves with tools that can be used in disaster response, military or similar topics.
New Media	Here we sort papers into that talk about AI planning being used in new media forms that rely on computers. Meaning no radio, television or news paper.
Internet	All the different tools that are used online or try to transform offline tools into online tools.
Robotics	Papers that talk about autonomous robots or AI planning being used in robotics is sorted into this class.
Space	The papers sorted into this group talk about the use of AI planning in space exploration missions.
Assisted living	This means the paper talks about something that helps the common person in his day to day life, for example smart homes.
Enterprise planning	Tools mentioned in these papers talk about the importance of AI planning for enterprise security or logistics.
Public Service	Papers that mention AI planning tools being used for public planning, like traffic planning, are sorted in here.
Unclassified	The papers in this category were not compatible with one of the groups above and not compatible with each other.

Table 3.7: Classes for RQ 4

4 Results

This chapter serves as the place to present the result of the SMS and describe the shown data, as well as simple explanations will be made on unclear information. A more thorough discussion of the shown data will be made in Chapter 5.
The source papers for the shown results in this thesis are available in the Appendix A.
Figure 4.1 depicts how the paper number changed throughout the whole SMS, in a general and condensed way.

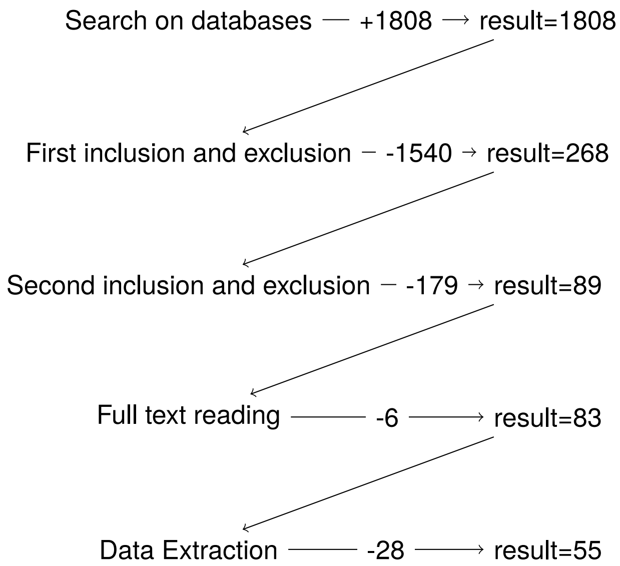

Figure 4.1: Numbers of Results after Search Steps

Table 4.1 shows a detailed distribution between the different libraries, after the initial paper search.

Libraries	**Papers**
ACM	485
DBLP	38
IEEE	93
Elsevier	464
Springer	466
WebOfScience	262
Total	1808

Table 4.1: Papers found from database search

Table 4.2 depicts the paper count after the first and second inclusion/exclusion step, as well as after the text reading step.

Libraries	Numbers after first inclusion	After second inclusion	After text reading
ACM	62	16	16
DBLP	11	9	8
IEEE	51	12	11
Elsevier	58	19	19
Springer	39	23	21
WebOfScience	47	10	8
Total	268	89	83

Table 4.2: Number of papers after Inclusion

The remaining number of papers, as seen in Table 4.3, is then the final set of papers with the data collected and prepared for the next step, the classification scheme.

Libraries	Number of papers
ACM	9
DBLP	6
IEEE	10
Elsevier	12
Springer	14
WebOfScience	4
Total	55

Table 4.3: Papers after Data extraction

4.1 Information about the papers

In Figure 4.2 we can see the distribution of the papers based on the years they were published. As one can see, half of the papers were published in the period of 2015 to 2020 (52.7%). One of the earliest AI planning tools that were collected in this SMS was from 1991 the planner 'O-Plan' [CT91].

Figure 4.3 illustrates the spread of the paper types of the collected papers. There can be seen, most papers in this study come from journals, with 27 of 55 papers (49.1%), after that come conference papers with 21 of 55 papers (38.2%) and lastly come 7 of 55 sources from books (12.7%).

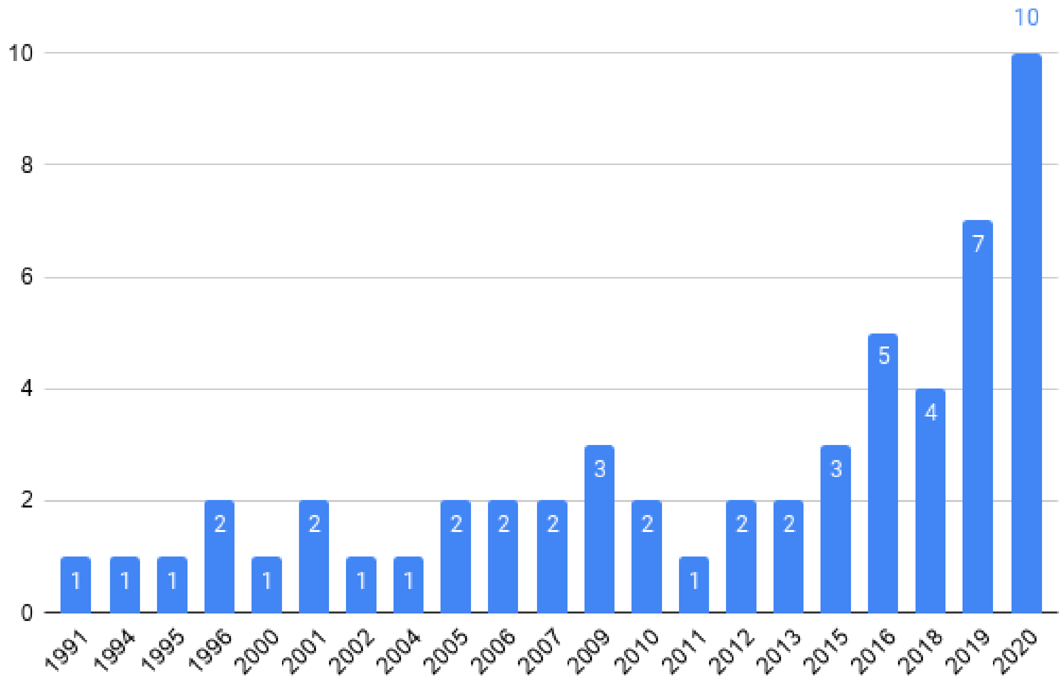

Figure 4.2: Number of Papers published throughout the years mentioning about AI planning tools

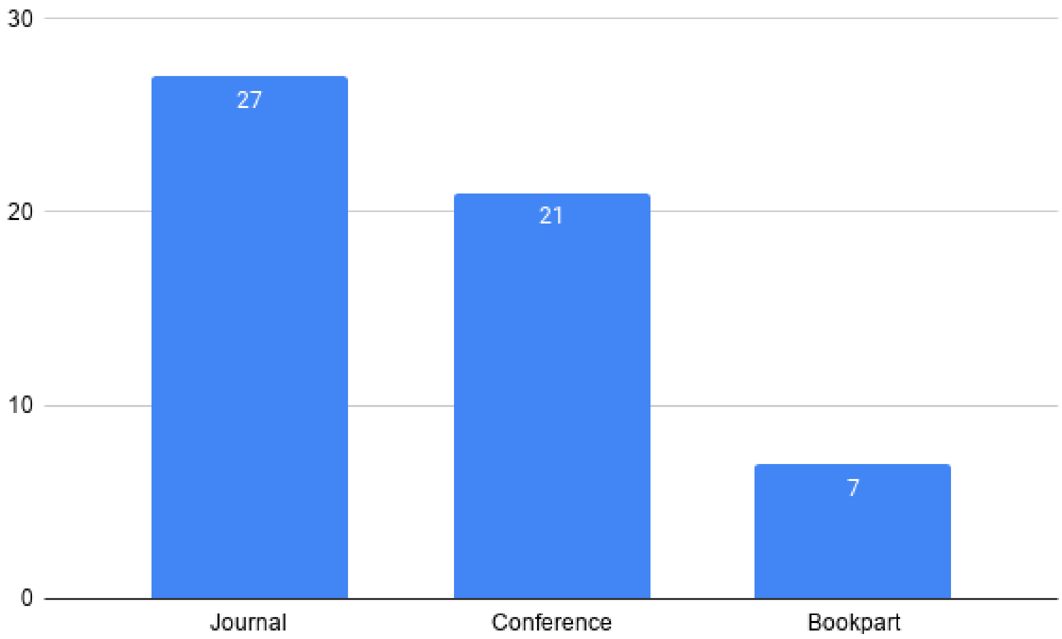

Figure 4.3: Published papers sorted by paper type

4.2 Research Question 1

Figure 4.4 gives a small glimpse at the tools we found through this study and how we sorted them into classes.

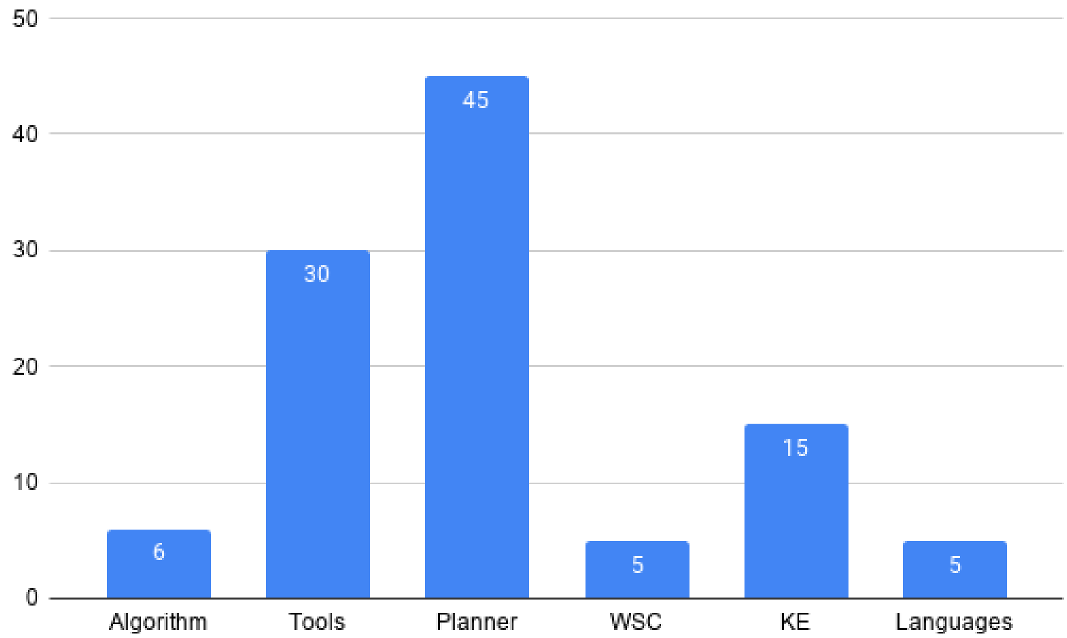

Figure 4.4: Tools in different classes

Planners are the most mentioned tools in AI planning with 45 planners mentioned.
The second biggest class is the sup-class 'Tools', which combined has 30 tools referenced in all the collected papers that mention tools. Within the sup-class, the class 'Build Tools' includes 19 tools, 'Planning Tools' has 9 tools that are presented and 'Transformation Tools' has only 2 tools that are talked about. Only the classes 'Build Tools' and 'Planning Tools' have sub-classes, out of the 3 classes in the sup-class 'Tools'. Within the 'Build Tools' the sub-classes 'Post-Design Tool', 'Planning Workbench', 'Model Analysis' and 'Attack Graph Builder' all have only 1 tool associated with them. The sub-class 'PDE' itself has 15 tools connected to that term. The term 'PDE' combines tools that are classified as a debugging tool, an editor, a validation tool or as an IDE, and is the abbreviation for 'Planning Development Environment'.
After those two bigger classes comes the class 'Knowledge Engineering' with 15 tools. Here is the distribution between the sub-classes as follows: 4 'Pre-/Post-Design Analysis' tools, 4 'learning action models' tools and 7 'Framework' tools.
Following in the fourth place is the class 'Algorithm', which combines the sub-classes 'Planning algorithm' with 5 algorithms and 'Learning algorithm' with 2 algorithms.
Afterwards are the two classes 'Web service composition' and 'Languages', where both have 5 tools or languages.
In the appendix is Table A.4 showing in which class which tool is classified. There is also Table A.5 which shows what paper, that is included in the SMS, references which tool.

4.3 Research Question 2

With Figure 4.5 we can see that we found 8 different Software engineering principles out of all the 54 papers. From these 8 mentioned Software engineering principles, 3 come from the same paper [WCM15]. This means only 5 papers (9.1%) name Software engineering principles, that were used in the creation of the tool.

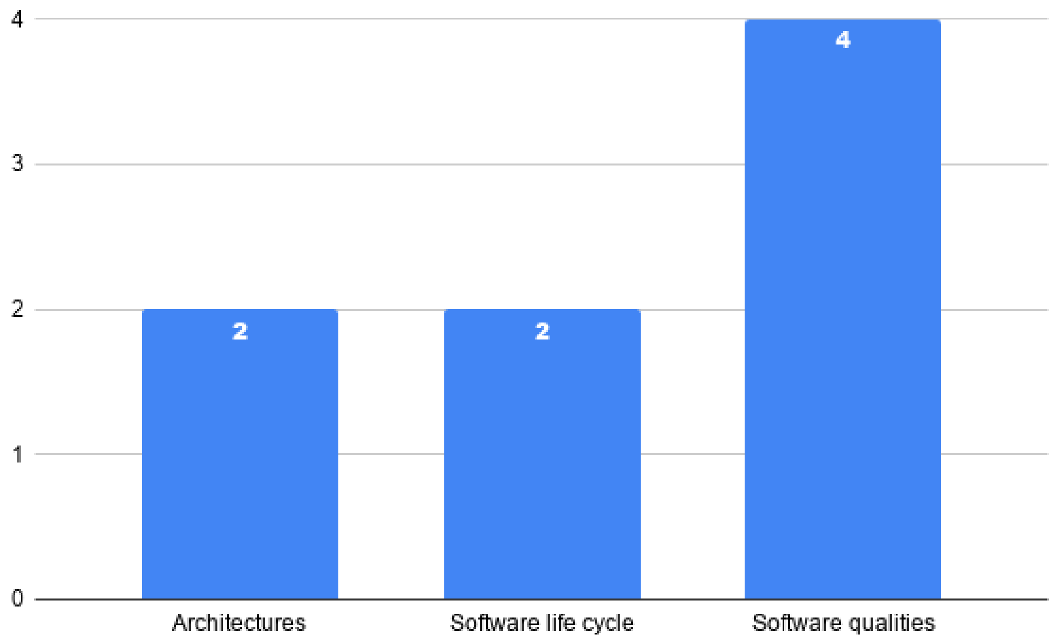

Figure 4.5: Mentioned Types of Software Engineering Principles

Table A.6, in the Appendix, shows exactly what paper contributed into what category.

4.4 Research Question 3

Figure 4.6 shows the difference of tools used in the industry and tools used in research. From the viewed papers we say, based on either authors, publishers or description of the tool, 15 tools are used in the industry environment or were created to be used in such an environment after more research and refinement. 42 papers talk about AI planning tools that are used only in the research area or are talking about tools that are in the research phase, but are created in the concept of being used in some industry sector.

The graph numbers make it clear that papers talking about industrial tools that are still in the testing or research phase have been counted in both categories, considering there are 42 papers mentioning tools in research and 15 papers mentioning tools for the industry where there are only 55 papers in the final set of papers.

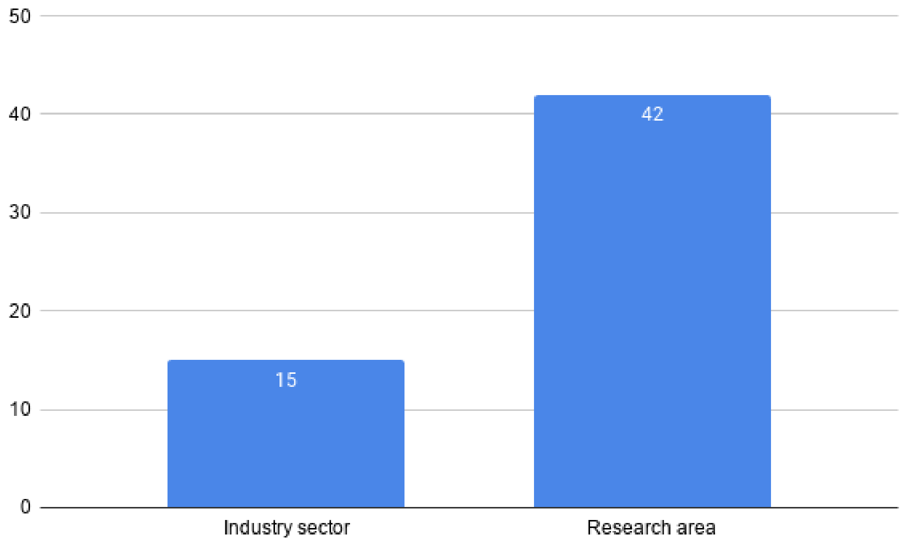

Figure 4.6: Mentioning of tools in industry vs research

In Figure 4.7 we can see a clear uprise in 2019 and 2020, compared to the years from 1994 until 2016. In the time period of 1994 up to 2016 there were only a few papers in the final set that brought up some industry tools. It can be noted that the time period from 1994 to 2016 had combined 9 papers that discussed to some extent about industry tools, while in 2019 and 2020 there were combined 7 papers in the included set of papers that mentioned industry tools.

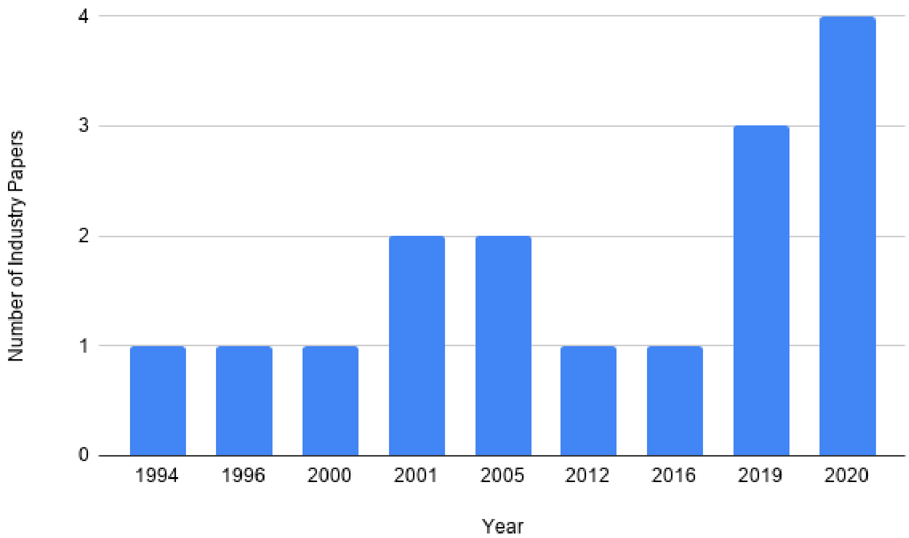

Figure 4.7: Number of industry papers over the years

The Table A.7, in the appendix, shows which paper was sorted in what category and Table A.8 shows when papers from the 'Industry sector' classification were published.

4.5 Research Question 4

Figure 4.8 reveals the areas that use some of these AI planning tools. One can clearly see the two peaks coming from the 'Emergency' category having 7 real-world domains. The second biggest category is 'Robotics' with 6 real-world domains mentioned. But other areas like 'Enterprise', with 5 mentions, and 'Space', with 4 mentions, are closely following the two front runners. 'New media', 'Assisted living' and 'Public service' share the same count with 3 mentions and after that comes the smallest domain with only 2 mentions, 'Internet'. Two mentions went into the 'Unclassified' category, because the 2 domains are incompatible with each other and the other already established real-world domains are not compatible with these 2 domains. These 2 mentions are 'Cybersecurity' [BRT19] and 'Knowledge engineering' [SGV16].

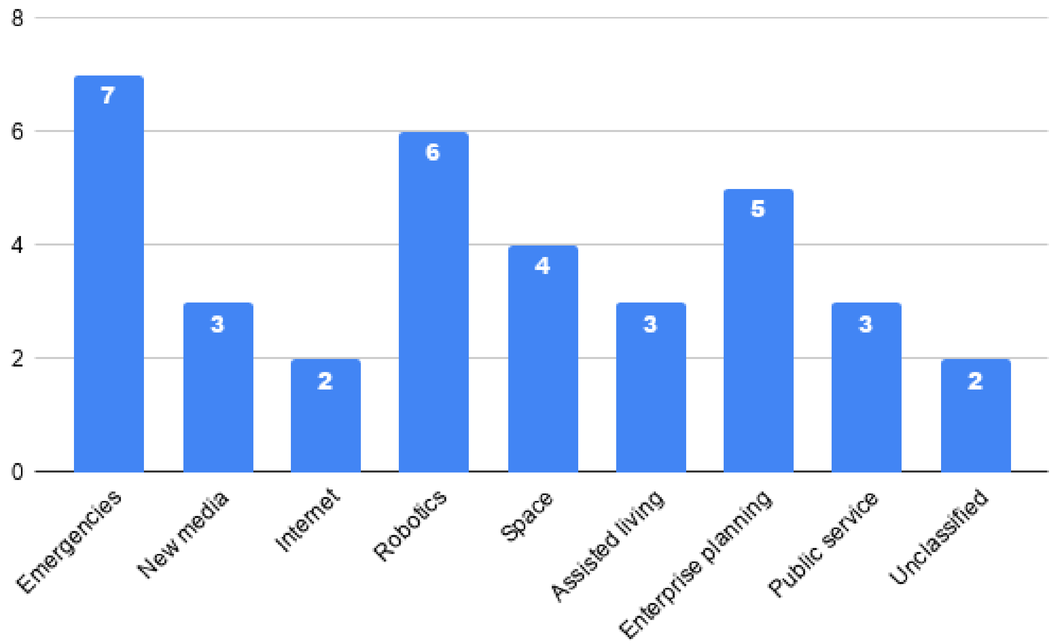

Figure 4.8: Different industry sectors using AI planning

In Figure 4.9 we can see the published papers per year and the categorization of the these papers, according to the classifications mentioned above. Here we can see, that 'Emergencies' is a topic that comes up constantly, from 1994 until 2020. The topic 'Internet' is mentioned sporadically, once in the year 2012 and once in the year 2020. Another sporadic category that is mentioned is 'Space', once in the year 2001 and after that once in the year 2013 and two times in the year 2020. 'Public service' is also mentioned with a certain time gap, once in the year 2006 and after that in the years 2019 and 2020 also one time. 'New media' as a category is mentioned in 3 papers in a small time frame, once in the year 2016, then in the year 2019 and lastly in the year 2020. The category 'Robotics' is represented by 5 papers, where the first mention in our papers is from 2005, the second in the year 2016 and the last 3 papers are in the year 2020. 'Enterprise planning' is a newcomer with 3 papers mentioning topics of this category in the years 2019 and 2020, where 1 paper from the year 2020 mentions multiple different parts of Enterprise planning [SSV20]. 'Assisted living' is a topic that is mentioned in 3 different papers, one being published in the year 2010, another one in the year 2016 and the last in the year 2019.

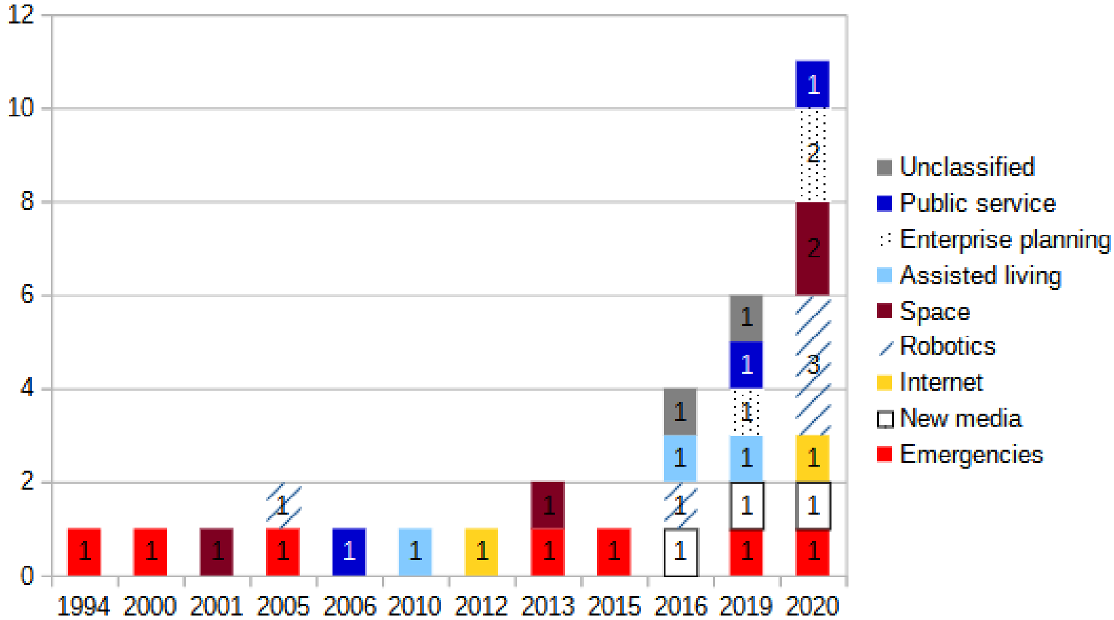

Figure 4.9: Distribution of papers over the years per category

In the appendix the Table A.9 shows the correlating papers to the classifications shown above and Table A.10 depicts the Figure 4.9 in table form.

5 Discussion

In this part of the thesis we discuss the graphs and information collected from the papers, as well as discuss what could have been done differently.

5.1 Information about the papers

As seen in Figure 4.2, one of the first papers is from 1991 which talks about O-Plan [CT91]. There is a steady income of papers talking about the AI planning tools that are used in the field or are presented for the first time, but since 2015 there is an increasing count of papers talking about the tools and assistance in the AI planning domain. Papers from 2016 [SGV16] [GEM16], talk about many existing tools that were the inspiration to create a new tool with a new purpose in a changed environment. The newer papers mention more and more tools that were either used to compare with their novel approach of a tool or as an inspiration. A reason or possible explanation for this boom in the papers that talk about new and upcoming tools, might be the rising importance of 'Industry 4.0', the Internet of Things (IoT) and similar things. Before the 2010s, AI planning was used in many important areas that were more reserved to a specific area like 'spacecraft mission control' [Lon05]. But since the rising development of smartphones, smart homes and the importance of the internet in every industry [Cho20] we can expect a higher demand and supply of AI planning tools.
With Table 4.3 we can only assume some things like, where most papers concerning AI planning tools are published and where a newcomer into the field might have a better chance finding what he searches for. We have to put aside that other sources, like Google Scholar or the sites where the papers of the International Planning Competition (IPC), Association for the Advancement of Artificial Intelligence (AAAI), International Conference on Automated Planning and Scheduling (ICAPS) or International Joint Conference on Artificial Intelligence (IJCAI) are published, could be a better place to look for papers concerning AI planning tools. The cause for this might be that the papers published on the mentioned sites of the IPC, AAAI, ICAPS or IJCAI mostly talk about AI technology or even AI planning in a specific sense. On the other hand Google Scholar delivers more papers, which means a researcher can find more important papers, but at the same time has to discard more papers because they do not talk about AI planning enough or use it as a pretence to lure more people to their paper.
In Figure 4.3 we see the distribution between the different paper types, being journal papers, conference papers or book parts. There we see that most papers are sorted under the 'Journal' category, which could mean that papers talking about AI planning tools are mostly published in journals meaning it could be a good point to look for information and new, upcoming tools. Popular journals for that are the 'Artificial Intelligence' or 'Applied Intelligence'. That is followed by conference papers and after that come the chapters out of a book. An example of a big and well-known conference is the 'IEEE International Conference on Tools with Artificial Intelligence'. But this Figure 4.3 could look different, if we had included the papers from renowned conferences

or competitions like the IPC or AAAI. An example could be the paper 'Representation in a Domain-Independent Planner' [Wil83], which is out of a book but was not found through the search from the used databases.

5.2 Research Question 1

The graph seen in Figure 4.4 shows, that without a doubt planners are the most used tool and are developed the most, to no surprise. One of the most mentioned planners is 'O-Plan' [CT91], being mentioned in 3 different papers, what can be seen in Table A.5.
The second place is composed of the three classes 'Planning Tools', 'Build Tools' and 'Transformation Tools', which forms the sup-class 'Tools'. From the 30 mentioned tools, surprisingly the sub-class 'PDE' gives us most of the tools, which also has one of the most mentioned tools ('FlowOpt', 3 mentions) in the whole sup-class. That shows us that the visualization of plans and the easy modelling and editing of planning problems play an important part in the AI planning area [SURH20].
Surprising is the fact that planning languages, namely STRIPS, PDDL and ADL, are not as much talked about as one might suggest. Only 5 languages are mentioned (PDDL, PDDAML, STRIPS, WoTDL and ASPEN) and only 3 of them are mentioned in 2 papers (PDDL, STRIPS and WoTDL). The importance of PDDL [AHK+98] is undeniable as a state-of-the-art language, with it having multiple variations and versions (in this thesis PDDAML), as well as tools that try to make editing of PDDL easier (namely MyPDDL or PDDL Studio) [SK20].
Interestingly the class 'Knowledge Engineering' has around 15 different tools mentioned, where 'GIPO' and 'EUROPA' are the most mentioned (4 mentions). It is communicated that there needs to be a knowledge base, made through KE tools, to derive input for planners [SSV20]. With the rising importance and demand for autonomous systems, it makes sense that KE makes the 3 biggest class in this thesis.
'Algorithm' which makes the fourth largest class, besides the 'Undefined' class, has planning and learning algorithms combined, but each of them is only mentioned once. That might give the impression that AI planning related algorithms, for different objectives, are not as relevant as other classes.
Compared to tools in the 'WSC' class, this impression might be true. Most of the mentioned tools have more than one mention, with only 'PORSCE' having only one mention.

5.3 Research Question 2

Seeing the graph in Figure 4.6, one can see that most papers do not write about what software engineering principles they used to create a new tool. It is clear that papers, for example [GHL+09], do not talk about that topic. But it is surprising that papers that talk about specifically creating a tool, like 'CADET' [KBG+05], do not give any insight in how it was made or which software engineering principles were considered or followed. But that is not the case for every paper of that sort, because the paper for the tool 'postDAM' [VSB13] states that they followed the principles of prototyping in order to create the tool.

Interesting to point out is that none of the papers before 2010, that were included in the final set of included papers, named any software engineering principle. A reason for that is unknown, and it can only be speculated why that is the case.

5.4 Research Question 3

One would consider that Figure 4.7 is speaking a clear language:
most of the AI planning tools are used in the research department, the industry sector has only a little part to play in the development of AI planning tools. That thought would be a false conclusion because, as already mentioned in chapter 4.4, some tools were in the research phase but are intended for the industry (for example [NG19a]) or some papers mentioned a multitude of tools and there is no clear indication, in the paper, which tool is only used in research and what tool is intended for an industry domain (an example [HVN+12]). To make better predictions which tools are used in practice in the different industry domains, one would have to make a deeper dive into the different tools and determine it for sure.
The problem also is that situation changes with the flow of time. There may be paper that not specifically intended for the usage in the industry, but a high number of planners, or other kinds of AI planning tools, that are used in the industry use the called out tools. For example was it never mentioned in the original paper of PDDL [AHK+98] that it is intended for the industry or the research area, but it is used in both fields because it is stable in many areas and needed for more than enough tools and planners.
To sum up, one can say there is no clear definition of when a tool is intended for the industry or the research area, if it is not clearly stated.

5.5 Research Question 4

From looking at Figure 4.8 it is no surprise that robotics is one of the biggest real-worlds domains that use AI planning tools. Considering the high importance of automated robots in the industry makes it more than plausible [MRB16]. Unexpected mentions are more entertainment focused robotics, like robot bartenders [PF20].
Still, the high usage of AI planning tools in the 'Emergencies' domain is definitely unexpected. Expressions like 'Crisis planning' [des94] or 'Disaster planning' [FM13] define that class to some extent.
'Enterprise planning', which combines terms like 'logistics' [SSV20] or 'process planning' [Cho20], is also not too unexpected with the reason of the rising automation of the industry.
The classification 'Space' forms possibly one of the oldest real-world domains that use AI planning tools, considering the fact that the moon landing and other space operations need to do such things automated and fast [Lon05]. Considering the history of AI planning in space exploration missions, it is remarkable that there are not more papers that mention tools being used by the NASA or other comparable organizations.
The 'New media' term is inspired by the answer 'Narrative generation in New media' [SSV20]. It describes the usage of AI planning in interactive video games or other computer based mediums [GEM16], to either analyse or create a story.
The usage of AI in the personal environment is a new trend, which is compressed into the class

’Assisted living’. Here comes the aspect of automatically cleaning the house [CKS10] or the concept of smart homes into play [NG19a], which can automatically turn on lights or heat up rooms.
It is surprising to see that ’Public service’, which includes terms like ’traffic management’ [SSV20], is on the same level as ’New media’ or ’Assisted living’. Mainly because the increase in automated sections in those two classes is better perceived, than the increase of AI planning in the control of traffic lights.
The last real class ’Internet’ is composed of the terms ’Web Service Composition’ [HVN+12] and ’web based information gathering’ [Cho20], which makes sense when you think about the practices of Google and Co. that gather as much information as possible to analyse the data and improve the output to the user.
Overall we can say that some parts are expected, mostly the big representation of ’Robotics’ and ’Enterprise planning’, and some real-worlds domains are surprising to see, either because one is unaware of the usage of AI planning in those areas (for example ’Emergencies’) or it is interesting to see that is not as strong represented as the expected (for example ’Assisted living’).

5.6 What could have been done differently?

In this paper there were used 6 search libraries: ACM, DBLP, IEEE Xplore, Elsevier, Springer Link and WebOfScience. All these databases are great and offer a wide variety of papers, but they do not cover 100% of the available papers on AI planning. To cover even more papers the search engine ’Google Scholar’ could have been used. Another approach could also have been to get the papers from the IPC, the AAAI, the ICAPS and the IJCAI.
Google Scholar was not included in the search of papers, because it gives a broad number of papers back while a lot of them do not meet the criteria for this study (not written in English, not available or accessible through any means). The search term ’AI planning tool’ alone gives 1,770,000 results, which almost 1000 times more than the number of papers that we got through the search in the 6 databases together. There is also the fact that probably all the papers that ended up in the final set of selected papers, could have been also found through Google Scholar alone, but it would have been a huge time investment to go through all 1,700,000 results of Google Scholar and the 1808 results from the 6 databases. But Google Scholar was a gigantic aid to find related work or the source for most of the mentioned tools, but were not explained in the paper it was extracted from.
On the other hand, the papers from the different conference meeting and competitions could have been a huge addition and help in this SMS. The only problem is that the accessibility to these papers is not as simple as the search in one of the search libraries. Only later, in the classification step, did the use of Google Scholar help find access to papers from the mentioned conferences and competitions.
Another point to consider is the validity of the study. For that we shall look at the following types of validity: descriptive validity, theoretical validity, interpretive validity and repeatability.
The descriptive validity concerns itself with an objective and precise description of the collected data. Following the example of [PVK15], we created a data collection form to reduce the risk of breaking the descriptive validity of the study.
Theoretical validity relies on the ability of capturing the intended data to answer each RQ as good as possible. Points to look out for are the bias of the researcher in each step of the SMS. Above we already mentioned the possibility of missing out important papers in the sampling step by not using Google Scholar or the papers of the different conferences (IPC, AAAI, ICAPS, IJCAI). In

other regards, the fact that only one researcher worked in the Inclusion/Exclusion step is also a threat to the theoretical validity. To minimize the risk, the Inclusion/Exclusion step was divided into two steps, as mentioned in chapter 3. Also in the data extraction and classification step, the threat remains that the researcher extracts data subjectively. To minimize this risk there could have been a step where another researcher looks the collected and classified data through, which was not possible for this study.
Interpretive validity is when the drawn conclusions are reasonable, as stated by [PVK15]. Here researcher bias is also a possible complication. To address this problem it is only possible to ask other experts in the field to validate the drawn conclusion from the presented data.
To ensure repeatability, we documented our process and the actions we took. It was supported by using the guidelines [PVK15] and [PFMM08].

6 Conclusion

To conclude this thesis we can say the variety of tools is widespread through many industry domains and in this SMS alone we presented only 106 tools with many functions and application fields. We can also say that in the 55 papers that were analysed only 5 papers mentioned software engineering principles that were used in the construction of some tools. At some point, we concluded that there is a discrepancy between tools that are talked about in the industry and tools that are mostly mentioned in the research. And lastly, we pointed out a trend of increasing popularity of AI planning tools being presented or mentioned in the last 5 years, making up a bit more than half of the included papers.
If there should be a remake of an SMS of this kind, we suggest including the sources mentioned in chapter 5, section 6 and by that broadening the spectrum of AI planning tools covered.
Seeing the upward trend in recent years, there should be a bigger distribution between the different industry domains considering the digital transformation of the trend of IoT.

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All links were last followed on February 28, 2021.

A Appendix

Year	Source Papers
1991	[CT91]
1994	[des94]
1995	[Pol95]
1996	[Chi96] [MKP96]
2000	[APR00]
2001	[SY01] [RRCB01]
2002	[MD02]
2004	[MBKY04]
2005	[KBG+05] [BG05]
2006	[VG06] [KG06]
2007	[GFB+07] [YWJ07]
2009	[CFH+09] [HMV+09] [GHL+09]
2010	[ZYHL10] [CKS10]
2011	[RG11]
2012	[HVN+12] [DMM12]
2013	[FM13] [VSB13]
2015	[JCKV15] [KWD15] [WCM15]
2016	[MRB16] [GEM16] [SGV16] [GA16] [KLA16]
2018	[LTDD18] [AB18] [GGR18] [VCK18]
2019	[PV19] [SS19] [NG19b] [SKH+19] [AJO19] [NG19a] [BRT19]
2020	[TSL+20] [Pir20] [SSV20] [SK20] [MPMM20] [PF20] [Bar20] [Cho20] [SURH20] [GS20]

Table A.1: All the source papers per year.

Paper Types	Source Papers
Journal	[GS20] [Pir20] [SKH+19] [AJO19] [SS19] [LTDD18] [MRB16] [KLA16] [GA16] [GEM16] [VSB13] [FM13] [HVN+12] [DMM12] [ZYHL10] [CKS10] [CFH+09] [GHL+09] [GFB+07] [YWJ07] [VG06] [BG05] [KBG+05] [SY01] [APR00] [Pol95] [CT91]
Conference	[TSL+20] [BRT19] [NG19b] [NG19a] [PV19] [VCK18] [GGR18] [AB18] [SGV16] [WCM15] [JCKV15] [KWD15] [RG11] [HMV+09] [KG06] [MBKY04] [MD02] [RRCB01] [Chi96] [MKP96] [des94]
Book parts	[Cho20] [MPMM20] [SK20] [PF20] [Bar20] [SURH20] [SSV20]

Table A.2: Paper types of the source papers

Library	Source Papers
ACM	[NG19b] [NG19a] [PV19] [GA16] [SGV16] [GEM16] [CKS10] [SY01] [Pol95]
DBLP	[MPMM20] [SK20] [PF20] [Bar20] [SURH20] [SSV20]
Elsevier	[Pir20] [AJO19] [SS19] [MRB16] [KLA16] [VSB13] [FM13] [ZYHL10] [CFH+09] [GHL+09] [YWJ07] [VG06]
IEEE	[LTDD18] [KWD15] [HVN+12] [RG11] [HMV+09] [KG06] [MBKY04] [RRCB01] [MKP96] [des94]
Springer	[Chi96] [APR00] [MD02] [KBG+05] [DMM12] [JCKV15] [WCM15] [AB18] [GGR18] [VCK18] [BRT19] [Cho20] [GS20] [TSL+20]
WebOfScience	[SKH+19] [GFB+07] [BG05] [CT91]

Table A.3: Libraries of all the included source papers

Classification	**Tools**
Languages	PDDL, PDDAML, STRIPS, WoTDL, ASPEN
WSC	SHOP2, PORSCE, PORSCE 2, OWLS-XPlan, SWORD
Planners	O-Plan, CRIKEY, UP2TA, TLPlan, Prodigy, MVP, CHARADE, NONLIN, UPMurphi, SIPE, SIPE-2, CPT, CPT2, CPPlanner, TALplanner, ZENO, FDP, MAXPLAN, MIPS-BDD, MIPS-XXL, SATPLAN, IPPLAN, HA-PTLplan, CADET, IxTeT, Downward04sa, YochanPS, HPlan-P, VHPOP, SAPA, TP4, HSP^*, SG-Plan5, LPG, SANCTUM, PbP, B^2APE, DDPS, SOCAP, Mood-Plan, TGP, LPGP, TFD, FMD, SPA
KE Framework	Viz, JABBAH, itSIMPLE, GIPO, EUROPA, MARIO, KEWI
KE learning action models	SLAF, LAMP, LOCM, ARMS
KE Pre-/Post-Design Analysis	TIM, RSA, RedOP, ASCoL
Algorithm Planning	SNLP, TWEAK, UCPOP, MBP, Cedalion
Algorithm Learning	FAMA
Transformation Tools	Event-B2PDDL, GROOVE
Build Tools Post-Design tool	postDAM
Build Tools Model Analysis	DISCOPLAN
Build Tools PDE	LTS++, PlanWorks, VAL, InVAL, ReviVAL, PDVer, ValidPlan, MrSPOCK, MyPDDL, PDDL Studio, Web Planner, VisPlan, FlowOpt, iGantt, VLEPpO
Build Tools Planning Workbench	ModPlan
Build Tools Attack Graph Builder	AGBuilder
Planning Tools Framework	POMCP, DIEGESIS, MEA-Graph, RuGPlanner, IBaCoP
Planning Tools Architecture	GrOWTH
Planning Tools Models	PHAMs
Planning Tools Planning Portfolio	MIPlan
Planning Tools Dynamic Plan Simulator	CoastWatch

Table A.4: Tools of RQ1

Source Paper	Tools mentioned
[CT91]	O-Plan
[des94]	SOCAP
[Pol95]	TWEAK, SNLP, NONLIN
[MKP96]	FMD, SIPE, O-Plan
[Chi96]	MVP
[APR00]	CHARADE
[RRCB01]	ASPEN
[MD02]	PDDAML
[MBKY04]	Prodigy, UCPOP
[KBG+05]	CADET
[BG05]	PHAMs
[KG06]	SHOP2, OWLS-XPlan
[VG06]	CPT
[YWJ07]	ARMS
[GFB+07]	MEA-Graph
[HMV+09]	PORSCE, PORSCE II
[GHL+09]	CPT2, FDP, IPPLAN, MAXPLAN, MIPS-BDD, SATPLAN, Downward04sa, MIPS-XXL, SGPlan5, HPlan-P, YochanPS
[CFH+09]	CRIKEY
[CKS10]	HA-PTLplan
[ZYHL10]	LAMP
[RG11]	ZENO, IxTeT, VHPOP, CPT, TGP, LPG, LPGP, CPPlanner, TP4, SAPA, HSP*, CRIKEY, TFD
[HVN+12]	PORSCE II, VLEPPO, MBP, SWORD, OWLS-XPlan
[DMM12]	UPMurphi
[FM13]	DDPS
[VSB13]	postDAM
[KWD15]	POMDP
[JCKV15]	ASCoL
[WCM15]	KEWI
[GEM16]	DIEGESIS, PDDL
[SGV16]	VLEPpO, GIPO, SIPE-2, EUROPA, itSimple, VisPlan, ValidPlan
[GA16]	PDDL
[KLA16]	RuGPlanner
[MRB16]	UP2TA
[LTDD18]	TLPlan, TALplanner, SHOP2
[AB18]	Event-B2PDDL
[GGR18]	B^2APE
[VCK18]	PbP, Cedalion, MIPlan, IBaCoP
[PV19]	SANCTUM
[NG19a]	WoTDL, GrOWTH, SWORD, PORSCE 2
[NG19b]	WoTDL
[SS19]	DISCOPLAN, EUROPA, GIPO, FlowOpt, itSIMPLE, JABBAH, MoodPlan, Viz
[AJO19]	FAMA
[BRT19]	AGBuilder
[SKH+19]	SPA
[SSV20]	O-Plan, SIPE, GIPO, itSIMPLE, EUROPA, ModPlan, VIZ, TIM, DISCOPLAN, RSA, RedOp, VAL, PlanWorks, MrSPOCK, JABBAH, PORSCE II, CoastWatch, FlowOpt, MARIO, SLAF, LAMP, LOCM, ARMS
[SURH20]	LTS++
[Bar20]	VisPlan, FlowOpt, iGantt
[PF20]	STRIPS
[SK20]	MyPDDL, PDDL Studio
[MPMM20]	Web Planner, InVAL, ReviVAL, GIPO, PDVer, itSIMPLE
[Pir20]	GROOVE, STRIPS
[GS20]	DISCOPLAN
[TSL+20]	JSHOP2

Table A.5: Source papers for all the Tools

RQ2 Classifications	Source Papers
Architecture	[WCM15] [FM13]
Software life cycle	[VSB13] [SSV20]
Software qualities	[NG19b] [GEM16] [WCM15]

Table A.6: Source papers for all the found software engineering principles

Area of Use	Source Papers
Industry	[des94] [Chi96] [APR00] [SY01] [RRCB01] [KBG+05] [BG05] [HVN+12] [SGV16] [NG19a] [SS19] [SKH+19] [SSV20] [SURH20] [PF20] [SK20]
Research	[CT91] [Pol95] [MKP96] [SY01] [MD02] [MBKY04] [KG06] [VG06] [YWJ07] [GFB+07] [HMV+09] [GHL+09] [CFH+09] [CKS10] [ZYHL10] [RG11] [HVN+12] [DMM12] [FM13] [VSB13] [KWD15] [JCKV15] [WCM15] [SGV16] [GA16] [KLA16] [MRB16] [LTDD18] [AB18] [GGR18] [VCK18] [PV19] [NG19a] [NG19b] [AJO19] [BRT19] [SSV20] [Bar20] [SK20] [MPMM20] [Pir20] [GS20] [TSL+20]

Table A.7: Source papers for classification of RQ3

Year	Source Papers
1994	[des94]
1996	[Chi96]
2000	[APR00]
2001	[SY01]
2005	[KBG+05] [BG05]
2012	[HVN+12]
2016	[SGV16]
2019	[NG19a] [SS19] [SKH+19]
2020	[SSV20] [PF20] [SURH20] [SK20]

Table A.8: Industry papers by the years

RQ4 Classification	Source Papers
Emergencies	[des94] [APR00] [KBG+05] [FM13] [KWD15] [PV19] [SSV20]
New Media	[SS19] [GEM16]
Internet	[HVN+12] [Cho20]
Robotics	[Cho20] [PF20] [SSV20] [MRB16] [BG05]
Space	[Cho20] [SSV20] [VSB13] [RRCB01]
Assisted living	[NG19a] [GA16] [CKS10]
Enterprise planning	[Cho20] [SSV20] [SKH+19]
Public service	[SS19] [SSV20] [KG06]
Unclassified	[BRT19] [SGV16]

Table A.9: Source papers for all the industry domains mentioned in RQ4

Years	Emergencies	New Media	Internet	Robotics	Space	Assisted living	Enterprise planning	Public service	Unclassified
1994	[des94]								
2000	[APR00]								
2001					[RRCB01]				
2005	[KBG+05]			[BG05]					
2006								[KG06]	
2010						[CKS10]			
2012			[HVN+12]						
2013	[FM13]				[VSB13]				
2015	[KWD15]								
2016		[GEM16]		[MRB16]		[GA16]			[SGV16]
2019	[PV19]	[SS19]				[NG19a]	[SKH+19]	[SS19]	[BRT19]
2020	[SSV20]		[Cho20]	[Cho20] [PF20] [SSV20]	[Cho20] [SSV20]		[Cho20] [SSV20]	[SSV20]	

Table A.10: Source papers for RQ4 shown by years and classification

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

LB, 24.03.21, Philipp

place, date, signature