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Educational robotics competitions as out-of-school learning setting for STEM education

An empirical study on students' learning of problem solving skills through participation in the World Robot Olympiad

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Abstract

Educational robotics is an innovative approach to teaching and learning a variety of different concepts and skills as well as motivating students in the field of Science, Technology, Engineering, and Mathematics (STEM) education. This especially applies to educational robotics competitions such as, for example, the *FIRST LEGO League*, the *RoboCup Junior*, or the *World Robot Olympiad* as out-of-school and goal-oriented approach to educational robotics. These competitions have gained greatly in popularity in recent years and thousands of students participate in these competitions worldwide each year. Moreover, the corresponding technology became more accessible for teachers and students to use it in their classrooms and has arguably a high potential to impact the nature of science education at all levels.

One skill, which is said to be benefitting from educational robotics, is problem solving. This thesis understands problem solving skills as engineering design skills (in contrast to scientific inquiry). Problem solving skills count as important skills as demanded by industry leaders and policy makers in the context of 21st century skills, which are relevant for students to be well-prepared for their future working life in today's world, shaped by an ongoing process of automation, globalization, and digitalization.

The overall aim of this thesis is to try to answer the question if educational robotics competitions such as the World Robot Olympiad (WRO) have a positive impact on students' learning in terms of their problem solving skills (as part of 21st century skills). In detail, this thesis focuses on

a) if students can improve their problem solving skills through participation in educational robotics competitions,
b) how this skill development is accomplished, and
c) the teachers' support of their students during their learning process in the competition.

The corresponding empirical studies were conducted throughout the seasons of 2018 and 2019 of the WRO in Germany.

The results show overall positive effects of the participation in the WRO on students' learning of problem solving skills. They display an increase of students' problem solving skills, which is not moderated by other variables such as the competition's category or age group, the students' gender or experience, or the success of the teams at the competition. Moreover, the results indicate that students develop their problem solving skills by using a systematic engineering design process and sophisticated problem solving strategies. Lastly, the teacher's role in the educational robotics competitions as manager and guide (in terms of the constructionist learning theory) of the students' learning process (especially regarding the affective level) is underlined by the results of this thesis.

All in all, this thesis contributes to the research gap concerning the lack of *systematic* evaluation of educational robotics to promote students' learning by providing more (methodologically) sophisticated research on this topic. Thereby, this thesis follows the call for more rigorous (quantitative) research by the educational robotics community, which is necessary to validate the impact of educational robotics.

Zusammenfassung

Die Robotik stellt einen handlungsorientierten („hands-on") Zugang zur Bildung in Mathematik, Informatik, Naturwissenschaften und Technik (MINT) dar. Dabei fördert sie das Lernen von Schülerinnen und Schülern nicht nur auf kognitiver Ebene, sondern trägt auch zu einer erhöhten Motivation und erhöhtem Interesse bei (affektive Ebene). In den letzten Jahren erfreuen sich gerade Roboterwettbewerbe als außerschulisches Lernangebot steigender Beliebtheit und verzeichnen weltweit jährlich wachsende Teilnehmerzahlen. Beispiele dafür sind die *FIRST LEGO League*, der *RoboCup Junior* und die *World Robot Olympiad*. Zudem steigt auch die Verfügbarkeit der nötigen Robotersysteme für Schülerinnen und Schüler sowie Lehrkräfte, um sie in der Schule einzusetzen und damit verschiedenste Lerninhalte in allen Jahrgangsstufen zu vermitteln.

Ein Lerninhalt, der durch die Robotik besonders gefördert werden können soll, ist das Problemlösen. Problemlösen wird in dieser Arbeit als ingenieurwissenschaftliche Denk- und Arbeitsweise verstanden (im Gegensatz zu naturwissenschaftlichen Denk- und Arbeitsweisen). Das Problemlösen gilt dabei als eine wichtige Fähigkeit im Kontext von sog. *21st century skills*. Diese beschreiben wichtige Fähigkeiten für die Arbeitswelt von morgen. Sie resultieren aus einer fortschreitenden Automatisierung, Globalisierung und Digitalisierung unserer Welt und werden regelmäßig von Vertretern von Industrie und Politik gefordert.

Eine Forschungslücke stellt aber weiterhin die unzureichende *systematische* wissenschaftliche Forschung und Evaluation hinsichtlich des positiven Einflusses der Robotik auf das Lernen dar. Die fehlende Systematik geht dabei vor allem die Verwendung wenig aussagekräftiger Methodik (z.B. deskriptive Erfahrungsberichte von einzelnen Lehrkräften) zurück.

Das übergreifende Ziel dieser Arbeit ist es, zu untersuchen, ob eine Teilnahme an der World Robot Olympiad (WRO) (als Beispiel für einen beliebten Roboterwettbewerb) einen positiven Einfluss auf die Problemlösefähigkeiten (als Teil der 21st century skills) der Schülerinnen und Schüler hat. Dabei wird im Detail untersucht,

a) ob die Problemlösefähigkeiten der Schülerinnen und Schüler durch eine Teilnahme an Roboterwettbewerben verbessert werden können,
b) wie diese Verbesserung zustande kommt und
c) wie die Team-Coaches die Schülerinnen und Schüler während ihres Lernprozesses unterstützen.

Die dazu durchgeführten empirischen Studien fanden in den beiden Jahren 2018 und 2019 im Rahmen der WRO in Deutschland statt.

Die Ergebnisse dieser Arbeit zeigen einen insgesamt positiven Einfluss einer Teilnahme an der WRO auf die Problemlösefähigkeiten der Schülerinnen und Schüler. Dies zeigt sich in einer

Verbesserung ihrer Problemlösefähigkeiten durch die Teilnahme, die nicht durch andere Variablen wie der Kategorie und Altersklasse der WRO, dem Geschlecht und der Erfahrung der Schülerinnen und Schüler sowie deren Erfolg beim Roboterwettbewerb moderiert wurde. Die Verbesserung der Problemlösefähigkeiten erfolgt durch die Verwendung von systematischen ingenieurwissenschaftlichen Denk- und Arbeitsweisen sowie fortgeschrittenen Problemlösestrategien. Die Rolle des Team-Coaches als Manager und Lernbegleiter (im Sinne einer konstruktionistischen Didaktik) im Roboterwettbewerb (besonders bezüglich der affektiven Ebene) wird durch die Ergebnisse der Arbeit ebenfalls unterstrichen.

Zusammenfassend lässt sich also sagen, dass diese Arbeit einen Beitrag hinsichtlich der Forschungslücke leistet und damit dem Aufruf der Community nach weiterer (quantitativer) wissenschaftlicher Forschung nachkommt, der nötig ist, um den positiven Einfluss der Robotik auf das Lernen der Schülerinnen und Schüler zu bestätigen.

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1 Introduction

1.1 Motivation

Preparing students for their working life is one essential goal in education. In recent years, due to the ongoing process of automation, globalization, and digitalization in the world's economy and society, the requirements for students' knowledge and skills to compete on the global job market have changed. Not only have these changes contributed to, for example, the efforts to teach Computer Science (CS) in schools to promote their digital literacy, but a whole new skill set is frequently demanded by industry leaders and policy makers. In today's knowledge society,

> *[t]he current workplace requires highly skilled workers faced with increasingly complex and interactive tasks. Such workers are expected to efficiently select knowledge from the amount of available information and effectively apply such knowledge, both in their professional and personal lives. Employees not only need excellent technical preparation; they also need sufficient skills to adapt to the changing requirements of the job. […] Knowledge has become vital in the 21st century and people need to acquire such skills to enter the workforce called 21st century skills. (van Laar et al., 2017, p. 577)*

Nonetheless, the teaching of this new skill set, which includes skills such as communication, collaboration, or problem solving among others, is still open for debate, especially since these skills are best developed in interdisciplinary, learner-centered, and inquiry-based learning settings, as Eguchi (2017) argues:

> *The skills to innovate cannot be cultivated through current educational practice focusing heavily on the memorization of knowledge without providing opportunities for students to transfer them to practice. There are urgent calls for innovative educational approaches worldwide that can foster skills for innovators including critical thinking, problem-solving, creativity, inventiveness, collaboration and teamwork, and communication skills through transdisciplinary, learner-centered, collaborative, and project-based learning. (Eguchi, 2017, p. 8)*

This thesis deals with educational robotics as an example of such an innovative approach to foster these skills. *Educational robotics* is a phrase used to describe the use of robotics as a learning tool, which "encourages the exploration of ideas using technically and computationally enhanced tangible objects" (Eguchi, 2017, p. 11), in the CS and Science, Technology, Engineering, and Mathematics (STEM)[1] classroom (Eguchi, 2017). In recent years, educational robotics

[1] For the remainder of this theses, the term *STEM (Science, Technology, Engineering, and Mathematics)* will be used as umbrella term, which includes CS in the letter *E* (*engineering*) and T (*technology*) (or the intersection thereof) (Daugherty, 2009; Guzdial & Morrison, 2016). Even though the German pendant *MINT (Mathematik, Informatik, Naturwissenschaften und Technik)* would generally fit better since it explicitly includes CS in the letter *I* (*Informatik*) and does not reduce CS to its engineering tradition (in contrast to its analytical and scientific

gained popular interest at an astonishing rate not only in general society but even more so in the educational community (Benitti, 2012). Additionally, at the same time, the corresponding technology became more accessible for teachers and students to use in their classrooms and has arguably a high potential to impact the nature of science education at all levels, from kindergarten to university (Benitti, 2012).

But is it worth it? Up to now, there is still a major lack of evidence on the impact of this technology on students' learning. Even though many studies have already dealt with the investigation of the impact of educational robotics on students' learning, there is still a lack of *systematic* evaluation (Alimisis, 2013). Benitti (2012), for example, points out that most of the research on educational robotics is descriptive and focuses on reports by teachers (in terms of anecdotal experience reports) achieving positive outcomes with individual, small-scale studies. Additionally, Bredenfeld reports that in many other cases unclear findings in research studies are due to the lack of a transparent research methodology. Consequently, Alimisis (2013) recalls that more rigorous quantitative research is necessary to validate the impact of educational robotics.

Thus, this thesis aims at contributing to this research gap concerning the lack of systematic evaluation of educational robotics to promote students' learning. It focuses on the learning and development of students' problem solving skills as part of their 21st century skills and investigates this in the setting of the *World Robot Olympiad* (WRO), a popular international educational robotics competition. The overall research question of this thesis is:

Do educational robotics competitions such as the World Robot Olympiad have a positive impact on students' learning in terms of their problem solving skills as part of 21st century skills?

The main contribution of this thesis is the detailed examination of engineering design skills as one form of (general) problem solving skills and an empirical study on students' development of their problem solving skills, which was conducted in the WRO in 2018 and 2019. The following section presents the structure of this thesis.

1.2 The model of educational reconstruction as research framework

The structure of this thesis is strongly aligned with the overall research question as mentioned above. Regardless, to embed this research question into a broader educational context, the *model of educational reconstruction* is used as a research framework.

tradition Tedre (2018); Tedre and Apiola (2013)), this thesis is not only explicitly focusing on the engineering tradition of CS but the term STEM is also well established within the English speaking education community. Thus, using *STEM* as umbrella term seems like a reasonable choice.

The model of educational reconstruction was designed by Duit et al. (2005; 2012) (see also Duit (2007)) because of

> *[…] the need to bring science content related and educational issues into balance when teaching and learning sequences are designed that aim at the improvement of understanding science and hence may foster the sufficient levels of scientific literacy. (Duit, 2007, p. 5)*

Thus, this model tries to capture the complex situation in which educational research takes place and can be used in teacher education as well as a framework for science education research (Duit, 2007). Even though the model of educational reconstruction was originally designed for reviewing new content structures to make them accessible for education, Duit (2007) emphasizes the cyclic process of educational reconstruction, which includes the steps of *theoretical reflection, conceptual analysis, small scale curriculum development,* and *classroom research on the interaction of teaching and learning processes*. Duit (2007) coins this *developmental research*. Accordingly, this thesis works in an advanced stage of the cyclic process of educational research, which investigates and evaluates the learning of science content, which has already been put into practice.

In this thesis, the focus itself is not science *content*, but rather on science *processes*. Duit (2007) argues that the modern understanding of scientific literacy claims that *science processes, nature of science,* and *views on daily life in society* are equally important for improved practice. Additionally, this thesis is highly interdisciplinary and investigates problem solving as a science process skill in its position within an overall picture of STEM education.

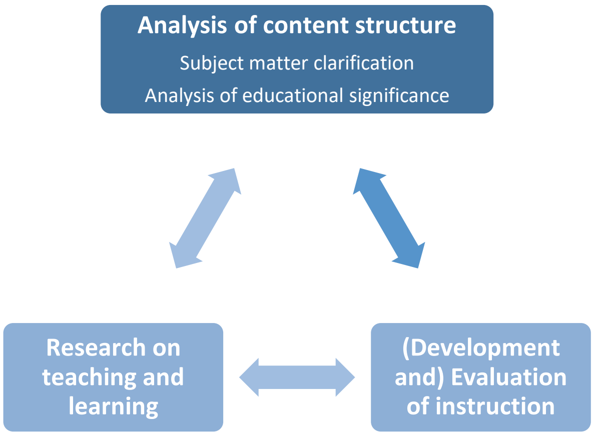

Figure 1: The model of educational reconstruction adapted from Duit (2007).

As indicated in Fig. 1, research on teaching and learning needs to investigate the content structure in the educational setting with its characteristics and constraints. This thesis will process the three components of the model of educational reconstruction as follows:

- Firstly, the **analysis of content structure** consists of the two processes *subject matter clarification* and *analysis of educational significance*. The main idea of the subject matter clarification is to transform science content structures (or here science *process* structures) into a *content structure for instruction*. This transformation (left-to-right arrow in Fig. 2, p. 4) includes the process of *elementarization* (chapters 2, p. 7, and 3, p.16) to reveal the elementary ideas of the content (down arrow in Fig 2.) and the *construction of content structure for instruction* (up arrow in Fig. 2) (chapter 4, p. 26). In this thesis, the elementarization describes the process of explaining and simplifying the science process of problem solving into an appropriate level for educational instruction: the engineering design process as one form of problem solving. Duit et al. (2012) argue that many teachers and researchers think of this process as a form of *reduction*, a view the authors consider as flawed or incomplete. In many cases, the content structure for instruction must indeed be more complex than the science content itself and it is often necessary to embed the abstract notion of science contents and processes (general problem solving skills) into various contexts (engineering design process) to address the learners. In the following, the elementary ideas of the content must be enriched to put them into context for the learners. In this thesis, the engineering design process is implemented in the context of educational robotics (competitions). (Duit et al., 2012)
  The analysis of educational significance for this thesis aims at describing the relevance of the teaching and learning of problem solving skills (as part of 21st century skills). This consists of the normative perspective (i.e. problem solving in frameworks, standards, and curricula) on the one hand (chapter 5, p. 41) and the descriptive perspective (i.e. students' opinion on relevant skills for the 21st century job market) on the other hand (chapter 6, p. 49). The descriptive perspective on the relevance of these skills is particularly interesting because it influences, for example, students' motivation towards learning.

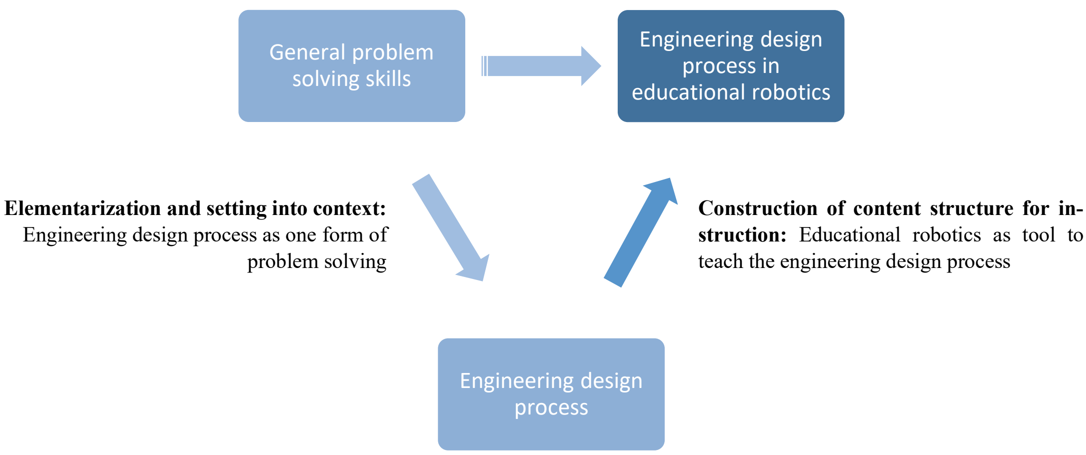

Figure 2: The subject matter clarification describes the process of educational transformation through elementarization of content structure and construction of content structure for instruction.

- Secondly, **(development and) evaluation of instruction**: Duit et al. (2012) state that the design of learning supporting environments is the key to this component of the model of educational reconstruction. Regardless, they continue by saying that the respective evaluation of already implemented environments in further steps of the cycle of development research is equally important (Duit et al., 2012). In this thesis, the specific learning environment is educational robotics competitions, which aim at fostering students' learning of the engineering design process (chapter 7, p. 55). These competitions currently attract a lot of attention in the educational community with thousands of participating students worldwide. Popular examples of educational robotics competitions for students are, for example, the *FIRST Lego League*, *RoboCup Junior*, or the *World Robot Olympiad*.
- And thirdly, **research on teaching and learning**: In the model of educational reconstruction, Duit et al. (2012) stress the importance of evidence-based teaching and learning. Thus, the analysis of the content structure and evaluation of instruction needs to be in accordance with results from empirical research on teaching and learning (Duit et al., 2012). The focus of this thesis is on an empirical study regarding students' learning of problem solving skills (in terms of the engineering design process) in educational robotics competitions. In detail, this evaluation study (chapters 9, p. 73 to 13, p. 117) investigates if
  a) students can improve their problem solving skills through participation in educational robotics competitions (chapter 10, p. 82),
  b) how this skill development is accomplished (chapter 11, p. 93), and
  c) the teachers' support of their students during their learning process in the competition (chapter 12, p. 108).

  In summary, this evaluation study contributes to the research gap mentioned above by examining the impact of educational robotics competitions on students' learning.

The decision in favor of the model of educational reconstruction (Duit et al., 2005; Duit, 2007; Duit et al., 2012) as a research framework relies on its holistic character of research and development and its interdisciplinarity. In contrast to other research frameworks, which focus on, for example, the *development and design of new learning environments* to improve the quality of instruction or refinement of learning theories (development research) or the *empirical investigation of the effectiveness of instructional interventions* (effectiveness research) (Gesellschaft für Fachdidaktik, 2015), the model of educational construction combines these components and interrelates them. Additionally, the model of educational reconstruction is intended for science education in general and is not subject-specific such as, for example, the model by Diethelm et al. (2012) for CS education. Their model explicitly focuses on identifying new contexts (in terms of *real world phenomena*) for instruction. The two central points of this thesis are the analysis of engineering design skills using educational robotics as one form of (general) problem solving and its empirical investigation in an educational robotics competition. Especially the analysis of content structure provides a valid framework to explain engineering design skills using educational robotics as one form of (general) problem solving (within 21st century learning) and contrast them to other forms of problem solving in science education to offer a general perspective (Fig. 2, p. 4).

2 21st century learning

2.1 Genesis

The progressive development of automation, globalization, and digitalization in today's world has a great impact on the future of our working life. Debates about the tendency of this impact mainly show two opposing perspectives: positive and negative. Whereas devotees of the negative perspective fear that technological advancements could lead to, for example, the loss of jobs (especially for less- or unqualified workers), adherents of the positive perspective believe that those technological advancements are more likely to change our professional world in terms of, for example, job profiles.

One very popular example of the negative perspective is a study, which attracted international attention after its publication, by Frey and Osborne (2017). They surveyed the probability of automation (*computerization*) of around 700 occupations in the US to identify the ones at risk. The results of the study show that in the US 47 % of the inhabitants currently work in a job, which is at risk. (Frey & Osborne, 2017)

Even though the worldwide popularity of their study led to the reproduction of it in many other countries, critics argue that Frey and Osborne did not consider the adaptability of workers and occupations. In contrast to the negative perspective, the positive perspective assumes that technological advancements do not necessarily lead to a substitution of jobs, but also create new ones. Regardless, the adaption to the demands of the new job profiles does not happen incidentally. It is the task of education to foster these new skills to prepare students for their future working life.

Today's technological advancements, which led to the phrasing of today's age as *knowledge* or *information age*, present students, teachers, and all other stakeholders in education with the challenge to adapt to this development. The skills, which students need to adapt to, are commonly described as *21st century skills*.

In the following, this chapter aims at defining 21st century skills. For this purpose, the popular framework of 21st century skills by the *Partnership for 21st century skills* is presented and compared with other frameworks and meta-analyses of other 21st century skills frameworks to identify the main components of this new skill set.

2.2 Partnership for 21st century skills' framework

2.2.1 Overview

The *Partnership for 21st century skills*[2] (P21) is a US non-profit organization and a coalition of important partners from the fields of education, businesses (e.g. Apple, Microsoft, Cisco, etc.), and policy makers (US department of education, National Education Association), which collaborate to pursue their common goal to equip students with 21st century skills (Trilling & Fadel, 2009).

The organization raised initial public awareness in 2006 with an article in the *TIME magazine* entitled *How to Bring Our Schools Out of the 20th Century* on the one hand and a survey on the importance of 21st century skills for students on the other (Trilling & Fadel, 2009).

The authors of the article argue that students will not accomplish to be successful in today's economy if they do not acquire these new skills:

> *This story is about […] an entire generation of kids [, who] will fail to make the grade in global economy because they can't think their way through abstract problems, work in teams, distinguish good information from bad or speak a language other than [their mother tongue]. (Wallis & Steptoe, 2006, p. 1)*

They continue their article with an explanation of relevant skills, which students of the 21st century need to obtain:

- *Knowing more about the world*: students need to become global citizens with an understanding of global trade literacy, sensitivity towards foreign cultures, and the ability to speak multiple languages.
- *Thinking outside the box*: New job profiles require students to work creatively and innovatively, recognize patterns in big amounts of data, and develop interdisciplinary perspectives.
- *Become smarter about new sources of information*: In the information age, students must be able to process information quickly, distinguish between reliable and unreliable sources, and manage, interpret, and validate information appropriately.
- *Developing good people skills*: In today's world, students' emotional intelligence is as important as their general intelligence. Because today's innovations usually involve people from all over the world, students need to acquire communication skills and the ability to work in teams. (Wallis & Steptoe, 2006)

Even though these points sound like lurid headlines, they are backed up by a US-wide poll, which asked a sample of 425 representatives from industry to rate the importance of 20 basic knowledge areas and applied skills for job success and the readiness of new employees in their

[2] The *Partnership for 21st century skills* can be found online: https://www.p21.org (last accessed 8th April 2020)

businesses regarding the respective areas. Results show a great discrepancy between the employers' expectancy and the entrants' skills for all educational levels. Employers rate skills such as *professionalism and work ethic, oral and written communications, teamwork or collaboration*, and *critical thinking and problem solving* the highest. Applied skills, which describe the ability to use basic knowledge, which the students learned in school, in an effective way in the workplace, outrank basic knowledge in terms of relevance for job success. (Cavanagh et al., 2006)

The major contribution of the organization is the development of a framework, which arranges knowledge areas and skills of 21st century learning. The framework consists *of knowledge domains* (*the rainbow*), which describe the relevant knowledge areas and skills, and *support systems*, which outline the organizational general terms and conditions of the educational system (Fig. 3). Additionally, Tab. 1 presents an overview with a short description of the different components of the model. A more detailed description of the framework can be found in Trilling and Fadel (2009).

Since this thesis is particularly interested in the role of problem solving skills in 21st century learning, the learning and innovation skills (which include problem solving) are described in the following section in greater detail.

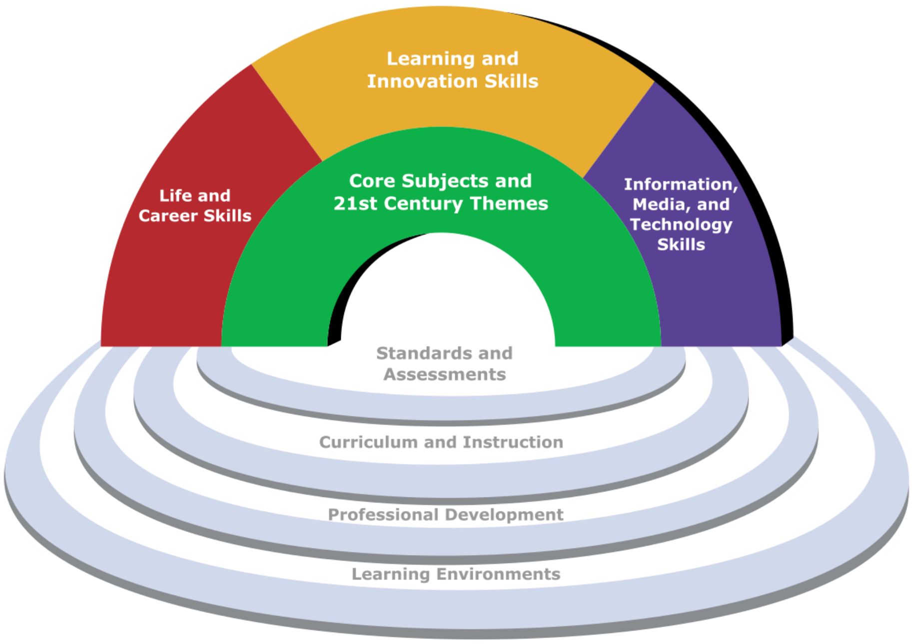

Figure 3: Framework of 21st century skills by the Partnership for 21st century skills. (Trilling & Fadel, 2009)[3]

[3] Even though there are slight derivations in the names of the knowledge domains and support systems in the book by Trilling and Fadel (2009) and the definitions of these in the framework by the Partnership for 21st century learning (2019), they are mainly interchangeable.

Table 1: Overview of the framework of 21st century learning with a short description of the different components as adapted from Trilling and Fadel (2009)

Component		**Description**
Knowledge domains	Core subjects and 21st century themes	Core subjects include (foreign) languages, arts, mathematics, economics, science, geography, history, and government, and civics. Additionally, interdisciplinary themes, which are targeted at the promotion of an advanced understanding of current social issues. They include *global awareness, financial, economic, business, and entrepreneurial literacy, civic literacy, health literacy,* and *environmental health literacy.*
	Life and career skills	Life and career skills describe the ability to deal with the new situation within a rapidly changing working life in the information age. They are comprised of *flexibility and adaptability, social and cross-cultural skills, productivity and accountability,* and *leadership and responsibility.*
	Learning and innovation skills	The learning and innovation skills describe the ability to become self-reliant lifelong learners. They comprise *creativity and innovation, critical thinking and problem solving,* and *communication and collaboration.*
	Information, media, and technology skills (or digital skills)	The ubiquitous penetration of technology in all industries demands a higher degree of digital literacy skills. They include *information literacy, media literacy,* and *information and communication technologies (ICT) literacy.*
Support systems	Standards and assessments	Standards describe what students need to learn. They are output-oriented (i.e. describe competencies of students at different levels) and link subject-specific contents to interdisciplinary and real-world problems, which deal with current societal issues in a global context (e.g. bioengineering or green energy technology). Methods of assessment of 21st century learning require methods of formative assessment (i.e. focusing on the process of learning) supplementary to summative assessment. Examples are evaluations of portfolios or student project work, classroom observations, performance rubrics, quizzes, simulations, etc. They provide instant feedback and allow changes in the instruction process.

	Curriculum and instruction	Instructional methods in 21st century learning use inquiry- or problem-based and design-based activities that focus on interdisciplinary themes.
	Professional development	Teachers in 21st century learning adopt a new role as mentor, who use methods of instruction and assessment in their classrooms. Professional development needs to teach teachers the implementation of these new methods by having teachers to design, implement, and evaluate 21st century learning projects in collaboration with colleagues.
	Learning environments	Learning environments in 21st century learning do not only refer to physical classrooms but also temporal and organizational environments (i.e. schedules, courses, activities, educational technology, etc.). 21st century learning demands a higher degree of flexibility for students. For example, classrooms should be designed as learning studios, which allow multiple forms of student-teacher-interactions (e.g. space for project work, group presentations, labs, and workshops for (design) experiments, individual study areas, etc.).

2.2.2 Learning and innovation skills

The learning and innovation skills are highly demanded by 21st century employers and foster the ability of students to become self-reliant lifelong learners. They are composed of the skills *creativity and innovation*, *critical thinking and problem solving*, and *communication and collaboration.* (Trilling & Fadel, 2009)

Thinking creatively is a relevant skill to fight current issues and problems of today's world:

> *[…] the ability to solve problems in new ways (like the greening of energy use), to invent new technologies (like bio- and nanotechnology) or create the next […] application of existing technologies (like efficient and affordable electric cars and solar panels), or even to discover new branches of knowledge and invent entirely new industries, will all be highly prized. (Trilling & Fadel, 2009, p. 56)*

However, teaching creativity appears to be difficult, but can be achieved in learning environments, which promote asking questions, are open to new ideas, and learning from mistakes (Trilling & Fadel, 2009).

Critical thinking and problem solving and *creativity and innovation* are closely linked. Creative thinking is indispensable when solving real-world problems. Firstly, to come up with a creative and innovative solution to a problem, using various ways of reasoning (inductive, deductive, or abductive) and analyzing how parts of a whole interact with each other in complex systems is necessary. Secondly, when an idea for a solution was proposed, analyzing, and evaluating evidence and alternative approaches are important to draw conclusions and critically reflect on the initial idea. Thus, critical thinking and problem solving gradually improve a solution to a problem, which consequently leads to a better solution. (Trilling & Fadel, 2009)

Since most of today's employees do not work on a project on their own but in collaboration within (global) teams with members of different businesses and institutions, communication and collaboration skills are crucial. They include the ability to articulate in oral, written, and non-verbal forms of communication in different contexts, to understand the meaning of messages by others, including their attitudes and intentions, and to use communication for many purposes such as, for example, informing, instructing, motivating, persuading, etc. Moreover, since those teams often collaborate remotely, the effective use of technology for communication is required. Finally, successfully working together in a team demands the willingness to make compromises to accomplish a common goal and share responsibility for the common work, where each team member made an important contribution. (Trilling & Fadel, 2009)

Design challenge projects, which ask students to come up with (and gradually develop) a solution to a real-world problem can be one way of effective teaching. In these projects, students need to work collaboratively and communicate throughout the whole process and present their solution at the end of the project. (Trilling & Fadel, 2009)

2.3 Other frameworks and meta-analyses of 21st century skills framework

Of course, the Partnership for 21st century skills is not the only organization, which developed a framework for 21st century learning. Other suggestions include frameworks by, for example, the *International Society for Technology in Education* (ISTE) or the *Organization for Economic Cooperation and Development* (OECD) (Kereluik et al., 2013). Due to the high number of frameworks, meta-analyses have evolved, which compare different frameworks to identify commonalities and differences.

One example of such a meta-analysis was conducted by Kereluik et al. (2013). They contrasted 15 frameworks of 21st century learning and concluded three types of knowledge: *foundational*, *meta*, and *humanistic knowledge*.

The first cluster, which appeared in the text analysis by the authors, is *foundational knowledge* and describes *what* students need to know (Kereluik et al., 2013). This cluster consists of three components:

- *Core content knowledge* is highly linked to knowledge in the traditional domains. Regardless, core content knowledge always needs to connect to the real world, for example, in mathematics by applying mathematical thinking to solve everyday problems or, in science, applying scientific ways of thinking to understand the natural world.

- *Cross-disciplinary knowledge* focuses on the integration of knowledge from multiple domains either to synthesize information from those or to apply knowledge from one domain in another to generate new ideas.
- *Digital or ICT literacy* is often mistaken for the mere use of technology, as often proposed by the general public, but describes the process of effectively and thoughtfully processing (evaluate, navigate, and construct) information using a wide range of technological tools. This literacy also includes a moral and ethical understanding and responsible use of technology. (Kereluik et al., 2013)

The second cluster is *meta knowledge*. This type of knowledge describes the process of working *with* foundational knowledge (Kereluik et al., 2013). Again, three subtypes can be identified:

- *Creativity and innovation* are the application of a wide range of knowledge and skills in novel ways.
- *Critical thinking and problem solving*: Whereas critical thinking is the ability to evaluate information and make smart decisions based on this information, problem solving uses critical thinking in the process of solving a specific problem towards a goal.
- *Communication and collaboration* describe clear articulation via different mediums and the mindset to actively and effectively cooperate in diverse groups. (Kereluik et al., 2013)

The last cluster is entitled *humanistic knowledge* and describes the role of the individual using its foundational and meta knowledge in a social context (Kereluik et al., 2013). The three subtypes are:

- *Life and job skills* are necessary to prepare students for lifelong learning outside the classroom.
- *Ethical and emotional awareness* defines the ability to show empathy towards others and understand their actions in a culturally different society.
- *Cultural competen*ce is closely related to ethical and emotional awareness and focuses on personal and inter- and intrapersonal aspects of communication and collaboration. (Kereluik et al., 2013)

Even though the role of technology seems to get lost in this synthesis with its only reference in the subtype of digital and ICT literacy, Kereluik et al. (2013) argue that technology implicitly influences all clusters. For example, whereas, for foundational knowledge, technology has changed the methods of acquiring, representing, and manipulating knowledge in all disciplines, for meta knowledge, *acting* with technology comprises not only the mere use of it in basic ways but also includes reusing and repurposing it (*remixing*) and has influenced ways of communicating and collaborating (Kereluik et al., 2013).

Another meta-analysis by Voogt and Roblin (2012) concludes that the following skills can be found in many or most 21st century skills frameworks: *collaboration, communication, digital literacy, citizenship, creativity, critical thinking, problem solving,* and *productivity* (Voogt & Roblin, 2012).

2.4 Implications for educational practice

One follow-up question to the definition of 21st century learning regards the implications of this new type of learning on educational practice. First remarks concerning the influences of 21st century learning on aspects such as *standards and assessment, curriculum, professional development,* and *learning environments* have already been made before. Continuing, we now want to examine the teacher's perspective on 21st century learning.

A study by Mishra and Mehta (2016) asked 738 teachers in the US via an online survey to rate the importance of each of the nine subtypes of 21st century learning, which resulted from the meta-analysis by Kereluik et al. (2013) (section 2.3, p. 12). Results show that teachers consider meta knowledge (creativity and innovation, critical thinking and problem solving, and communication and collaboration) as the most important of the three clusters. Within meta knowledge, critical thinking and problem solving are assessed the highest. Foundational knowledge is considered the least important. (Mishra & Mehta, 2016)

But how are critical thinking and problem solving (among other types of meta knowledge) taught? Trilling and Fadel (2009) argue that critical thinking and problem solving can only be taught by applying the *scientific method*:

> *The careful construction of basic questions about our natural world and the imaginative search for accurate answers to them are at the center of the scientific method - our most important innovation for exploring and uncovering new knowledge. (Trilling & Fadel, 2009)*

At the heart of this learning process are the following two concepts: *questions* and *problems*:

> *Questions and problems are the foundations for the two most powerful approaches humankind has yet developed for gaining new knowledge and creating new ways of living: science and engineering. (Trilling & Fadel, 2009, p. 90)*

Whereas (natural) scientists are motivated by unanswered questions, engineers are challenged by new problems to solve (Trilling & Fadel, 2009):

> *Scientists use experiments to test an explanation or hypothesis, and engineers devise prototypes or create new designs to see how well their solution works. Applying both scientific and engineering methods to basic questions and the problems of our times has*

> *vastly accelerated the growth of new knowledge, new skills, and the innovations of modern living. Along with the arts and culture, and our evolving social and political structures, science, and engineering have propelled human progress. (Trilling & Fadel, 2009, p. 92)*

The corresponding teaching approaches are called *inquiry-based learning* for questions and *design-based learning* for problems (Trilling & Fadel, 2009). In general, problem solving as 21st century skill can only be learned through these corresponding teaching approaches.

As mentioned before, the teachers in the study consider foundational knowledge the least important. Regardless, it is not obsolete and meta knowledge needs foundational knowledge as a basis. Mishra and Mehta (2016) argue that meta knowledge is not content-neutral and that, for example, being a creative mathematician does not have to be the same as being a creative musician. The same applies to other disciplines. Even though these skills are often considered similar and transferable, teaching them must be applied in multiple disciplines. Thus, in the next chapter, the manifestation of problem solving skills (as an umbrella term of scientific inquiry and (engineering) design) will be examined in the variety of STEM disciplines to identify commonalities and differences.

3 Problem solving in STEM education as part of 21st century skills

3.1 The interdisciplinary perspective

General problem solving skills are relevant for all STEM disciplines. Regardless, Priemer et al. (2020) argue that all disciplines have worked with domain-specific models of problem solving to teach and learn those skills in the respective domains so far. However, due to the increasing demand for integrated STEM education when working on natural phenomena and authentic contexts for problem solving, those domain-specific approaches fall short and demand an integrated framework. (Priemer et al., 2020)

Nonetheless, they do not suggest a single method to solve problems in their integrated framework but provide

> *[…] a set of idealized, principal problem-solving processes (epistemological ways) originating from the STEM disciplines that can be selected and possibly combined, adapted, and applied to a specific context. (Priemer et al., 2020, p. 106)*
>
> and
>
> *[…] a novel domain-general framework (detached from context) that works as methodological 'quarry', where students choose bits and pieces and customize and apply them according to their specific problem. (Priemer et al., 2020, p. 106)*

Even though they call for a domain-general model of problem solving, Priemer et al. (2020) emphasize that teaching general problem solving skills is inappropriate. In contrast, depending on the specific problem, single parts or paths from their model can be used to solve the problem in its context. However, the students need to acquire an understanding of the generalizability of their domain-specific problem solving activities towards the domain-general framework (abstraction/concretization). This is following the opinion of Mishra and Mehta (2016), who argue that teaching using the scientific method (as means to foster meta knowledge) is not content-neutral, but needs foundational knowledge to act upon.

Regarding the model of educational reconstruction, the steps of abstraction/concretization, which the students are required to take for a general understanding of problem solving, resemble the process of *elementarization*. Whereas for science *content* structures it is necessary to simplify the content structures to reveal the elementary ideas of the content, the abstract notion of science *process* structures (general problem solving skills) needs to be put into various contexts (engineering design) for teaching the learners.

Fig. 4 presents a visual representation of their domain-general model of problem solving for science education, which is the result of a literature review of domain-specific problem solving approaches in STEM (Priemer et al., 2020).

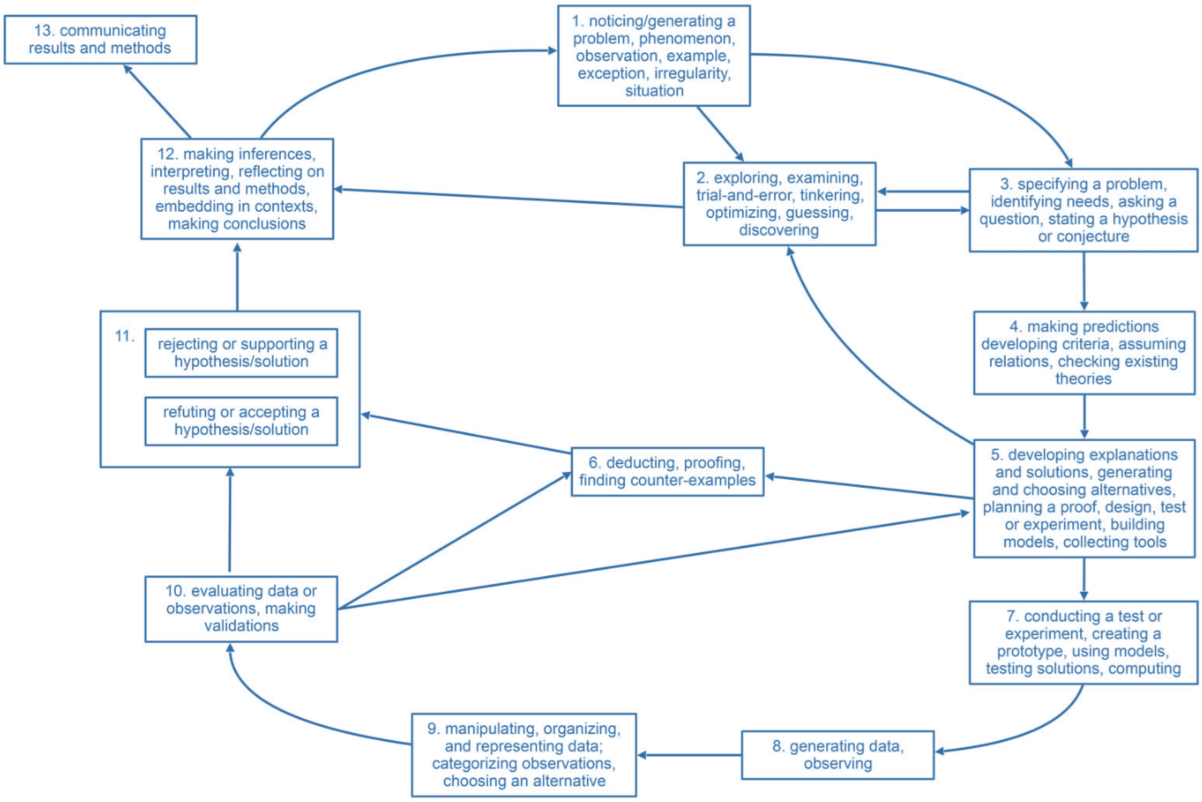

Figure 4: Integrated domain-general model of problem solving as adapted from Priemer et al. (2020).

As indicated above, single parts or paths in this model can be used to solve a problem in its context. For example, inquiry-based learning in natural sciences involves the steps *noticing a phenomenon, asking a question, stating a hypothesis, planning an experiment, conducting an experiment, generating, manipulating, and evaluating data, rejecting or supporting the hypothesis, and making inferences, embedding in contexts*, and *reflecting on the results and methods.* In contrast, in design-based learning, the optimization of a device is often the goal of development and be achieved through a problem solving process, which comprises the steps *noticing a problem, identifying needs, developing criteria, developing solutions, creating a prototype, evaluating, rejecting or supporting the solution, making inferences, embedding prototype in contexts*, and *reflecting on the results and methods.* (Priemer et al., 2020)

In the following, the domain-specific perspectives from science, mathematics, engineering, and technology, and CS will be contrasted and the engineering design process as *one* form of general problem solving skills will be deducted.

3.2 Problem solving in different disciplines

3.2.1 Science

In Science, problem solving is highly connected to *inquiry learning* and *scientific reasoning* (Pedaste et al., 2015; Priemer et al., 2020). Pedaste et al. (2015) define inquiry learning as

> *[…] an educational strategy in which students follow methods and practices similar to those of professional scientists in order to construct knowledge. It can be defined as a process of discovering new casual relations, with the learner formulating and testing them by conducting experiments and/or making observations." (Pedaste et al., 2015, p. 48)*

They concluded a comprehensive framework for inquiry learning from a systematic literature review, which resulted in the *inquiry cycle*. This inquiry cycle consists of the following phases: *orientation, conceptualization, investigation, conclusion,* and *discussion*. Fig. 5 presents an overview of the inquiry learning cycle (Pedaste et al., 2015).

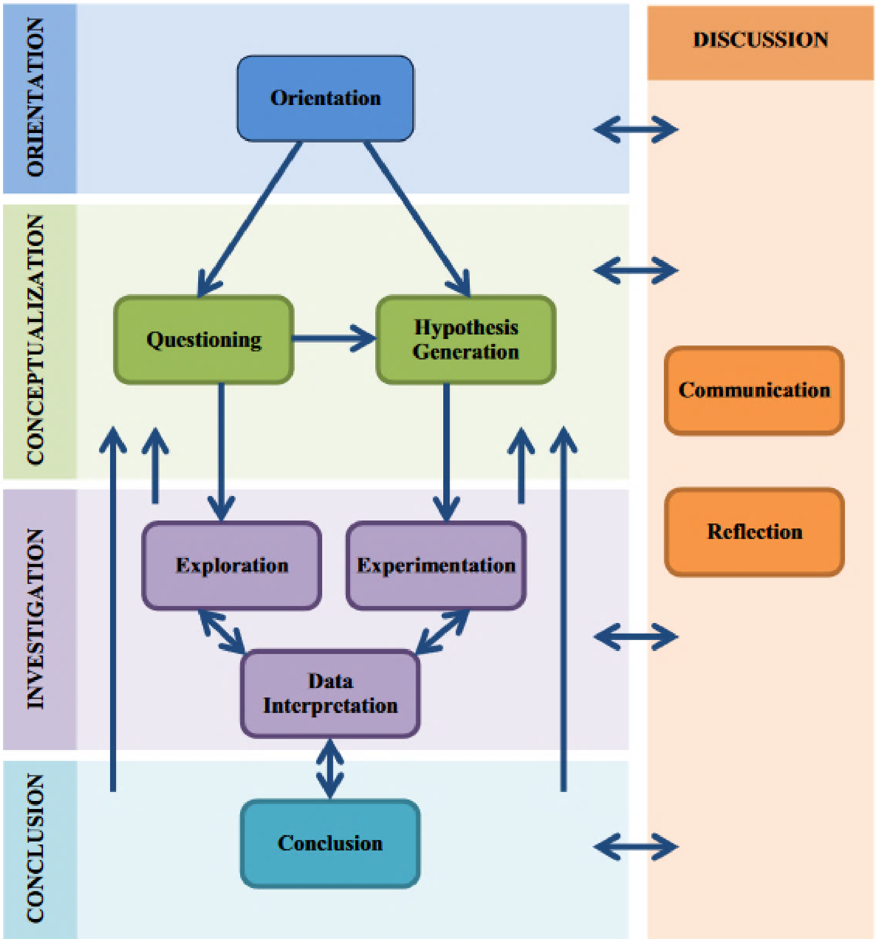

Figure 5: The inquiry cycle (as a result of a systematic literature review) by Pedaste et al. (2015).

Even though the description in Fig. 5 might suggest a linear model, the authors emphasize the possibility of different pathways through the model (Pedaste et al., 2015). By way of example, they suggest three approaches with the following steps, from open-ended to target-oriented starting points:

- *Data-driven* approach: If students have no specific idea what to explore, they should start with exploring a phenomenon; this approach includes the phases *orientation, questioning, exploration, questioning, exploration, data interpretation,* and *conclusion,* but the loop between questioning and exploration can be repeated many times.
- *Question-driven* approach: If students have an idea of questions, they need to collect background information to propose a valid hypothesis; this includes the phases of *orientation, questioning, hypothesis generation, experimentation, data interpretation, questioning, hypothesis generation, experimentation, data interpretation* and *conclusion* (the loop between hypothesis generation, experimentation and data interpretation can be repeated many times).
- *Hypothesis-driven* approach: If students have a theory in mind about what to investigate, they should follow the phases *orientation, hypothesis generation, experimentation, data interpretation, hypothesis generation, experimentation, data interpretation,* and *conclusion*; the loop between hypothesis generation, experimentation and data interpretation can be repeated many times. (Pedaste et al., 2015)

In physics education, a competence model for experimentation by Nawrath et al. (2011) agrees with the possibility of having different pathways through their model, which consists of the phases *develop questions*, *formulate hypotheses*, *plan an experiment*, *arrange experimental setup*, *observe, measure and document*, *cleanse data*, and *draw conclusions*. Thus, for instruction, teachers can focus on different aspects of the model (e.g. formulating hypotheses). Moreover, they constructed their model as a radar chart, which allows teachers, for example, to evaluate students' performance for each phase (Nawrath et al., 2011).

In biology education, Mayer (2007) defines scientific inquiry as a process, which includes the phases of *formulating questions, generating hypotheses, planning an experiment,* and *analyzing data and drawing conclusions*. He argues that there is a broad consensus among all natural sciences that scientific inquiry is a form of problem solving and that it is a skill, which needs to be separated from mere conceptual knowledge (Mayer, 2007).

In summary, the review by Pedaste et al. (2015) shows that specific phases are of general importance (e.g. experimentation, data interpretation, conclusion). Osborne et al. (2004) describe this general process *as reasoning based on evidence* or *scientific reasoning* (Osborne, 2013). The model of scientific reasoning by Osborne (2013) describes the phases of *investigating (experimentation), developing explanations and solutions (hypothesis generation), and evaluating (evidence evaluation).* Additionally, Kind and Osborne (2017) describe six different types of scientific reasoning:

- *Mathematical deduction:* The use of mathematics to represent the world for deductive argument.
- *Experimental evaluation:* The empirical investigation to establish patterns and to test the predictions of a hypothesis.
- *Hypothetical modeling:* The use of analogical and hypothetical models to represent the world.
- *Categorization and classification:* The ordering of elements by comparison and taxonomy.
- *Probabilistic reasoning:* The statistical analysis of regularities in populations, identification of patterns, and the calculus of their probability.
- *Historical-based evolutionary reasoning:* The construction of historical accounts of the derivation of the development elements of the world. (Kind & Osborne, 2017)

Following the idea of elementarization of science process structures in the model of educational reconstruction, the authors argue that students should touch on all of these different types of scientific reasoning to get a general understanding of scientific reasoning as a form of problem solving (Kind & Osborne, 2017).

3.2.2 Mathematics

The founding father of problem solving in mathematics is Polya (1957). He describes the process of problem solving as a set of steps and heuristic strategies to solve a problem (Polya, 1957). Regardless, Priemer et al. (2020) argue that, even though Polya's approach goes back to the 1950s and 60s, there are still similar approaches in today's mathematics education with *inquiry-based mathematics education* (Artigue & Baptist, 2012) and *mathematical experimentation* (Philipp, 2013).

Inquiry-based mathematics resembles inquiry learning in science to a great extent (Artigue & Baptist, 2012). Regardless, inquiry in mathematics differs from inquiry in science in terms of the *types of questions* it addresses and the *processes* it uses to answer them (Artigue & Baptist, 2012). One the one hand, questions of inquiry in mathematics can derive from *external sources* such as, for example, natural phenomena (e.g. how to understand and characterize changes in the shadow of an object cast by the sun), technical problems (e.g. how to measure inaccessible magnitudes and objects) and daily-life issues (e.g. how to choose between different offers on mobile telephony and internet), but they can also derive from *internal sources*, i.e. mathematical objects: what is the greatest product than can be obtained by decomposing a positive integer into a sum of positive integers and multiplying the terms by the sum? If two triangles have the same perimeter and the same area, are they necessarily isometric (Artigue & Baptist, 2012)? Depending on the type of question, inquiry-based mathematics uses different processes. Firstly, regarding questions from external sources, the most difficult part is the transformation of these questions into a mathematical shape, which leads towards a *modeling cycle* (Artigue & Baptist, 2012). Secondly, questions from internal sources can for example use deductive methods like *proofing* (Artigue & Baptist, 2012).

Priemer et al. (2020) describe this differentiation of problem solving approaches in general into e*mpirical-oriented* (inductive) and *theory-oriented approaches* (deductive). All in all, Artigue and Baptist (2012) describe several aspects of mathematical inquiry, which are similar to inquiry in science: *role of exploration, non-linearity of the process, definitive nature of the results,* and *importance of finding generalizations.*

According to Phillip (2013), *mathematical experimentation* is a form of explorative problem solving. In mathematical experimentation, students use a systematic investigation to explore examples and discover and confirm hypotheses. The process of mathematical experimentation consists of the four phases *create own examples*, *find structures*, *formulate hypotheses*, and *confirm hypothesis using examples* (Philipp, 2013).

3.2.3 Engineering and technology

Engineering and technology (technology as a result of the application process of engineering) share many similarities with scientific inquiry (Priemer et al., 2020). Typical phases of their problem solving process are *problem posing, developing empirical tests* and *drawing conclusions* (Priemer et al., 2020). The problem solving process by engineers is also described as *engineering design* (Katehi et al., 2009). Characteristic aspects of engineering design are its *purpose* and the *specifications and constraints* of the artifact as a product of the engineering design process (Katehi et al., 2009). In general, engineering design is a systematic and cyclic process, which consists of the following steps: *identifying the problem, generating ideas how to solve the problem* (e.g. brainstorming), *building and testing multiple prototypes*, *evaluation of prototypes* (with specifications and constraints in mind and including trade-offs to balance conflicting constraints (*optimization*)) (Katehi et al., 2009). In comparison to scientific inquiry, engineering design resembles similar features in their problem solving processes such as, for example, the use of similar cognitive tools (e.g. brainstorming, reasoning by analogy, mental models, and visual representations) in the search of possible solutions or the testing and evaluation of the product in terms of the artifact or scientific hypothesis (Katehi et al., 2009). Regardless, they also differ in some features. For example, budget or time constraints can influence the quality of engineering artifacts (Katehi et al., 2009). Additionally, using trade-offs in the process of optimization is distinctive for engineering design (Katehi et al., 2009). Interestingly, whereas scientific inquiry in science or mathematics is mostly about the generalization of a specific (natural) phenomenon, engineering design describes the development of an artifact as a particular solution (Katehi et al., 2009; Priemer et al., 2020).

3.2.4 Computer Science

The *engineering tradition* of CS as described by Tedre (2018) and Tedre and Apiola (2013) closely resembles engineering design. Engineering in CS can occur in the forms of, for example, computer engineering, software engineering, or electrical engineering (Tedre & Apiola, 2013). Methodologically, engineers in CS follow the same process as described in section 3.2.3. Tedre and Apiola (2013) describe an engineering cycle, which comprises the phases *defining requirements and specifications*, *designing*, *implementing*, and *testing*, which can be iterated multiple times (Tedre & Apiola, 2013). Additionally, they describe parameter variation as one of the most frequent working methods of engineers in CS (Tedre & Apiola, 2013). This systematic progression in engineering is also evident in the numerous process models for software engineering projects. This also includes new forms of agile software development, a topic, which has also been adapted for use in CS classrooms by Brichzin et al. (2018).

Moreover, engineering – as an experimental area of CS – attracts a lot of attention in today's CS education in terms of *physical computing* (Przybylla & Romeike, 2018):

> *Physical computing is the creative design and realization of interactive objects or installations, which are programmed, tangible artifacts that communicate with their environment using sensors and actuators. In physical computing, methods and concepts of embedded systems and interaction design are used. (Przybylla, 2018, p. 34)*

Characteristics of physical computing are the resulting *products*, the *tools* to build these products, and the working *processes*, which are required to make the products out of the tools (Przybylla, 2018).

Even though Przybylla (2018) describes *tinkering*, *project planning*, and *prototyping* as common practices in physical computing, Katehi et al. (2009) underline that engineering design is particularly different from tinkering because of the explicit goal for design since engineers have developed rules and principles, which control the development of a design. Katehi et al. (2009) even state that "[e]ngineering design is not the same as trial-and-error 'gadgeteering'".

An explicit link between physical computing and scientific inquiry has been made by Schulz and Pinkwart (2016). They define a physical computing process model based on a comparison of working methods of physical computing with the processes of scientific inquiry and experimentation in other STEM disciplines (Schulz & Pinkwart, 2016). Their model consists of the phases *preparation*, *implementation*, *performance*, and *evaluation* (Schulz & Pinkwart, 2016).

In general, CS as a discipline derives from three intertwined traditions: *analytical*, *scientific*, and *engineering* (Tedre, 2018; Tedre & Apiola, 2013). Firstly, the analytical tradition is theoretically-oriented and focuses on formal methods from mathematics and logic. Secondly, the scientific tradition is empirically oriented and emphasizes data and simulation and manipulation thereof.

And, thirdly, the engineering tradition is technologically oriented and accentuates the design and engineering methods. (Tedre, 2018; Tedre & Apiola, 2013)

Whereas the engineering tradition understands problem solving in terms of the engineering design cycle, the analytical tradition resembles problem solving in terms of (mathematical) proofing and the scientific tradition reflects problem solving as scientific inquiry as used in natural sciences. Tab. 2 presents the *modi operandi* of the three traditions compared (as adapted from Tedre and Apiola (2013)):

Table 2: Modi operandi of the analytical, engineering, and scientific tradition of CS

	Analytical tradition	Engineering tradition	Scientific tradition
Proposes	Conjectures	Actions	Observations
Works with	Axioms and theorems	Processes, rules, and heuristics	Models, theories, and laws
Uses methods	Analytical, deductive	Empirical, constructive	Empirical, deductive, and inductive

To gain a deeper understanding of engineering design in CS, the next section continues with an explanation of engineering design as problem solving process, including key concepts and skills, which are necessary to understand engineering design.

3.3 Engineering design as a problem solving process

The engineering design process is a problem solving approach used by engineers to solve problems. This approach stands in contrast to scientists, who use scientific inquiry to find solutions or hypotheses about natural phenomena (Katehi et al., 2009; Priemer et al., 2020; Trilling & Fadel, 2009). It resembles an iterative problem solving approach, which consists of the phases *identifying the problem*, *generating ideas how to solve the problem* (e.g. brainstorming), *building and testing multiple prototypes*, *evaluation of prototypes* (with specifications and constraints in mind and including trade-offs to balance conflicting constraints (*optimization*)) (Katehi et al., 2009).

In addition to the differences, which have been found between engineering design and scientific inquiry (e.g. the use of trade-offs to balance conflicting constraints), several concepts and skills are key to understanding engineering design:

Systems describe the collection of individual components and how they work together to perform a function. Engineering design is about the analysis and design of systems. Thinking in systems also includes an understanding of the concept of *structure-behavior-function*. It links the components of a system (structure) to their purpose (function) and the mechanisms, which lead to specific *behavior* of the system. Thus, engineering design is about the investigation of *cause-and-effect principles*. The process of *optimization* describes the manipulation of the system towards better functionality and higher effectiveness by manipulating *multiple variables*. Regardless, to manipulate variables, the cause-and-effect principles of these variables must be clear, and *trade-offs* have to be made during the process of optimization when the manipulation of one variable influences another variable. This dependency of multiple variables is rarely straightforward but mostly highly complex. (Katehi et al., 2009)

Apart from these concepts, engineering design also constitutes skills: *drawing, representing, and modeling* and *experimenting and testing*. Before designing a system, engineers use models to understand a system. Models (of systems) can comprise *representational models* (e.g. drawings), which give the first idea about the system and can be advanced to *mathematical models*. Models allow engineers to conduct *predictive analyses* of the system. Based on these analyses, the prototypes of the system can be built and evaluated. This includes *experimenting and testing*. Through multiple iterations of experimenting and testing, the system can be *optimized* in light of the requirements the system has to meet and the constraints it has to adapt to. (Katehi et al., 2009)

Priemer et al. (2020) argue that in engineering and practical areas of CS the optimization of a device can be the goal of a (system) design activity. To link design-based activities with students' conceptual learning and address issues of assessment of such activities, Rahimi et al. (2018) introduced an advancement of the learning-by-design framework by Kolodner et al. (2003), which focused on the intermediate products, which students create during these activities, as connection points of the making and learning cycle (Fig. 6).

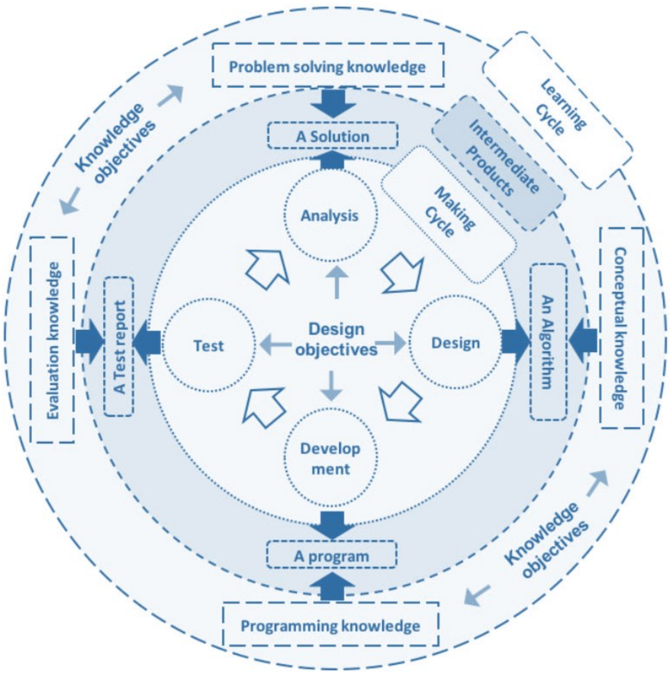

Figure 6: An instructional model to link design-based activities and students' conceptual learning. (Rahimi et al., 2018)

This instructional model defines four intermediate products, which ought to display students' learning in design-based activities. These include a *conceptual solution* (i.e. overview of the design problem), an *algorithm* in terms of a flowchart as language-independent and visual representation, a *program,* and a *test report.* These products can serve as evidence of students' learning and be used in (formative) assessment. (Rahimi et al., 2018)

One example of a system or object, which students can design, is educational robots, which are thought to exhibit specific behavior, which is usually accomplished through an iterative process of design and redesign. They are a great tool to teach the engineering design process as one distinct form of problem solving. (Katehi et al., 2009; Priemer et al., 2020)

Consequently, the next chapter introduces educational robotics as a hands-on learning tool for STEM education.

4 Educational robotics as a *hands-on*-learning tool for STEM education

4.1 The engineering tradition of CS and constructionism as fundamental theory of learning in educational robotics

In the past, many have discussed the importance of the three different traditions of CS (analytical, engineering, and scientific). Whereas questioning the analytical tradition was hardly an issue, the debate was rather about whether to accept the (scientific and) engineering tradition as traditions of CS. Regardless, Tedre (2018) points out that the working practice of most computer scientists nowadays is indeed in engineering, design, and development, and, thus, the engineering tradition is of great importance for CS education at a school level. Additionally, he argues that others base their opinion regarding the importance of CS education on the methods and practices of CS, which reveal its engineering nature (design and programming as *art, craft, trade or skill*). (Tedre, 2018)

On a school level, the engineering tradition is not only associated with the mere development of software in terms of programming exercises but can also be expanded to the real world by using *physical computing* devices, such as microcontroller systems or educational robots. The integration of physical computing in the classroom has already been discussed by many, such as, for example, Przybylla and Romeike (2018). Educational robotics, as a specific area of physical computing, is a well-tested approach of the engineering tradition, which is widely used in the CS classroom and presents a significant research base (Przybylla & Romeike, 2018; Tedre & Apiola, 2013).

As part of the engineering tradition of CS, educational robotics has its roots in the learning theory of *constructionism*. This theory was developed as a derivative of Jean Piaget's *constructivism*, by Piaget's student Seymour Papert. The essence of constructivism is the idea that knowledge cannot be transmitted from the teacher to the student, but is constructed individually by experience:

> *Knowledge is not a commodity to be transmitted. Nor is it information to be delivered from one end, encoded, stored, and reapplied at the other end. Instead, knowledge is experienced, in the sense that it is actively constructed and reconstructed through direct interaction with the environment. (Ackermann, 2012, p. 26)*

Piaget argues that it is crucial for students' learning process to continuously interact with the world to make sense of it and that knowledge construction happens out of their prior knowledge by manipulating artifacts of their environment and observing their behavior (Eguchi, 2017). Hence, the job of educational settings in this context is to provide learning opportunities for students to enhance their learning by allowing them to engage with hands-on exploration of artifacts (Eguchi, 2017).

Based on this, in Papert's constructionism, the idea of *constructing* knowledge is taken literally, as a popular quote by Papert and Harel (1991, p. 1) illustrates:

> *Constructionism – the N word as opposed to the V word – shares constructivism's connotation of learning as 'building knowledge structures' irrespective of the circumstances of the learning. It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sandcastle on the beach or a theory of the universe.*

This theory by Papert became reality with the invention of the programming language *Logo*, which was specially designed for children at the end of the 1960s. One of the most famous features of Logo was the Turtle graphics.

Logo and its Turtle graphics were a first step on the road towards educational robotics. After the initial success of the Logo programming language in the 1960s and 70s and the global success with Papert's publication of *Mindstorms: Children, Computers and Powerful Ideas* in 1980, the research group, which developed Logo at the Massachusetts Institute of Technology (MIT), started a collaboration with the LEGO Group in the mid-1980s. They combined the LEGO Technic product with the Logo programming language by building an interface to manipulate and program a LEGO robot using Logo. This prototype was called the *MIT Logo brick* and introduced in 1987. (Martin et al., 2000)

Since then, and with the increasing popularity of educational robotics in today's classrooms, a variety of different educational robotics system has been introduced. The following section will give a broad overview of available educational robotics systems, which are designed for different target groups, from kindergarten to university, and can roughly be separated into construction and ready-to-use kits.

4.2 Robotics systems for the use in the classroom

4.2.1 Construction kits

One of the most popular construction kits, which is also the most used in the STEM classrooms, is *LEGO Mindstorms* (Eguchi, 2017). Additionally, LEGO has also developed many other construction kits for different target groups such as *LEGO WeDo* for primary school and *LEGO SPIKE Prime* for (lower) secondary school. Moreover, with *LEGO BOOST*, the company has also developed an educational robotics system for the students to play with at home.

Besides the LEGO products, many other educational robotics systems exist such as, for example, robots by *fischertechnik* or the *mBot*. Other educational robotics systems can also be developed with popular microcontroller systems such as *Arduino* or *RaspberryPi*. Of course, this is not a complete list of available educational robotics systems, but it gives a first glance at the many alternatives on the market.

LEGO Mindstorms

The LEGO Mindstorms kit is LEGO's most prominent construction kit. Since 2013, the latest version (*EV3*) is out on the market. Older versions are the *NXT* (2006) and the *RCX* (1998). The LEGO Mindstorms education EV3 set contains the EV3 brick, a rechargeable battery, three servo motors, five sensors (one ultrasonic sensor, one color sensor, one gyro sensor, and two touch sensors), and 541 LEGO (Technic) parts for building a robot. The EV3 is programmable in a variety of languages. The most popular is LEGO Mindstorms's block-based programming language, which is based on LabVIEW, which will be replaced by the LEGO MINDSTORMS EV3 classroom software, which is based on Scratch[4], in 2020. Additionally, it is programmable with other block-based programming languages or text-based programming languages such as Java, Python, etc. The target group of LEGO Mindstorms is secondary school (students aged ten years or older) but is also used in introductory computer science and programming classes at a university level. (LEGO Education, n.d.–c)

LEGO provides a variety of teaching materials for their educational robotics kits for the STEM classroom. They are available through their website.[5]

An overview of the use of LEGO Mindstorms in the STEM classroom is delivered by Souza et al. (2018).

LEGO WeDo

LEGO *WeDo* is designed for a younger target group of students in primary school (aged seven years or older). The LEGO Education WeDo set contains the WeDo *Smarthub*, a motor, two sensors (gyro sensor and touch sensor), and 280 (regular and Technic) LEGO parts for building a robot. It is programmable through its block-based programming language, which is based on ScratchJr[6]. (LEGO Education, n.d.–b)

Mayerové and Veselovská (2017), for example, present activities for LEGO WeDo for primary education.

LEGO SPIKE Prime

LEGO's latest product is LEGO *SPIKE Prime* and came on the market in 2019. It is designed to link LEGO Mindstorms (for older students) and LEGO WeDo (for younger students) educational robotics systems. Thus, its target group is lower secondary school (students aged ten to 14 years). The Lego Education SPIKE Prime set contains a programmable hub, a rechargeable battery, three motors (one large and two medium), three sensors (ultrasonic sensor, color sensor, and touch sensor), and 523 LEGO parts for building a robot. The LEGO parts are both

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[4] Scratch can be found online: https://scratch.mit.edu/ (last accessed: 29th February 2020)

[5] The teaching material for LEGO's educational robotics systems can be found online: https://education.lego.com/de-de/downloads (last accessed: 29th February 2020)

[6] ScratchJr can be found online: https://www.scratchjr.org/ (last accessed: 29th February 2020)

regular and LEGO Technic elements and can be combined using special integrating elements. LEGO SPIKE Prime is programmable through its block-based programming language, which is based on Scratch. (LEGO Education, n.d.–a)

LEGO BOOST

Whereas LEGO Mindstorms, WeDo, and SPIKE Prime are designed for educational purposes in schools, LEGO *BOOST* is LEGO's educational robotics kit alternative for students (aged seven to twelve years) to play with at home. Since this kit is not integrated into LEGO's education program but sold separately through the LEGO store, there is no teaching material available for LEGO BOOST. The LEGO BOOST Creative Toolbox set contains the move hub with two integrated motors and a gyro sensor, one additional motor, an integrated color, an ultrasonic motor, and 840 (regular) LEGO parts for building a robot. This set provides building instructions for five different LEGO BOOST models (*Vernie* – a moving, talking robot, *M.T.R.4* (Multi-Tooled Rover) – a robust, versatile rover, the *Guitar4000*, *Frankie the Cat* – an interactive robot pet and *AutoBuilder* – an automated production line). It is programmable through its block-based programming language, which is based on ScratchJr. It provides custom-designed blocks for each of the five models but can also be programmed independently of the models using *free programming* mode. (LEGO, n.d.)

Even though LEGO BOOST is designed for students to play with at home, it provides all the functionality to be used in regular STEM classrooms at a lower secondary level as Pöhner and Hennecke (2019b) illustrate.

fischertechnik

The German company *fischer* produces construction kits in its ROBOTICS line for students aged eight years and above. The construction kits in the ROBOTICS line are divided into kits, which are pre-programmed and kits, which must be programmed by the students. The hardware consists of proprietary building bricks. One example of a construction kit of fischertechnik is the *TXT Discovery Set*. It consists of the ROBOTICS TXT controller, a camera module, three motors, two LEDs, two touch sensors, and 310 bricks for building a robot. The robots are programmable through the proprietary ROBO PRO software, which uses flowcharts to represent the programs' workflow. (Fischertechnik, n.d.)

mBot

The *mBot* is an educational robot by the Chinese company *makeblock* for students aged eight years and above. It is advertised as an entry-level educational robot kit. The basic mBot construction kit consists of a chassis, two motors, an ultrasonic sensor, a light sensor, and two wheels. In contrast to the construction kits by LEGO or fischertechnik, the mBot uses screws to connect single parts. It is programmable through the *mBlock* software, which is based on

Scratch. Additionally, advanced students can program the mBot with the Arduino IDE or Python. (Makeblock, n.d.)

For advanced projects, the mBot is expandable with makeblocks' add-on packs (e.g. talkative pet, six-legged robot, etc.). The resource library by makeblock offers a range of teaching materials for the use of mBot in the classroom.[7] (Makeblock, n.d.)

The use of mBot in the STEM classroom has been investigated by, for example, Sáez-López et al. (2019).

4.2.2 Ready-to-use kits

One major issue with the use of construction kits in the classroom is that the construction of the robots is very time-consuming. Depending on the learning objectives, this could be problematic if the focus is supposed to be on programming the robot rather than building it. In many cases, teachers would pre-build the robots so that the students could immediately begin with programming it. Moreover, especially for younger students in kindergarten or primary school and educational robotics beginners in general, the construction of a robot could be too complex since it involves knowledge from other fields such as physics, mathematics, etc. Consequently, ready-to-use robots provide an opportunity to start with programming the robot straightaway.

Selected examples for ready-to-use kits (especially for the use in kindergarten and primary school) are BeeBot and KIBO. Yet, there are also educational robotics systems for secondary schools (and even tertiary education) such as, for example, the programmable humanoid robot NAO.

BeeBot

The *BeeBot* is a ready-to-use robot for students aged four to twelve years. The robot can go forward and backward and turn 90 degrees to either side. These movements are programmed by the students through the buttons on the robot. Students can program up to 200 steps of the robot's movement. The use of the BeeBot together with specific mats (e.g. treasure island, farm, alphabet, etc.) allows us to create interesting stories and tasks for the robotics activities. (B-Bot, n.d.)

KIBO

KIBO is an educational robot for students aged four to seven. It consists of the robot itself, three motors, wheels, three sensors (light sensor, sound sensor, and distance sensor), and a light bulb and playback module as actors. It is programmable through wooden blocks, which are linked together to implement behaviors. There are blocks for control structures (begin, end, conditionals, loops, parameters), movements (forward, backward, turn, spin, shake, etc.), and sensors

[7] The teaching material for the mBot educational robotics systems can be found online: https://education.makeblock.com/resource/ (last accessed: 29th February 2020)

and actors (wait for clap, sing, etc.). These blocks are equipped with barcodes, which need to be scanned by the robot to program it. (KinderLab Robotics, n.d.)

KinderLab Robotics, the founders of the KIBO robot, provide a wide range of teaching material on their website[8].

NAO

NAO is a humanoid and programmable robot by the Japanese company *SoftBank Robotics*. The 58 cm tall robot is equipped with 25 degrees of freedom, seven touch sensors on different body parts, four microphones and speakers, two cameras, and speech recognition and dialogue in many different languages. As an advanced development platform, NAO is programmable in a variety of ways: through the visual programming environment *Choregraphe* (including Python functionality) or block-based programming in the *OpenRobertaLab*[9] or through text-based programming in Python, Java, C++, and others. The NAO robot is currently the standard platform for the *RoboCupSoccer standard platform league*, a league where all the teams participate with the same robot. In general, the NAO robot is used on many different levels in education, from primary to secondary and higher education and even in special needs education. (Softbank Robotics, n.d.)

One example of the use in higher education is provided by Pöhner and Hennecke (2018a).

4.3 Research findings on the benefits of learning with educational robotics

The literature on educational robotics and its use in education is rich and can roughly be divided into two perspectives. On the one hand, the literature focuses on the technological perspective of educational robotics, which deals with topics such as the invention of new robotics devices or programming environments for robotics systems for education. On the other hand, the pedagogical perspective focuses on the use of educational robotics in the classroom including the introduction of new teaching material, curricula, etc. (Tedre & Apiola, 2013)

Within the pedagogical perspective, one topic is the evaluation of the impact of educational robotics and focuses, for example, on the investigation of the benefits of learning.

In the following, an overview will be presented on research results regarding the benefits of learning with educational robotics (pedagogical perspective). This overview is based on a meta-analysis of published research articles on this topic by Benitti and Spolaor (2017), which examined around 60 research articles published from 2013 to 2016. An earlier study by Benitti (2012) has already conducted a similar analysis with literature published until 2010. The overall aim of

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[8] The teaching material for the KIBO educational robotics systems can be found online: https://kinderlabrobotics.com/teacher-materials/ (last accessed: 29th February 2020)

[9] Like many other educational robotics kits, which have been mentioned in this section, the *OpenRobertaLab* offers a Scratch-like platform to program many the NAO robot. It can be found online: https://lab.open-roberta.org/ (last accessed: 29th February 2020)

these articles is to identify the contributions of educational robotics to students' learning and define future research perspectives.

4.3.1 Cognitive factors

Learning of content knowledge

To investigate the learning of content knowledge, Benitti and Spolaor (2017) allocated the selected studies to the explored subjects *science, technology, engineering, mathematics,* and *others*. The most frequent topics, which are related to the use of educational robotics are *robotics* (25 studies), *programming* (29), and *sensors* (12). Firstly, of course, the connection of educational robotics to robotics itself is obvious since educational robotics is a simplified version of robotics as they are used in industry, etc. They explain the core functionality and give students an insight into the operating principle of these machines (system thinking). Secondly, the use of educational robotics to promote learning of programming and, thirdly, the use of interaction with sensors is very popular. Regarding the learning of programming, many subtopics of programming have been explored such as visual programming (three), control flow (two), programming logic (two), Java programming (one), programming action sequencing (one), smartphone programming (one), algorithmic thinking (one), general programming (one). (Benitti & Spolaor, 2017)

Apart from the most frequent topics, their study shows the broad range of use of educational robotics in all STEM subjects and even beyond in, for example, arts and music (Benitti & Spolaor, 2017).

Even though these studies have been associated with the learning of content knowledge in specific content areas, the identification of single content areas appeared to be an arduous task, since very few publications seem to focus on a single content area, but on more general topics (such as robotics), which underlines the interdisciplinary nature of educational robotics as a learning tool. (Benitti & Spolaor, 2017)

Unfortunately, from the methodological perspective, only 13 out of 60 articles, which have been reviewed by Benitti and Spolaor (2017) proved to be of good methodological quality (i.e. the studies applied to at least three of the following criteria). They applied five different criteria (differentiating between quantitative (a) and qualitative studies (b)) to assess the quality of the reviewed studies. These criteria are:

Table 3: Criteria for methodological quality of studies on educational robotics (Benitti & Spolaor, 2017)

Quantitative studies	**Qualitative studies**
Have the teachers or mentors been trained to use educational robotics? (QC1)	
Is the educational robotics application based on any learning theory? (QC2)	
Is there a comparison or control group? (QC3a)	How well defined is the sample design/target selection of cases/documents? (QC3b)
Does the quantitative assessment described in the publication involve a statistical analysis of significance (inferential statistics)? (QC4a)	How well is the eventual sample composition of the coverage described? (QC4b)
Is any reliability or validity analysis carried out during the quantitative analysis? (QC5a)	How well was the qualitative data collection carried out? (QC5b)

Two high-quality studies shall be given as examples. Nugent et al. (2016) present a study on evaluation results of a project, which delivered educational robotics in the form of one-week summer camps to students aged nine to 14 years. During eight years of practice, 1825 students participated in their summer camps. The summer camp was based on a curriculum, which included sample tasks such as, for example, programming the robot motors for various movements and turns, using loops and conditionals, navigation to avoid obstacles using touch and ultrasonic sensors, and programming the light sensor to track a line. To assess the students' learning of STEM knowledge, the authors used a multiple-choice questionnaire, which included questions on mathematics (including fractions and ratios), computer programming (including loops and conditionals), engineering concepts and processes (including gears and sensors), and engineering design in a pre-post-test design. (Nugent et al., 2016)

In another study, Kaloti-Hallak et al. (2015a) report the effectiveness of robotics competitions on students' learning of the CS concepts *input-output* and *interfacing with sensors*. In this study, a total of 99 students organized in eight groups (aged 13 to 15 years) were observed (and some interviewed) during their preparation for the FIRST LEGO League competition. The observation was conducted through video recordings and later transcriptions thereof. Using these transcriptions and the interviews the authors assessed students' learning based on the cognitive process dimension of the revised Bloom taxonomy, which includes the phases *remembering*, *understanding*, *applying*, *analyzing*, *evaluating*, and *creating*. (Kaloti-Hallak et al., 2015a)

The results of these studies show that the summer camps have a positive impact on students' knowledge, which especially derives from a knowledge gain in engineering and computer programming. Moreover, students argued that learning in camp was different than learning in school and that they learned more in camp in these knowledge areas than in school, except for mathematics, where students believed that they learned more in school than in camp. (Nugent et al., 2016)

Additionally, in the study by Kaloti-Hallak et al. (2015a) student groups achieved meaningful learning up to the level of understanding / applying for both concepts. Regardless, the authors criticize the scope of the learning of some students as narrow, since the students, for example, decided to discard missions, which required the use of sensors, since the students were not able to identify errors regarding the sensor information, which would have been the basis for the level of analyzing. (Kaloti-Hallak et al., 2015a)

Skill development

Regarding skill development and educational robotics, Benitti and Spolaor (2017) recall that the most common skills mentioned are *teamwork* and *problem solving*. Additionally, some studies also report experiences on communication skills, brainstorming, presentation, creative thinking, critical thinking, strategy making, and leadership. (Benitti & Spolaor, 2017)

Sullivan (2008), for example, presents a study on students learning of thinking skills (observation, estimation, and manipulation) and science process skills (evaluation of a solution, hypothesis generation, hypothesis testing, and control of variables) along with skills in computer programming as part of the students' scientific literacy. In her study, 26 students (aged eleven to twelve years) participated in a three-week summer camp using the LEGO Mindstorms construction kit. The summer camp consisted of different tasks focusing on educational robotics such as, for example, basic concepts of computer programming such as loops, conditionals, etc., and more complex challenges as the building and programming of a ping-pong ball-sorting machine. This machine was designed to differentiate between dark- and light-colored ping-pong balls and sort them in different bins and keeping count of the number of the balls in the bins. Moreover, another challenge required the students to design a robot, which follows a black line on a paper-track and stops when encountering an object on the way. (Sullivan, 2008)

To analyze the students' working process, different challenges with the students were videotaped and transcribed into logs after the summer camp. The author coded these logs with the use of a coding scheme focusing on the relevant skills. The results show that observation (thinking skill), evaluation of a solution (science process skill), and estimation (thinking skill) have the most frequent use of thinking and science process skills in the students' working process in this study. All in all, she concludes that her qualitative study reveals the use of an educational robotics system and an appropriate pedagogical approach, which allows open-ended tasks, can foster the students' thinking and science process skills. (Sullivan, 2008)

Besides the presented results of the educational robotics on students' learning of content knowledge and skill development, this systematic review reveals that most applications of educational robotics in school still fall into the category of extracurricular learning or *hybrid* learning, which describes, for example, the application of educational robotics as a combination of in- and out-of-school learn or extracurricular activities, which are based on a curriculum.

Moreover, the most frequently used educational robotics kit in the reviewed studies was the LEGO Mindstorms kit. (Benitti & Spolaor, 2017)

4.3.2 Affective factors

Besides the positive impact of the use of educational robotics on students' learning on a cognitive level, literature (e.g. the systematic review by Anwar et al. (2019)) also presents research results on the positive impact on factors on the affective level such *as motivation and interest* and *self-efficacy*.

Motivation and interest

Students' motivation and interest in educational robotics is another broadly researched field (Anwar et al., 2019). For example, Kaloti-Hallak et al. (2015b) examined the motivation towards STEM of 59 students, who participated in the FIRST LEGO League in 2012 - 2014 using questionnaires on intrinsic and extrinsic motivation in a pre-post-test design.

In 2012, Melchior et al. (2018) conducted a study on assessing the impact of the FIRST LEGO League competition on its participants regarding their interest in science and technology (among other factors).

To address these questions, the authors used questionnaires at the end of the FIRST LEGO League season for the students, their team coaches, and parents. The questionnaires were distributed to a random sample of 626 teams across the US. The data for the sampling process was taken from the competitions' registration system. (Melchior et al., 2018)

Results of these studies show that overall motivation did not increase significantly because of the educational robotics activities. Instead, students were already highly motivated in the beginning and maintained their motivation at a high level until after the competition. (Kaloti-Hallak et al., 2015b)

Additionally, the authors also mention that students' motivation might have been highly influenced by their parents and teachers. Whereas the parents believed that these activities could help their children in their future studies and careers, the teachers were very interested in positive results in the competition, which influenced the students as well. (Kaloti-Hallak et al., 2015b)

Melchior et al.'s study (2018) reveals an overall positive outcome, which largely parallels the results from two prior studies, which have been conducted in 2003/04 and 2008/09. Students, team coaches, and parents agreed that the students' interest in science and technology has increased because of the participation in the FIRST LEGO League. Students reported that they wanted to learn more about science and technology, computers, and robotics and wanted to learn more about how science and technology can be used to solve real-world problems. (Melchior et al., 2018)

Self-efficacy

The self-efficacy towards performing educational robotics tasks was examined by, for example, Nugent et al. (2016). In their project, as it was described in section 4.3.1, they did not only investigate students, who participated in the one-week summer camps but also students, who were part of school clubs for educational robotics (458 students) and students, who participated in the educational robotics competition FIRST LEGO League (458 students) over the eight years of practice of their project. The school clubs usually met once a week for one school year and the competition participants spend around 40 hours (which roughly equals the number of time students spend on educational robotics activities in their summer camp) for the preparation towards the educational robotics competition according to responses by the corresponding team coaches. (Nugent et al., 2016)

To measure the self-efficacy of participating students, in addition to the cognitive instrument as described in section 4.3.1, the authors used an attitudinal instrument, which contained not only questions regarding students' self-efficacy, but also questions on the perceived value of STEM, workplace skills, etc. (Nugent et al., 2016)

When comparing these three types of educational robotics practices, results indicate positive outcomes of students' self-confidence in performing educational robotics tasks for all three types. Self-efficacy generally increases as they gain experience building and programming their robots. (Nugent et al., 2016)

4.3.3 The STEM-pipeline as an analogy for sustainable development in STEM education

All in all, the length of the educational robotics program plays an important role in the impact level of educational robotics on the students. Whereas shorter programs aim at increasing students' motivation and interest (affective level), longer programs want to promote students' learning (cognitive level) in the field. Thus, shorter programs may encourage students to further engage with educational robotics and explore other possibilities to do so, which may as a consequence lead to increased students' learning. (Nugent et al., 2016)

This idea is also incorporated by the STEM-pipeline as described by, for example, Mead et al. (2012). The STEM-pipeline is an analogy for the sustainable development of STEM education (e.g. through educational robotics) throughout different levels of education (Fig. 7).

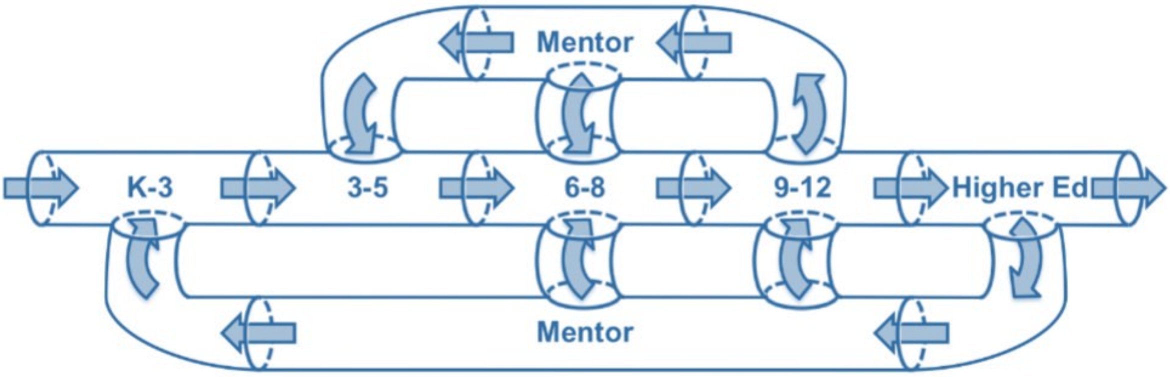

Figure 7: STEM-pipeline as defined by Mead et al. (2012).

Mead et al. (2012) define goals and implementation strategies for each level of the STEM-pipeline for educational robotics. Starting from primary goals such as engaging interest, providing opportunities for (future) success through first educational robotics activities (implementation strategy) in the first two stages, the students develop knowledge and skills throughout the other three stages through further educational robotics activities with open-ended building and programming tasks, which they present at competitions, robot showcases and science fairs. (Mead et al., 2012)

In the STEM-pipeline older students function as role models for younger students and support them in their activities as mentors (Mead et al., 2012). The STEM-pipeline as an analogy underlines the importance of attracting students as early as in kindergarten and primary education. A detailed description of the goals and implementation strategies for the STEM-pipeline for educational robotics can be found in Mead et al. (2012).

The high dropout rates of students throughout the years, especially around the age of 15 and for girls more than for boys, also lead to the phrase *leaky pipeline* and is highly connected to the strong decrease in students' interest and self-concept towards STEM. (Taskinen & Lazarides, 2020)

The idea of the STEM-pipeline for educational robotics has also been tested empirically by Nugent et al. (2015). Using structural equation modeling, they investigated the relationship of various factors, which influence students' learning and career orientation. The authors conducted this research in the context of one-week summer camps on educational robotics using the LEGO Mindstorms kit. Data was collected from around 800 students (aged ten to 14 years), who participated in educational robotics summer camps. The investigated factors are *background and context (educator, peers, family, and prior knowledge)*, *interest*, *self-efficacy*, and *expectancy* (career outcome expectancy), learning strategies, and *outcomes* (knowledge and career orientation). In summary, it confirms the suggested chronology of primary goals (affective level) and secondary goals (cognitive level) as mentioned before. (Nugent et al., 2015)

4.4 Approaches to educational robotics in the classroom

For the application of educational robotics in the classroom, Eguchi (2010) defines three different approaches: *project-based, theme-based,* and *goal-oriented learning.*

In the *project-based learning* approach, students work collaboratively in groups to explore real-world problems. This approach uses educational robotics merely as a learning tool to teach specific topics such as, for example, physics. (Eguchi, 2010)

Theme-based learning is an approach to teach different skills and contents by integrating these relevant skills and contents as defined by the curriculum around a specific topic. This approach also allows integrating students' interests in the classroom. Thus, students appreciate their learning as much more useful and they can relate skills and contents to topics of their interest and experience. Additionally, this approach emphasizes inquiry-learning and communicative collaboration. (Eguchi, 2010)

Educational robotics competitions as a *goal-oriented learning* approach to educational robotics had the greatest impact on its growing popularity in K-12 settings. These competitions use the goal-oriented approach, which is popular in the fields of engineering or CS. Each year, the competitions set out new themes and tasks, which students need to work on. Their task is to build and program an educational robot to solve the tasks better than any of the other teams. (Eguchi, 2010)

Popular examples of educational robotics competitions are the FIRST LEGO League, RoboCup (Junior), and the World Robot Olympiad[10]. An overview of these will be given in chapter 7 (p. 55).

In summary, the choice for a specific approach depends on the intended learning outcomes of the students. Moreover, the approaches differ regarding their degree of student-centeredness and students' freedom. Whereas the project-based learning approach allows the teacher to create very structured lesson plans and objectives, the theme-based learning approach is more open for students to explore, has a higher degree of freedom, and is more student-centered. The highest degree of freedom and the most student-centered approach is the goal-oriented learning approach. All in all, the students are free in their way of achieving the goals as set out by the teacher, competition organizers, etc. (Eguchi, 2010)

[10] All these competitions can be found online:

- FIRST LEGO League: http://www.firstlegoleague.org/ (last accessed: 29th February 2020)
- RoboCup (Junior): https://junior.robocup.org/ (last accessed: 29th February 2020)
- World Robot Olympiad: https://wro-association.org/home/ (last accessed: 29th February 2020)

4.5 Implications for future research

Even though existing literature showed that the most common outcome of the use of educational robotics is positive, there is still a great demand for more rigorous research in the field. All in all, the main areas for future research are the following: *early childhood education*, *integration of educational robotics in curricular activities*, and *impact evaluation*.

Benitti and Spolaor (2017) conclude from their meta-analysis that they found the use of educational robotics at each level in education. Regardless, (pre-)kindergarten and primary school studies are still underrepresented. Following the idea of the STEM-pipeline as an analogy of sustainable education in the field, this idea for future research is very relevant. Nonetheless, reasons for students dropping out (leaky pipeline) should still be examined further.

Educational robotics is still mostly used in extracurricular activities (Benitti & Spolaor, 2017). Possible reasons why the presence of educational robotics in the curricular context lacks could, for example, be the following:

- Lack of infrastructure to meet a high number of students
- Lack of knowledge to teach educational robotics by teachers
- Lack of evidence that educational robotics delivers positive results (Benitti & Spolaor, 2017)

In general, more studies should focus on the use of educational robotics in the regular classroom. But, as the last bullet point from above indicates, before integrating educational robotics in the regular classroom, more positive evidence is necessary to prove the positive impact of educational robotics on students' learning and personal development. Consequently, this evidence helps to justify costly measures to integrate educational robotics into the regular classroom and qualify teachers accordingly to be able to teach it effectively. (Benitti & Spolaor, 2017)

Alimisis (2013), for example, argues that there is a lack of systematic evaluations and reliable experimental designs. Accordingly, Benitti (2012) concludes that most research in the field is descriptive and based on reports describing positive outcomes with individual, small-scale studies. The lack of a systematic evaluation is also evident in unclear research methodologies (Bredenfeld, 2010). Accordingly, Alimisis (2013) recalls that more rigorous quantitative research is necessary to validate the impact of educational robotics. Benitti and Spolaor (2017) agree and argue that it is necessary to standardize evaluation techniques to quantify learning with educational robotics. Moreover, statistical analysis, surveys, and interviews could be merged to provide more complete findings (Benitti & Spolaor, 2017). In summary, instead of just reporting a plethora of teachers' experience reports with educational robotics, the educational robotics community is required to conduct more impact evaluation studies using more sophisticated methodological approaches.

To conclude, the last three chapters presented the first part of the analysis of the content structure of the model of educational reconstruction. This consisted of the transformation of general problem solving skills as science content (or rather process) structure into a content structure for instruction. The following two chapters will continue with the analysis of educational significance from a normative and descriptive perspective.

5 Problem solving in frameworks, standards, and curricula

5.1 Problem solving in international K-12 standards and curricula

The relevance of problem solving skills in STEM education has been discussed by many so far. For example, in his policy analysis, Passey (2017) revises the shift from mere application of technology in terms of information and communication technologies (ICT) in the classroom towards a more general understanding of the underlying concepts of CS with its fundamental principles of, for example, problem solving, creativity, programming, etc. (Passey, 2017). He advocates the introduction of CS in school education with reference to different arguments: *economic, organizational, community, education, learning,* and *learner argument* (Passey, 2017). Regarding problem solving skills, especially the economic and educational argument are essential. The economic argument focuses heavily on the great demand for specialists in technological industries (Passey, 2017). It addresses not only the high number of open positions in the field but also the new skill set (in terms of 21st century skills), which workers are required to possess (Passey, 2017).

Concerning the educational argument, Passey (2017) states that

> *[w]ith computing technologies becoming increasingly ubiquitous, it can be argued that younger as well as older users should have an increasing understanding of, and capabilities to use, the full range of computing facilities that exist, whether these facilities are accessed through programming, or through application. (Passey, 2017, p. 427)*

Both arguments can also be discovered in *The Cambridge Handbook of Computing Education Research*, namely as *labor market rationale* and *computational thinking rationale*. The link between problem solving and computational thinking will be made explicit later in this chapter. (Blikstein & Moghadam, 2019)

Passey (2017) concludes his analysis with the implication that learners should gain skills and competencies, which are relevant for them in the present and future and that those include problem solving and creativity skills as well as programming skills among others. Regardless, appropriate ways of teaching those skills are still under investigation. He argues that, for example, even though constructivist forms of pedagogies are currently very popular, it is still unclear whether they can appropriately foster these skills. (Passey, 2017)

In the following, further examination of international K-12 standards and curricula will provide an overview of the relevance of problem solving skills in today's STEM education.

One piece of evidence is an analysis of international CS curricula by Hubwieser et al. (2015). They conducted a deductive qualitative text analysis on case studies reporting the respective national situation of CS education in 14 countries and states such as, for example, Bavaria and North Rhine-Westphalia in Germany, France, Italy, Sweden, Finland, United Kingdom, Russia, and others. One research question of their analysis is concerned with the specific learning contents in K-12 education in each case study. Apart from the declarative content (or knowledge) areas of *algorithmic concepts, computer and communication devices*, and *operating systems*, the only procedural content areas (or skills), which occurred in all of the national reports of the investigated countries or states, are *problem solving* and *programming*. (Hubwieser et al., 2015)

International CS standards for K-12 education are delivered by, for example, the *Computer Science Teacher Association (CSTA)*. These standards are based on the *K-12 Computer Science Framework* (k12cs.org, 2016), but whereas the framework itself "[…] provides overarching, high-level guidance per grade bands, […] the standards provide detailed, measurable student performance expectations" (Computer Science Teacher Association [CSTA], 2017, p. 3). They argue that "Computer Science ways of thinking, problem solving, and creating have become invaluable to all parts of life and are important beyond ensuring that we have enough skilled technology workers" (k12cs.org, 2016, p. 10).

They divide the learning content for CS education into *concepts* and *practices*, which describe declarative and procedural types of knowledge (CSTA, 2017). In many of today's CS education standards, problem solving is highly connected to the idea of *computational thinking* as practice, which "[…] is essentially a problem-solving process that involves designing solutions that capitalize on the power of computers" (k12cs.org, 2016, p. 69) and "[…] refers to the thought processes involved in expressing solutions as computational steps or algorithms that can be carried out by a computer" (k12cs.org, 2016, p. 69). Moreover, Wing (2008) argues that computational thinking is primarily a human ability, even though the name might suggest differently. Grover and Roy (2018, p. 22) agree by stating that "[…] [computational thinking] is not *thinking like a computer*, rather it is about *thinking like a computer scientist*. It's the problem solving approaches commonly used by computer scientists that constitute computational thinking".

In recent years, this focus on computational thinking as human ability has supported developments of teaching CS unplugged (i.e. without computers), especially in primary education and for non-CS students. Regardless, computational thinking as a problem solving process can of course also be implemented with the use of computers, i.e. when creating computational artifacts. Thus, evidence of problem solving in the CSTA standards can primarily be found in the practices part of the framework and include:

- recognizing and defining computational problems
- developing and using abstractions
- creating computational artifacts
- testing and refining computational artifacts (CSTA, 2017)

Similar to the descriptions of problem solving skills in chapter 3 (p. 16), the CSTA (2017) defines problem solving when creating computational artifacts as a systematic iterative process, which

> *[…] embraces both creative expression and the exploration of ideas to create prototypes and solve computational problems. Students create artifacts that are personally relevant or beneficial to their community and beyond. Computational artifacts can be created by combining and modifying existing artifacts or by developing new artifacts. Examples of computational artifacts include programs, simulations, visualizations, digital animations, robotic systems, and apps. (CSTA, 2017, p. 21)*

Additionally, Grover and Roy (2018) also include the *creation of computational artifacts* and *iterative refinement (incremental development)* in their model of computational thinking as key practices.

In Germany, first attempts to implement national standards for CS education were conducted by a working group of the German CS society, namely the *Gesellschaft für Informatik* (GI), from 2003 to 2008 for lower secondary education (Gesellschaft für Informatik [GI], 2008; Pasternak et al., 2018). These attempts resulted in the respective standards, which were expanded for higher secondary education in 2016 (GI, 2016; Pasternak et al., 2018). Standards for primary education were added in 2019 (GI, 2019; Pasternak et al., 2018).

The GI describes the standards with a competency model, which, resembling the international standards, consists of *content standards* and *process standards (or practices)* (Fig. 8).

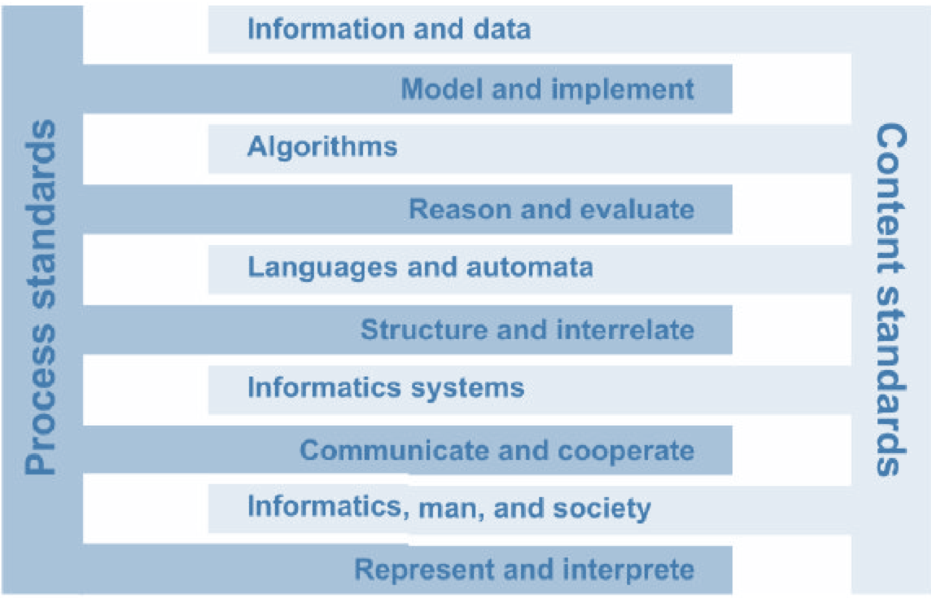

Figure 8: Competency model of the German CS society for CS education in lower secondary education. (Pasternak et al., 2018)

In contrast to the model for lower secondary education, the model for higher secondary education added a third dimension to the model: *stages of requirement* (Pasternak et al., 2018). The stages are *reproduction, reorganization and transfer*, and *reflection, and problem solving* (Pasternak et al., 2018). They describe different levels of difficulty and complexity of CS activities (i.e. processes or practices) (Pasternak et al., 2018). Thus, they are assigned to the practices part of the competency model (Pasternak et al., 2018). The different stages are described as follows:

- *Reproduction* describes the recall of known CS content and practices.
- *Reorganization and transfer* describe the self-reliant use of known CS content and practices and its adaption to further questions and problems in similar contexts and situations.
- *Reflection and problem solving* describe the use and application of known CS content and practices in new situations; the selection of appropriate methods to solve a given problem: a systematic approach to solving problems. (Pasternak et al., 2018)

For each of the five practices *model and implement, reason and evaluate, structure and interrelate, communicate and cooperate* and *represent and interpret* the three levels are defined (Pasternak et al., 2018). For example, for *model and implement*, one the first stage, students recall a known model (e.g. class diagram in the context of a programming project), which, for example, has been elaborated in collaboration with the teacher, or test a given implementation with given test cases (Pasternak et al., 2018). In the second stage, students develop a model (e.g. sequence diagram) concerning a given task using a known modeling technique or implement a program using appropriate programming environments (e.g. BlueJ for Java) based on a given model (Pasternak et al., 2018). Finally, in the third stage, students model and implement a complex problem using different modeling techniques or revise their solutions for efficiency, reusability, etc. (Pasternak et al., 2018).

To summarize, in the German as well as the international standards, problem solving skills are closely linked to process standards or practices.

5.2 Research findings on problem solving (and computational thinking)

Because of the relevance of problem solving skills for students as shown in the national and international K-12 standards, a lot of research has been dealing with the teaching and learning of those skills in recent years. However, the most recent research on problem solving skills of students (especially since Wing's article in 2006) occurred in the context of research on computational thinking.

In search of a definition of computational thinking and its core elements, problem solving is mainly described as *computational thinking practice*. Brennan and Resnick (2012) describe *computational practices* together with *computational concepts* and *computational perspectives* as dimensions of computational thinking. Computational concepts describe concepts, which programmers use (e.g. variables) and computational perspectives are students' understandings of themselves and their (technological) environment (Brennan & Resnick, 2012). Computational practices describe a problem solving process, which occurs in the process of programming (Brennan & Resnick, 2012). It incorporates, for example, *incremental and iterative development, testing and debugging,* or *abstracting and modularizing* (Brennan & Resnick, 2012).

Recent research on computational thinking is to a great extent associated with the following themes as explained by Curzon et al. (2019):

- Unplugged computational thinking
- Computational system design and programming
- Abstraction
- Assessment

Unplugged activities as published by Bell et al. (2009) are used for teaching fundamental CS concepts such as *decomposition, generalization*, and *abstraction* to younger students, for example, in primary education. Regarding its effectiveness, Curzon (2014), for example, argues that teaching computational thinking through unplugged activities in combination with contextually rich stories is beneficial.

The connection of computational thinking and computational system design and programming is visible in the five-step process model for students to help them in their problem solving process:

1. Abstract the problem from its description (abstraction)
2. Generate subproblems (decomposition)
3. Transform subproblems into sub solutions (generalization and algorithmic thinking)
4. Recompose (algorithmic thinking)
5. Evaluate and iterate (evaluation) (McCracken et al., 2001)

Additionally, research shows that computational thinking provides a foundation for programming skills, even though students still need to learn the syntax and semantics of the respective programming language to implement their design (Curzon et al., 2019).

The idea of abstraction as an entry point to computational thinking activities has grown into its own theme in research. In general, CS is often considered a "science of abstraction - creating the right model for thinking about a problem and devising the appropriate techniques to solve it" (Aho & Ullman, 1992). In the context of computational thinking, Wing (2006) argues that "[t]hinking like a computer scientist [...] requires thinking in multiple levels of abstraction". A central ability of CS experts is the move between different levels of abstraction (Statter & Armoni, 2020). They differentiate two perspectives of abstraction in CS:

- Changing the resolution: This describes the omission of numerous details of a problem, which are currently irrelevant.
- Ignoring the *how* and focusing on the *what*: This describes the use of black-boxes in the process of solving an algorithmic problem (e.g. as a subroutine). (Statter & Armoni, 2020)

For teaching abstraction to students, Statter and Armoni (2016, 2020) defined and investigated a hierarchical framework, which consists of four levels:

1. Execution level: interpretation of an algorithm as a specific run on a specific input and a concrete specific machine.
2. Program level: an algorithm is a process, described by a specific executable program, which is written in a specific programming language
3. Object level: an algorithm is an object, which is not associated with a specific programming language.
4. Problem level: At this level one is capable of dealing with a solution to a problem as a black-box and compare different algorithms to solve this problem regarding, for example, runtime or complexity.

In a study with students aged 13 to 14 years in the context of an after-school program, Statter and Armoni (2020) used an experimental and control group to test their hypothesis, whether students in the experimental group achieve higher levels of abstraction when they are taught with the hierarchical framework as mentioned above. The program was conducted for two school years with two hours each week. In total, 187 students, 99 boys (53%) and 88 girls (47%), which were randomly assigned to the experimental or control group, participated in the study. Statter and Armoni (2020) collected data in multiple ways using pre- and post-tests, class observations, interviews, and the students' final projects in Scratch. (Statter & Armoni, 2020)

All in all, the study's results show that students in the experimental group are more likely to work on the object (or algorithm) level, whereas students in the control group work on the lower levels of program and execution. (Statter & Armoni, 2020)

The last theme of recent research on computational thinking regards the assessment thereof. In general, the assessment of abstract concepts such as computational thinking is problematic, especially since computational thinking as practice or skill cannot be assessed without the use of specific computational thinking concepts (Curzon et al., 2019).

In general, computational thinking is mainly assessed in two ways, either through programming or through general problem solving (generally without programming) (Curzon et al., 2019). One example of assessing computational thinking through programming is with *Dr. Scratch*[11]. Dr. Scratch is a web-based tool, which evaluates students' Scratch projects summatively and calculates a computational thinking score with sub scores for the concepts of *abstraction, logical thinking, synchronization, parallelism, flow control, user interactivity,* and *data representation* (Moreno-León & Robles, 2015). Depending on the computational thinking score, a project is assigned the competency level of *basic, developing,* or *master* (Moreno-León & Robles, 2015). Criticism concerning Dr. Scratch mainly focuses on two aspects. Firstly, these tools expect computational thinking skills to ultimately be evident in students' programs, which in some cases might not be the case (Curzon et al., 2019). Secondly, the evaluation of students' programs summatively (in contrast to formative assessment) neglects the process of developing the program. Especially practices such as *tinkering* are not presented in the evaluation of students' programs but explicitly demanded in programming environments for students such as Scratch.

Assessing computational thinking through general problem solving can, for example, be conducted using *Bebras* tasks. Bebras[12] is an international challenge on computer science and computational thinking for students of all ages. During the first week of November students from around the world participate in the Bebras challenge online, which includes different Bebras tasks addressing different computational thinking concepts and practices. For the use in regular classrooms, Dagienė and Sentance (2016) link past Bebras tasks to a two-dimensional framework they developed (Dagienė et al., 2017), which consists of computational thinking concepts crossed with computational thinking skills. Their idea is to develop a database for teachers, which allows them to search for Bebras tasks depending on the intended content or skill in accordance to their specific curriculum content (Dagienė & Sentance, 2016).

All in all, assessing computational thinking is complex and should consequently be conducted through the use of multiple data sources. Brennan and Resnick (2012) suggest using students' projects, artifact-based interviews, and design challenges (and possibly others) to evaluate

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[11] Dr. Scratch can be found online: http://www.drscratch.org/ (last accessed: 6th April 2020)

[12] Bebras is available online here: https://www.bebras.org/ (last accessed: 6th April 2020)

students' progress in computational thinking concepts, practices, and perspectives. Regardless, they acknowledge the (dis-)advantages of some approaches (e.g. time consumption), especially with the constraints of different educational settings (Brennan & Resnick, 2012).

5.3 Implications for future research

Since the idea of computational thinking is still rather new (since Wing's article in 2006), many open questions remain. The major points of interest in research in the field are the following:

- Definition of computational thinking
- Transferability of computational thinking skills
- The teaching of computational thinking (Curzon et al., 2019)

The lack of a uniform definition might be one of the most urgent points of interest. Even though multiple definitions of computational thinking exist, there is no agreement about a single definition. Consequently, researchers in the field must be careful when reporting studies on this topic and make sure that they clearly state the definition they use. Moreover, they argue that the agreement about a definition is highly connected to the idea about the transferability of computational thinking skills. Are those skills considered as relevant for CS specialists only or for everyone in the digitalized world of today? Depending on the uniform definition of computational thinking and the way it transfers to other fields or people's general understanding of their world, the teaching of computational thinking needs to be adopted appropriately. If those skills are only useful for CS specialists, teaching them through programming seems the most reasonable way. If a definition is established, different approaches (e.g. unplugged activities) to foster these skills need to be evaluated comparatively to find the most appropriate teaching methods. (Curzon et al., 2019)

Other points of interest (e.g. assessment, the relationship of computational thinking and programming) come into mind as well, but they all depend on the agreement about a uniform definition of computational thinking, which consequently is of considerable significance.

6 Students' opinion on relevant skills for the 21st century job market

6.1 Introduction

The analysis of the educational significance of science contents (or processes) goes beyond the study of frameworks, standards, and curricula, which suggest the instruction of specific contents (*normative* perspective). Duit (2007) argues that research on students' perspectives regarding, for example, their pre-instructional concepts and affective variables like interest, self-concept, and attitudes play a major role in the model of educational reconstruction (*descriptive* perspective). In this case, especially the examination of the affective variables is important to understand since they influence the process of science learning in the cognitive domain (Pintrich et al., 1993). In this chapter, we analyze the students' opinion on relevant skills for the 21st century job market as part of their motivational beliefs.

6.2 Data collection

6.2.1 Study design

The setting of this study (and the whole empirical part of this thesis) is the World Robot Olympiad (WRO), an international educational robotics competition for students aged six to 19 years. This competition attracts thousands of students each year and works as an example of an educational robotics competition in this thesis[13]. In 2019, the author of this thesis was part of an impact evaluation study of the WRO in Germany. This impact evaluation study consisted of two partial studies. The first partial study investigated students' learning of 21st century skills (digital literacy, teamwork/collaboration, communication, and problem solving)[14] (Pöhner et al., 2020b), and the second study focused on the students' (i.e. the former participants in the educational robotics competition) self-concept and interest in STEM (Pöhner & Hennecke, 2019a). According to the theory of career decision making by Gottfredson (1981), they are important indicators of students' career choices. This second partial study comprises a questionnaire study with former participants of the WRO in Germany (N = 62). Apart from questions on the students' self-concept and interest in STEM, it also included a question on the students' opinion of relevant skills for the 21st century job market. Following the literature review in chapter 5 (p. 41), which underlined the relevance of problem solving in STEM education, the initial hypothesis in this study was that students consider problem solving skills as more important than other 21st century skills for the 21st century job market. The results regarding this question will be presented in this chapter. More detailed information and an overview of the whole

[13] More information of the WRO can be found in section 7.2.3 (p. 62).

[14] The results of the study on students learning of problem solving skills will be discussed later in chapter 10 (p. 82).

empirical part of this thesis (including the impact evaluation study of the WRO in Germany in 2019) is available in section 9.2 (p. 75).[15]

6.2.2 Instruments

To measure the students' opinion on relevant skills for the 21st century job market, which (were expected to) have developed through their participation in the WRO, the questionnaire study with former participants of the WRO included the following question:

Please rate the relevance of the following skills, which are ought to be developed through participation in the World Robot Olympiad, for your future education and working life.

Building a robot	Very low☐	☐	☐	☐	☐	☐	☐Very high	☐	I don't know
Programming a robot	Very low☐	☐	☐	☐	☐	☐	☐Very high	☐	I don't know
Teamwork	Very low☐	☐	☐	☐	☐	☐	☐Very high	☐	I don't know
Communication	Very low☐	☐	☐	☐	☐	☐	☐Very high	☐	I don't know
Problem solving	Very low☐	☐	☐	☐	☐	☐	☐Very high	☐	I don't know

Figure 9: Questions regarding students' opinion on relevant skills for the 21st century job market.

The study participants were asked to assess the relevance for each of the selected skills for their future education and working life on a 7-point Likert scale (very low – very high) (or use the option *I don't know*). The selection of the skills *building and programming a robot*, *teamwork (as digital literacy skills)*, *teamwork/collaboration*, *communication*, and *problem solving* was based on a theoretical framework of 21st century skills (and agreed upon with the organization TECHNIK BEGEISTERT e.V., the organizers of WRO Germany) as described in chapter 2 (p. 7).

The complete questionnaire of this study is available in appendix B.

6.3 Data analysis

For the analysis of the retrieved data, both descriptive and inferential statistics were used. Descriptive statistics with graphical (e.g. frequency distributions or boxplots) and numerical representations (mean values, standard derivations, etc.) of the data can be helpful to provide a first overview of the data. Regardless, to infer from the study's sample (i.e. the self-selected group of former participants) to larger populations (i.e. all participants in this educational robotics competition) techniques from inferential statistics are necessary. In this study, the Friedman-test was used. It is a non-parametric test to investigate differences across three or more related groups. Non-parametric tests are used when the requirements for the parametric alternatives (regarding sample size, normal distribution of data) are not fulfilled. The Friedman-test calculates the mean rank for each group and the significance level. Since the significance level only tells whether a specific result has occurred by chance, effect sizes were calculated to describe the size (or magnitude) of an effect. In general, effect sizes operate in two measures: measures of

[15] This chapter anticipates the chronological structure of this thesis. This incoherent structure was selected in favor of the argumentative structure in the context of the model of educational reconstruction as research framework.

difference (e.g. Cohen's d) or measures of association (e.g. correlation coefficient r). (Cohen et al., 2017)

6.4 Results

6.4.1 Sample description

In this study, a total of 62 former participants of the WRO participated. 52 (83.8 %) participants were boys and 10 (16.1 %) girls. The distribution of age group and current occupation was as follows:

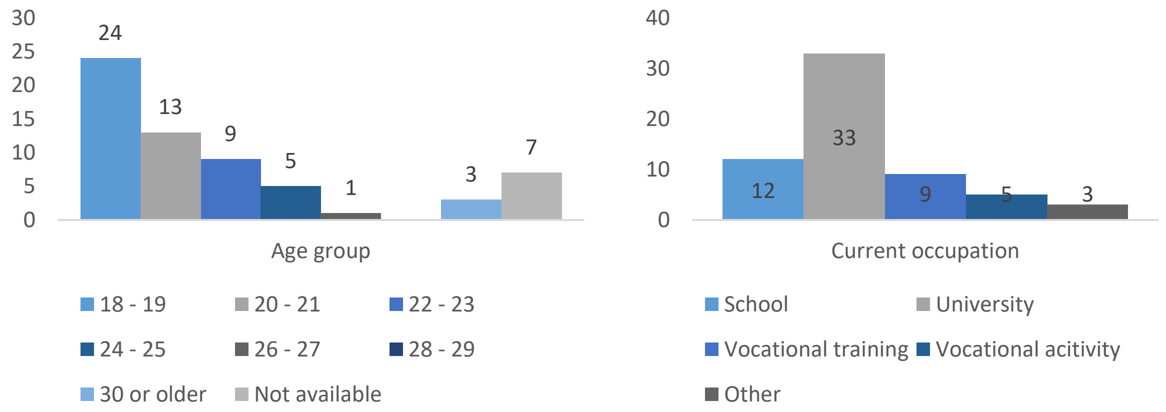

Figure 10: Age distribution (left) and distribution of current occupation (right) of study participants.

In summary, Fig. 10 shows that most study participants are university students and with an average age of 22 years. The majority of the school students visit a mathematical, science, or technology type of school (9 of 12, 75 %). Most of the university students do a degree in either engineering (8 of 33, 24.2 %) or mathematics, science, or technology (22 of 33, 60.6 %).

6.4.2 Overall analysis

The boxplot in Fig. 11 displays the answers of the study participants regarding their opinion on relevant skills for the 21st century job market.

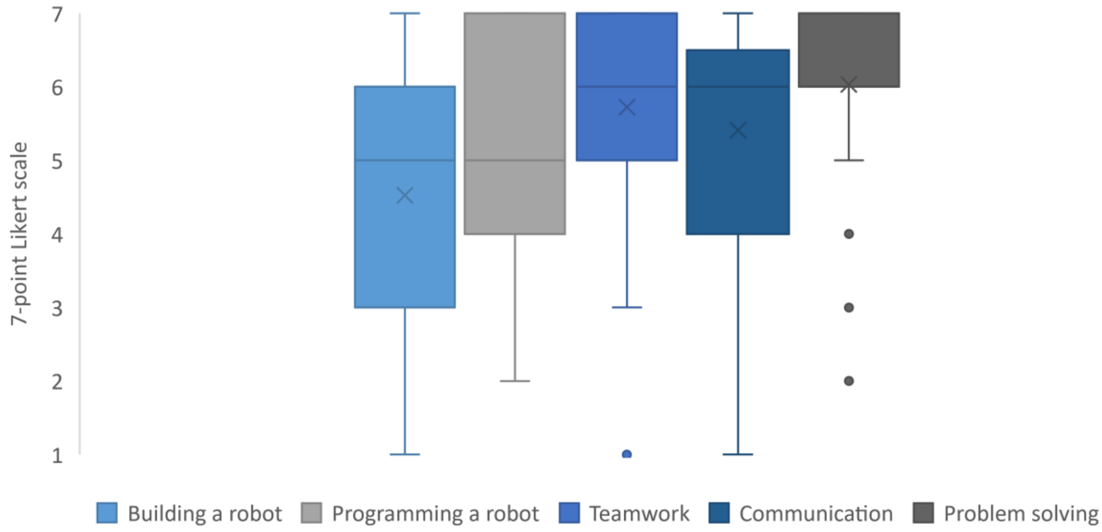

Figure 11: Boxplot of answers of study participants on their opinion on relevant skills for the 21st century job market.

The relevance of the skills is rated differently. Whereas building and programming a robot (*hard skills*) received lower ratings (in terms of their median), teamwork, communication and problem solving (*soft skills*) received higher ones. The boxplot in Fig. 11 also presents the variance of the answer to the study participants. Building and programming a robot show a higher variance (as indicated by the interquartile range (i.e. length of the box)). The variance of teamwork, communication, and problem solving are lower than for building and programming a robot.

Concerning students' opinion on the relevance of problem solving skills for the 21st century job market, the boxplot indicates the highest median value and the lowest variance for problem solving. Thus, students appear to agree that problem solving skills are more important than building and programming a robot, teamwork, and communication skills. Whether the results from the analysis of the descriptive statistics are sustainable will be tested via inferential statistics.

As described in 6.3, the Friedman-test is conducted to investigate differences across the answers by study participants regarding the five skills *building and programming a robot*, *teamwork*, *communication*, and *problem solving*.

Table 4: Descriptive statistics from the Friedman-test

	N[16]	Mean value	Standard derivation	Median	Middle rank
Building a robot	60	4.48	1.702	5.00	1.99
Programming a robot	60	5.20	1.412	5.00	2.85
Teamwork	60	5.70	1.369	6.00	3.38
Communication	60	5.38	1.379	6.00	2.96
Problem solving	60	6.02	1.081	6.00	3.83

The results of the Friedman-test reveal a significant difference between the students' opinions on the relevance of the five skills (χ^2 = 55.234(4), p < .001, N = 60). This tendency is in accordance with the results from the descriptive statistics (both graphical from the boxplot in Fig. 11 and the middle ranks from Tab. 4).

To find out which skills differ from each other, post-hoc-tests (Dunn-Bonferroni-tests) are necessary for the pairwise comparison of these skills (Cohen et al., 2017). Tab. 5 presents a cross matrix of all five skills and the results of the post-hoc-tests.

Table 5: Results from the post-hoc-tests (pairwise comparison) displaying the test statistics (z), statistical significance (p), and the effect size (correlation coefficient r) (ns = not significant)

	Building a robot	Programming a robot	Teamwork	Communication	Problem solving
Building a robot					
Programming a robot	z = -2.973 p = .029 r = 0.38				
Teamwork	z = -3.349 p = .008 r = 0.43	z = -1.819 p = .69 r = ns			
Communication	z = -4.792 p < .001 r = 0.62	z = 0.375 p = 1,0 r = ns	z = 1.443 p = 1.0 r = ns		
Problem solving	z = -6.351 p < .001 r = 0.86	z = -3.77 p = .007 r = 0.44	z = -1.559 p = 1.0 r = ns	z = -3.002 p = .027 r = 0.39	

The results of the post-hoc-tests display that the problem solving skills are considered as more relevant for the 21st century job market than all other skills (with medium to strong effect sizes

[16] Two cases were excluded from the total sample size of 62 because they did not give ratings for all five skills.

($0.39 \leq r \leq 0.86$)) except for the teamwork skills, which are not rated significantly different from the problem solving skills.

In summary, the students' opinion overlaps with the arguments from the literature underlining the importance of problem solving skills. Referring back to the introduction of this study in terms of the model of educational reconstruction, the students' opinion on the relevance of problem solving skills for their future working life (descriptive perspective) supports the normative perspective in the analysis of the educational significance of problem solving skills in STEM. Hence, they supplementary motivate further investigation of the potential of educational robotics competitions to foster students' problem solving skills.

7 Educational robotics competitions as a goal-oriented approach to educational robotics

7.1 The role of competitions in STEM education

In recent years, great efforts have been made to promote STEM education in formal and informal education. However, due to frequently reported constraints regarding time, finance, and other aspects in formal learning settings, informal (i.e. out-of-school) learning settings increase in popularity every year. (Baran et al., 2019)

Baran et al. (2019) argue that informal settings provide students with the freedom to explore STEM disciplines and the possibility to promote their technology, engineering design, and scientific literacy skills along with their choices in STEM careers. Moreover, students participate in authentic real-world problem solving activities. Thus, they are a valuable supplement to formal education. (Baran et al., 2019)

Informal settings in the field include a variety of different activities such as, for example, extra classes and workshops (in-school activities) or out-of-school field trips, summer camps, science clubs, museums, science fairs, competitions, etc. (Petersen et al., 2017).

A special type of activity is competitions. Competitions aim at providing a platform, which complements formal learning in terms of contents and methods of learning. Methodologically, competitions in the field of STEM create learning environments, which (mostly) focus on collaborative work in teams and the authenticity of interdisciplinary real-world problem solving. On the one hand, these competitions aim at fostering students' skills and, on the other hand, they try to arouse their interest in the field and to sustain a long-term engagement, which ultimately leads to students choosing careers in this field. (Petersen, 2015)

In terms of scientific thinking and working methods (*Wissenschaftspropädeutik*), formal learning does not always accomplish its aims due to different constraints such as, for example, the scope of the curriculum, the time pressure, the class size, the teaching methods, the (lack of) motivation of the students, and the lack of research-oriented instructional settings (Fauser & Beutel, 2007). In contrast, competitions have the potential to foster scientific thinking and workings methods, the ability to plan and structure one's learning process, communicate, document, and present projects, and students' scientific identity (Fauser & Beutel, 2007). Thus, they support formal learning regarding the teaching of science *processes* rather than science *contents*.

The increasing number of competitions impedes the selection of a competition for students and teachers. Petersen (2015) presents a list of characteristics, which allows us to differentiate between competitions (Tab. 6). Of course, the contrasting pairs in Tab. 6 are not mutually exclusive (Petersen, 2015).

Table 6: Characteristics of competitions (Petersen, 2015)

Characteristics	**Contrasts**	
Orientation	Performance	Motivation
Type of work	Tasks	Projects
Openness	Restricted	Open-ended
Working method	Theoretical	Experimental
Interdisciplinarity	Subject-specific	Interdisciplinary
Group size	Individual	Group
Number of levels	One level	Multiple levels
Distribution	(inter-)national	Regional
Regularity	Singular	Regular
Sponsoring	Publicly financed	Financed by sponsors

Popular examples of competitions in STEM are the annual *International Olympiad in Mathematics* (IMO), *Physics* (iPhO), *Chemistry* (IChO), *Informatics* (IOI), and *Biology* (IBO).[17] In contrast to these subject-specific competitions, the *European Science Olympiad* (EUSO) is an interdisciplinary and integrated pendant.[18] Another popular example in Germany, which is more project-oriented and experimental (similar to a science fair), is *Jugend forscht*.[19]

Organizers of many of these competitions have developed a structure of successive competitions ranging from elementary to tertiary education. For example, in CS education in Germany, the project *Bundeswettbewerbe Informatik*[20], includes four competitions:

- The initial stage of the project is represented by the *Informatikbiber*[21]. The Informatikbiber is an online-test, which started in 2007. Since 2016, is it also open for primary education (before it was only aimed at secondary education). It focuses on computational thinking and tries to motivate students to further engage with CS.
- The second stage is *Jugendwettbewerb Informatik* (since 2017). This competition consists of two parts: an online-test of computational problems in microworlds, which need

[17] More information on the presented competitions can be found online:
- Mathematics (IMO): https://www.imo-official.org/?language=en (last accessed 21st April 2020)
- Physics (IPhO): https://www.ipho-new.org/ (last accessed 21st April 2020)
- Chemistry (IChO): https://www.ichosc.org/ (last accessed 21st April 2020)
- Informatics (IOI): https://ioinformatics.org/ (last accessed 21st April 2020)
- Biology (IBO): https://www.ibo-info.org/en/ (last accessed 21st April 2020)

[18] More information on the European Science Olympiad (EUSO) can be found online: http://euso.eu/ (last accessed 21st April 2020)

[19] More information on Jugend forscht can be found online: https://www.jugend-forscht.de/ (last accessed 21st April 2020)

[20] More information on the project Bundeswettbewerbe Informatik and its corresponding competitions can be found online: https://bwinf.de/ (last accessed 21st April 2020)

[21] The international version of the Informatikbiber is called *Bebras Challenge*. More information on the Bebras challenge can be found online: https://www.bebras.org/ (last accessed 21st April 2020)

to be solved through block-based programming in the first round, and homework assignments in the second round. This competition requires basic knowledge and skills in CS.

- The third stage is the *Bundeswettbewerb Informatik*. It comprises homework assignments, which require advanced knowledge and skills in CS including algorithms and programming skills.
- The fourth and final stage is the *International Olympiad of Informatics* (IOI). The best participants from the Bundeswettbewerb Informatik can be selected to compete in the IOI for their national team. This final stage fosters especially talented students and teaches the knowledge of university standards. (Pohl, 2017)

Throughout the years and in addition to the competitions mentioned above, engineering and educational robotics competitions for students gained popularity immensely (Miller et al., 2018). These interdisciplinary contests are mostly performance- and projected-oriented, experimental, and collaborative. Popular examples are the *FIRST LEGO League*, *RoboCup Junior*, and the *World Robot Olympiad* and will be explained in greater detail in the following section.

7.2 Examples of educational robotics competitions

7.2.1 FIRST LEGO League

The FIRST LEGO League[22] (FLL) is an international research and educational robotics competition. The competition was founded in 1998 and it aims to engage children aged nine to 16 in research, problem solving, coding, and engineering. Additionally, the FLL wants to motivate children to pursue a career in STEM.

The FLL is one event by the US youth organization *For Inspiration and Recognition of Science and Technology* (FIRST)[23] and is organized in cooperation with the LEGO Group. The president and initiator of FIRST Dean Kamen argues that

> *[w]e need to show children that creating and constructing a video game or robot can be more fun than playing with it. (FIRST LEGO League, n.d.–a)*

The core values of FIRST are *discovery, innovation, impact, inclusion, teamwork*, and *fun* (FIRST LEGO League, n.d.–c).

FIRST also organizes other educational robotics competitions such as, for example, *FIRST LEGO League Jr.*, which is similar to FLL but aims at younger children aged six to ten years, *FIRST Tech Challenge* for students aged 13 to 18, and *FIRST Robotics Challenge* for students

[22] More information on the FIRST LEGO League can be found online: http://www.firstlegoleague.org/ (last accessed 22nd April 2020)

[23] More information the organization FIRST can be found online: https://www.firstinspires.org/ (last accessed 22nd April)

aged 14 to 18. The other events vary regarding their projects, timelines, robotics kits, sponsors, number of participating countries, etc. [24] (FIRST LEGO League, n.d.–c)

In Germany (together with Austria and Switzerland), the FIRST LEGO League and FIRST LEGO League Jr. are organized by the organization *HandsOnTechonology e.V.*[25]. In general, the FLL is organized in countries or regions (e.g. Central Europe) without competitions on an international level. (FIRST LEGO League, n.d.–a)

Statistically, the FLL in Central Europe experienced immense growth throughout the last years. Since the first organization of the FLL by HandsOnTechnology e.V. with 16 teams (78 participants, 35 % girls) in a pilot contest in Germany in 2001, it has grown to a multinational event in Central Europe with 1105 teams (7708 participants, 19 % girls) from multiple countries (Germany, Austria, Switzerland, Hungary, Czech Republic, Poland, Slovakia) in 2019. (FIRST LEGO League, n.d.–a)

The students work together in teams of two to 10 students together with one or two team coaches. The season starts with the release of the annual theme (e.g. *City Shaper*) in August. The teams have up to at least two twelve weeks to prepare for their regional competition, which takes place from mid-November until the end of January. Depending on the country or region, successful teams can qualify for further rounds of the FLL (e.g. in Germany, the semi-final, and Central European final). (FIRST LEGO League, n.d.–b)

The FLL is designed as a multi-disciplinary competition and consists of the following disciplines:

- *Robot-game*: In the robot-game teams build a LEGO robot (using the LEGO Mindstorms or LEGO SPIKE Prime construction kit) to solve missions on the tournament table (Fig. 12, p. 59) with a time limit of 2:30 minutes.
- *Robot-design*: The robot-design evaluates the robots' construction, programming, and strategy, and design in terms of, for example, robustness, innovation, effectivity, etc.
- *Research project*: The research project is linked to the annual theme of the FLL. Teams are required to develop innovative and creative solutions to a real-world problem connected to the annual theme and present it in front of a jury.

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[24] In 2020, FIRST renamed and -structured its competitions to a single program, the FIRST LEGO League, with three division: *FLL discover* (for students aged 4 to 6 years, using LEGO DUPLO blocks), *FLL explore* (formerly FLL Junior), and *FLL challenge* (formerly FLL). The main reason for this rebranding was to increase visibility and present the FLL as a single program, which consists of multiple divisions on a continuum with different division for students of all ages.
More information on the new rebranded FLL can be found online: http://www.firstlegoleague.org/ (last accessed 14th May 2020)

[25] More information the organization HandsOnTechnology e.V. can be found online: https://www.hands-on-technology.org/de/ (last accessed 22nd April)

- *Teamwork*: The teamwork discipline tests the teams' team spirit and collaboration. On the day of the competition, teams are asked questions about their teamwork throughout their FLL season and given small challenges (e.g. to build a bridge using only toothpicks and marshmallows). Regardless, success in solving these small challenges is not to come up with the best possible solution but how the team members collaborate as a team. (FIRST LEGO League, n.d.–d)

The team with the highest overall score will be crowned FLL champion.

Figure 12: FIRST LEGO League tournament table for the 2019 season (City Shaper) with markers for the single missions. (FIRST LEGO League, n.d.–d)

Fig. 12 presents the FLL tournament table for the 2019 season. The teams are confronted with a variety of missions they have to accomplish. The overall aim of the robot game of the City Shaper season is to design a city with more useful, accessible, and sustainable buildings. For example, in mission M13, the teams need to upgrade buildings they have constructed (using the units on the left of Fig. 12) with sustainability upgrades (e.g. solar panels, roof garden, or insulation). (FIRST LEGO League, n.d.–d)

7.2.2 RoboCup Junior

The *RoboCup Junior*[26] (RCJ) is a student competition for students aged ten to 19 years, which was founded in 2000. It is part of the international program *RoboCup*[27], a project which aims at fostering research in robotics and artificial intelligence. Their declared objective is

> *[…] a team of fully autonomous humanoid robot soccer players [, who] shall win a soccer game, complying with the official rules of FIFA, against the winner of the most recent World Cup [by the middle of the 21st century]. (RoboCup, n.d.–e)*

The RoboCup is designed for university students and scientists (RoboCup, n.d.–a). The international final of the RoboCup is accompanied by the RoboCup Symposium, a scientific workshop for presentations and discussions of research in the fields of robotics and artificial intelligence and educational activities. The results of this symposium are published in scientific books (e.g. for 2019: Chalup et al. (2019)). Since 2010, a separate workshop namely the *Workshop on Educational Robotics* (WEROB), which focuses on educational issues of educational robotics, is held concurrently with the RoboCup symposium.[28]

RoboCup used to focus on robot soccer but has expanded its leagues to *RoboCupRescue*, *RoboCup@Home*, and *RoboCupIndustrial*. The RCJ is considered an early entry point for students to robotics and artificial intelligence. (RoboCup, n.d.–a)

In its first deployment in 2000 in Melbourne, Australia, the international event of the RCJ comprised 25 teams from four countries (USA, Australia, Germany, UK). In recent years, around 200 to 300 teams participated in the international contest (e.g. in 2019 in Sydney, Australia, 177 teams from 32 countries). In Germany, 647 teams from 117 different locations participated in 2019. (RoboCup, n.d.–a, n.d.–d)

Teams in the RCJ comprise two to five students (even though there is no strict upper limit) (RoboCup, n.d.–c). In contrast to the FLL, the RCJ does not have annually changing themes but the rules are the same for every year (Eguchi, 2016b). Eguchi (2016b) argues that, without annual changes, the RCJ provides a scaffolded learning environment, which allows students to enhance their knowledge and skills year by year.

The seasons starts with the regional competitions in mid-February to mid-March and the national final at the end of April. The best teams can qualify for the European and international final. (RoboCup, n.d.–b)

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[26] More information on the RoboCup Junior can be found online: https://junior.robocup.org/ (last accessed 22nd April 2020)

[27] More information on the RoboCup can be found online: https://www.robocup.org/ (last accessed 22nd April 2020)

[28] These publications can also be browsed directly on the website of RoboCup: https://www.robocup.org/research/search (last accessed 22nd April 2020)

In contrast to the FLL, the RoboCup Junior allows multiple educational robotics kits (Eguchi, 2016b).

Students in the RCJ can participate in three leagues:

- *OnStage:* In the open-ended OnStage (formerly *Dance*) league students create a stage performance (including music) of autonomous robots (which takes around two minutes). These performances resemble dance performances or storytelling/theatre performances with robots. OnStage comprises *OnStage Preliminary* and *OnStage Advanced* levels. (RoboCup, n.d.–f)
- *Rescue:* The Rescue league requires students to build a robot, which can navigate through a course with obstacles and rescue victims. There are two sub-leagues:
    - *Rescue Line:* The robots must follow a black line to navigate through a course with ramps. On several occasions, the line is blocked by obstacles, which requires the robot to drive around it. At the end of the course, the robot rescues victims (in the form of black metallic balls).
    - *Rescue Maze:* In the Rescue Maze discipline, students build a robot, which can navigate through a maze and identify victims (in the form of heating elements, which can be detected with heat sensors or cameras).

  Both the Rescue Line and Rescue Maze discipline have an entry-level version (*Rescue LineEntry* and *Rescue MazeEntry*, respectively). Additionally, a *Rescue Simulation* discipline conducts the Rescue discipline a virtual world. (RoboCup, n.d.–g)
- *Soccer:* In the Soccer league, teams compete against each other in a two-vs-two robot soccer match. The Soccer league consists of two sub-leagues:
    - *Soccer Leightweight:* This league uses an infrared-ball, which can be detected by the robots with an infrared sensor.
    - *Soccer Open:* This league uses a color-coded ball, which can be identified by the robots with a color sensor or camera.

  Moreover, there are two entry-level versions of the Soccer league (*Soccer 1-1 Standard Kit* (using LEGO and fischertechnik educational robotics kits only) and *Soccer 1-1 Open*). (RoboCup, n.d.–h)

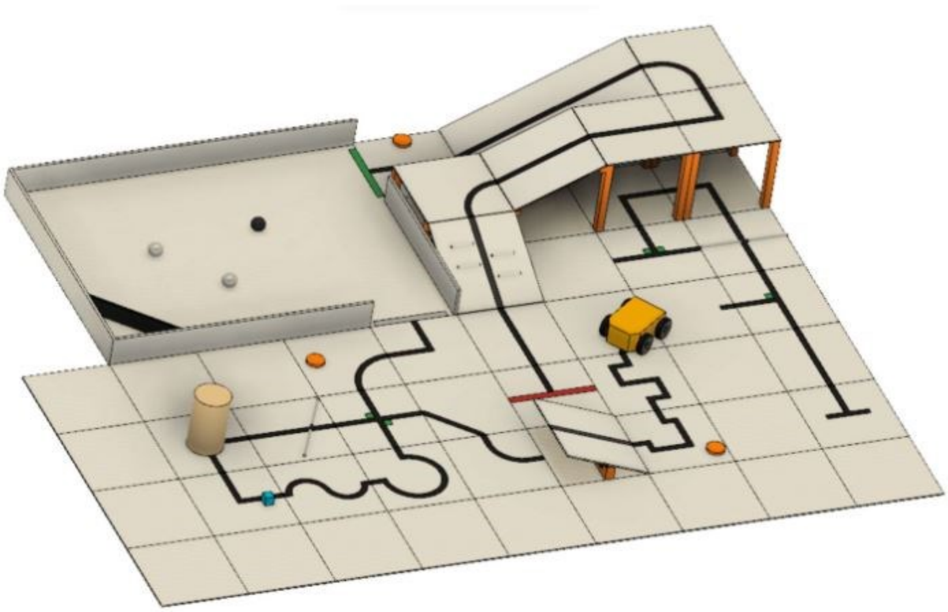


Figure 13: RoboCup Junior tournament table for the Rescue Line league in 2019. (RoboCup, n.d.–g)

7.2.3 World Robot Olympiad

The World Robot Olympiad (WRO) is an international educational robotics competition for students aged six to 19 years. Internationally, it is organized by the *World Robot Olympiad Association*, which was founded in 2004, and their mission is

> *[t]o bring together young people all over the world to develop their creativity, design and problem solving skills through challenging and educational robot competitions and activities." (World Robot Olympiad, n.d.–h)*

Beneath the international organization, the WRO has national organizers, for example, the organization *TECHNIK BEGEISTERT e.V.* [29] in Germany.

The WRO was initially launched in 2004 with 4418 participating teams from twelve countries. In 2019, 28911 teams from 76 countries took part. In Germany, the number of teams increased from 32 teams (in regional two regional competitions) in 2012 to 762 teams (2298 participants, in 33 regional competitions) in 2019. (World Robot Olympiad, n.d.–d, n.d.–g)

Teams in the WRO consist of two or three students and a team coach. The competition has annually changing themes (e.g. *Smart Cities* in 2019), which are the basis for the educational robotics activities. Each year the season begins with the release of the tasks in mid-January. The regional competitions take place in May, the national final in June. The most successful teams

[29] More information the organization TECHNIK BEGEISTERT e.V. can be found online: https://www.worldrobot-olympiad.de/technik-begeistert-ev/kurz-und-kompakt-vision-aktivitaeten-robotergeschichte (last accessed 22nd April 2020)

of the national final can qualify for the international final in November. (World Robot Olympiad, n.d.–a)

The teams can participate in three categories:

- *Regular*: In the Regular category teams build a robot, which solves tasks on a 3 m^2 course (e.g. transporting objects, sorting objects by size or color, etc.). This category comprises three different age groups: *Elementary* (six to twelve years), *Junior* (13 to 15 years), and *Senior* (16 to 19 years). Each age group solves independent tasks on different courses (e.g. Fig. 20, p. 80, for the Junior age group in 2019). The robots must be reassembled on the competition day. (World Robot Olympiad, n.d.–m)
- *Open*: The Open category is research-oriented. Teams develop a robot model, which offers a solution approach to a real-world problem concerning the annual theme of the WRO. Teams present their ideas in front of a jury on the competition day. (World Robot Olympiad, n.d.–j)
- *Football*: In the Football category teams compete against each other in a two-vs-two football/soccer match. An infrared-ball is used, which can be detected by the robots using an infrared sensor. (World Robot Olympiad, n.d.–f)

Additionally, efforts have been made to provide access to the WRO for younger children. Internationally, the Regular WeDo category aims at children up to 10 years using the LEGO WeDo kit. In Germany, the Starter age group was initiated for students aged six to twelve years (using Lego WeDo, Boost, or SPIKE Prime) in the Regular category and the Football category (using one robot instead of two per team). (World Robot Olympiad, n.d.–c, n.d.–i)

Until 2020, the WRO also offered a category for students aged 17 to 25 years, namely the *Advanced Robotics Challenge* (ARC). Students could use any hard- and software systems to build a robot to solve tasks similar to the ones of the Regular category. Regardless, since the WRO wants to focus more on K-12 education, it will no longer offer the ARC after the season of 2020. (World Robot Olympiad, n.d.–e)

Whereas teams in the Regular and Open category are only allowed to use educational robotics kits by LEGO, the Open category permits the use of different materials and hardware (e.g. other microcontroller kits such as, for example, *Arduino* or *RaspberryPi*). (World Robot Olympiad, n.d.–k)

Example tasks of the WRO in 2018 and 2019 will be presented in section 9.3. as an introduction the empirical part of this thesis.

7.3 Program evaluations of educational robotics competitions

Throughout the years, the organizers of these competitions have discovered the importance of taking impact measures of their programs on the participating students, teachers, and other stakeholders. One of the reasons for this discovery is the increasing number of competing programs in informal settings, which forces the competitions to work out their distinguishing features. Since informal learning increased in popularity, especially in the fields of STEM, criticism emerged that there was no evidence about the programs' value (Baran et al., 2019).

Impact evaluation was already identified as one implication for future research in educational robotics (section 4.5, p. 39) and includes the setting of educational robotics competitions, especially with the huge number of participating students worldwide and the money invested by sponsors and other organizations. In section 4.5 (p. 39), it was argued that more systematic evaluation was necessary to evaluate this impact instead of focusing on teachers' experience reports (Alimisis, 2013; Benitti, 2012). Consequently, several organizations have started evaluating their programs in recent years.

For example, the organization FIRST has cooperated with Brandeis University since 2002 to evaluate their educational robotics programs and to identify their impact on students' cognitive and affective variables, career choices, etc. in the US. Their cooperation has led to a great number of technical reports[30] focusing on specific competitions, which are organized by FIRST such as, for example, the FIRST LEGO League, FIRST LEGO League Jr, FIRST Tech Challenge, and FIRST Robotics Competition. Moreover, they have conducted evaluation studies with specific themes (e.g. equity, diversity, and inclusion) or regarding specific target groups (e.g. former participants). After multiple short-term evaluation studies, the focus shifted towards the long-term impact of FIRST programs. Since 2011, FIRST and Brandeis University have been conducting a multiple-year longitudinal study with around 1200 students to evaluate this long-term impact using a quasi-experimental, comparison group design. (Melchior et al., 2018)

The research questions of this study are:

- What are the short and longer-term impacts of the FLL, FTC, and FRC programs on program participants?
- What is the relationship between program experience and impact?
- To what extent are there differences in experiences and impacts among key subpopulations of FIRST participants? (Melchior et al., 2018)

Key findings from the 60-month-followup (after five years) indicate positive impacts regarding students' STEM-related interests and attitudes. They include increased interest in STEM,

[30] The technical reports of the evaluation studies by FIRST can be found online in their resource library: https://www.firstinspires.org/resource-library/first-impact (last accessed 28th April 2020)

involvement in STEM-related activities, STEM identity, STEM knowledge, and interest in STEM careers with students in FIRST programs being two or three times more likely to show gains on STEM-related measures in comparison to the comparison group. These positive impacts apply to all of FIRST's programs and impacts on STEM attitudes and interests are significantly greater for girls than boys. Moreover, these impacts last until college with FIRST alumni showing, for example, a greater interest in studying CS, engineering, and robotics. (Melchior et al., 2018)

In Germany, anecdotal evidence was obtained by HandsOn Technology e.V. using annual online questionnaires for the team coaches in the FLL regarding students' skills, attitudes, and interest in STEM with positive results. (HandsOnTechnology e.V., n.d.)

Regarding RCJ, Eguchi (2016b) reports two studies from 2012 and 2013, which were conducted with 796 students, who participated in the RCJ international final in Mexico City in 2012, and with 14 students of the international final in Eindhoven, respectively. Whereas the first study was quantitative, the second was qualitative to gain deeper insights into students' opinions on their learning in RCJ. Results indicate positive results regarding students learning in STEM and other relevant skills such as communication, collaboration, computational thinking, and engineering skills (Eguchi, 2016b). However, RCJ also contributed to scientific innovations in the fields of robotics. For example, two students from a Slovakian team developed a low-cost camera for RCJ soccer teams and other students from a Spanish team collaborated with Arduino to develop the low-cost *Arduino robotic kit* (Eguchi, 2016b).

The WRO conducted its first scientific evaluation study in Germany during the season in 2019. This evaluation study focused on students learning of 21st century skills (building and programming a robot (digital literacy skills), collaboration and teamwork, communication, and problem solving (learning and innovation skills)) (first study) and the competition's influence on students' self-concept and interest regarding STEM as indicators of their future career choices (second study). 413 teams (1053 students) participated in the first study and 62 former participants of the WRO in the second study. Results indicate positive effects on students' 21st century skills, especially their learning and innovation skills (see section 2.2.2). Moreover, the WRO strongly influences students' self-concept and interest regarding STEM. Thus, the competition indirectly impacts their future career choices in this field. (Pöhner et al., 2020b; Pöhner & Hennecke, 2019a)

All in all, educational robotics competitions highly differ regarding their effort and scope of impact evaluation studies. Whereas most evaluation studies report positive outcomes, the underlying methodological approaches range from anecdotal to scientific. Consequently, in accordance to the implications for future research of educational robotics in general, Alimisis (2013), for example, argues that there is a lack of systematic evaluations and reliable experimental designs and a demand for more rigorous quantitative research is necessary to validate the impact of educational robotics (competitions). To gain deeper insights into methodological approaches for impact evaluation of educational robotics competitions, the following chapter will deliver information on different aspects such as types of evaluation, evaluation and measurement methods, and contemporary issues and challenges with the evaluation of educational robotics programs.

8 The evaluation design process: a methodological guide

The selection of an appropriate (research or) evaluation methodology is a difficult task. Even though *research* and *evaluation* show differences, they also share commonalities (e.g. methodology, sampling, instrumentation, and data analysis, etc.) (one branch of research is often understood as *evaluative research* or *applied research*) (Cohen et al., 2017). Consequently, evaluation is generally more practically oriented and tries to overcome adversities of the setting, including informal science education projects (Friedman et al.). Friedman et al. (p. 16) argue that it is a challenge to "[…] select the most rigorous design appropriate for the work at hand" (despite any adversities or limitations). Educational robotics competitions are a special type of informal science education project. Therefore, this chapter provides an overview of the evaluation design process, a methodological guide for the design of evaluations of K-12 educational robotics programs, which is based on Stubbs et al. (2012).

8.1 Types of evaluation

8.1.1 Evaluation of program improvement

Definition

Evaluation of program improvement is a form of formative evaluation, which is conducted while the program is being introduced. Formative evaluation in educational robotics programs aims to identify problems or provide feedback about, for example, robot platforms, curricula, training materials, etc., and to find out whether any of these factors need to be modified before the next deployment of the program (Stubbs et al., 2012).

Formative evaluation follows a cyclic model (Fig. 14). It starts with the development of initial materials. Before the first deployment of the program with a small number of students or teachers, the measurement methods for the evaluation need to be developed. The data gathered in the first pilot study will be analyzed and materials, etc. will be modified before the next cycle begins. (Stubbs et al., 2012)

Figure 14: Cyclic model for formative evaluation in educational robotics (adapted from Stubbs et al. (2012)).

Evaluation subjects

Hard- and software

One aim of an educational robotics program could be the development of new hard- or software, e.g. a novel robotics system or programming interface. This could involve questions regarding e.g. the intuitivity of new hard- or software for the students and teachers. Stubbs et al. (2012) suggest the use of multiple data collection methods, which address empirical data (or log data) (i.e. objective perspective) of the use of the new technology and feedback from students and teachers (i.e. subjective perspective). The objective and subjective perspectives should be merged for an overall evaluation. (Stubbs et al., 2012)

Curricula

Other formative evaluation projects focus on the improvement of the program and its curriculum itself. In addition to the structure of the curriculum, feedback could also involve specific course activities or tasks. According to Stubbs et al. (2012), this information can be used to identify the most (dis-)liked or challenging activities in the curriculum. (Stubbs et al., 2012)

Professional development

For educational robotics to be used in classrooms, appropriate teacher training is necessary. The evaluation of teacher training allows to investigate the opinion of teachers about specific educational robotics programs and whether they are likely to use these activities in their classrooms (Stubbs et al., 2012).

8.1.2 Assessing program effectiveness

Definition

Assessing program effectiveness is another possible goal of evaluation in educational robotics. Contrary to formative evaluation, which, as mentioned before, focuses on the iterative process of program development and its possible modifications, assessing program effectiveness is a form of summative evaluation (Stubbs et al., 2012). For educational robotics programs, summative evaluation incorporates, for example, measuring what students have learned after their participation or how their attitudes towards, for example, the field of STEM have changed.

Summative evaluation follows a four-step process model to measure program effectiveness (Fig. 15, p. 69). Firstly, the target or aims of the program need to be identified. Based on these, the target group of the study (mostly students, but possibly also teachers, parents, political stakeholders, etc.) will be determined. Secondly, the researcher needs to identify which impact the program should have on the target group (e.g. skill development, change in attitudes towards STEM, etc.). The identified impact allows the researcher to formulate initial hypotheses, which shall be answered by the evaluation study. Thirdly, in the process of operationalization, the broader targets and aims by the program need to be made more specific and observable to be measurable. This involves the question of what kind of data is needed to answer the raised questions and to (dis-)prove the formulated hypotheses. Finally, the appropriate evaluation and measurement methods need to be selected. Regardless, sometimes pragmatic reasons (e.g. program activities or characteristics and other constraints) will even suggest or dissuade specific methods. (Stubbs et al., 2012)

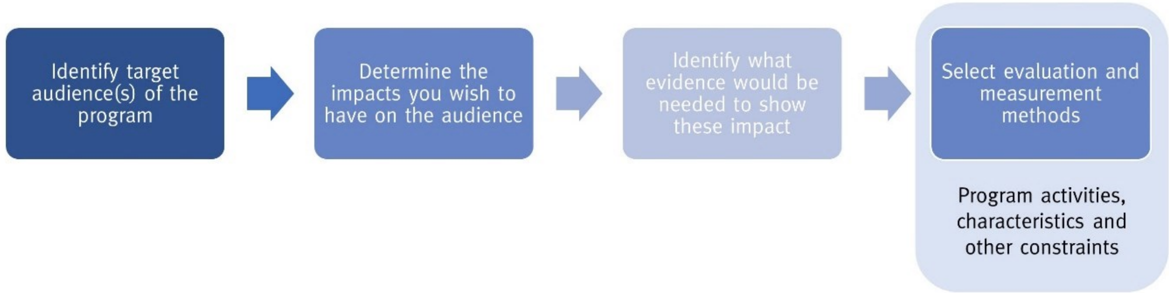


Figure 15: Four-step process model for summative evaluation in educational robotics (adapted from Stubbs et al. (2012)).

Evaluation subjects

Students' learning

The investigation of students' learning focuses on the development of procedural skills rather than declarative knowledge. The most accurate method of assessing students' learning is through a direct measure such as, for example, quizzes. A simpler technique of assessment is through students' self-report of their perceived learning using, for example, questionnaires. Even though the students' perspective provides direct feedback on their learning, an external perspective (e.g. the teacher's) can also be valuable and teachers can rate students' learning through questionnaires, interviews, etc. This technique is also useful when direct measures of students' learning are not feasible. (Stubbs et al., 2012)

Students' attitudes

Students' attitudes such as engagement, interest, or motivation display the students' perceptions of the program's topic. To assess students' attitudes the most frequent method are questionnaires. The focus of assessment is usually not only the mere attitudes of students regarding a specific topic but also the change of the attitudes over time. (Stubbs et al., 2012)

Students' behavior

Students' attitudes, as mentioned before, are the first step in examining the influence of the program on the students' future career choices. One of the main goals of out-of-school settings such as educational robotics competitions is to promote students to pursue a career in STEM. Regardless, investigating students' behavior is very challenging. Initiatives need to collect and maintain the contact information of the participants, which is hampered since it is a voluntary effort and students' contact information can change over time. (Stubbs et al., 2012)

8.2 Evaluation and measurement methods[31]

8.2.1 Evaluation methods

Pre- and post-tests

Pre- and post-tests are the most frequent method in educational robotics programs. They allow to investigate the change in students' learning and attitudes before and after the program and, thus, display the program's influence as an intervention. (Stubbs et al., 2012)

Comparison groups

According to Stubbs et al. (2012), comparison (or control) groups have been used less frequently due to the logistical problems involved. Especially in self-selecting programs, it is difficult to find an appropriate comparison group since the participants are more likely to be interested in STEM fields than those who do not participate. (Stubbs et al., 2012)

8.2.2 Measurement methods

Questionnaires

Questionnaires are a straightforward way of collecting data. They are flexible and can be designed with items using single or multiple-choice questions, open-ended questions, or Likert scales. Regardless, questionnaires need to be handled carefully in the process of data collection and analysis considering aspects such as validity and reliability and the use of methods of inferential statistics. (Stubbs et al., 2012)

Interviews

In contrast to questionnaires, interviews are of an open-ended nature which allows the interviewer to react to responses by the interviewee. Thus, interviews provide a more in-depth narrative of a specific topic. Interview flow can be controlled using guiding questions in an interview guideline. Transcripts of interviews can also be harder to analyze than questionnaires responses, but the use of a category system (in a deductive approach) allows for a systematic approach. (Stubbs et al., 2012)

Observations

According to Stubbs et al. (2012), observations provide a non-obtrusive way of collecting data. They suggest the use of a structured observation sheet, which focuses on the relevant aspects of research and guides the researcher throughout the observation process. Additionally, audio- and video recordings are recommended as documentation to help in the process of data analysis. (Stubbs et al., 2012)

[31] For further discussion of evaluation and measurement methods see the overview by Cohen et al. (2017) or Haden (2019a, 2019b) as they will only be mentioned briefly in this chapter. The used methods in our evaluation study will be explained in depth the corresponding chapters.

8.3 Issues and challenges

Since the nature of most educational robotics settings is out-of-school with self-selecting participants, obtaining statistically significant results is challenging and results are hard to be generalized to larger populations. Thus, given these limitations of educational robotics settings, researchers should yet consider the importance of aspects of methodology such as sample size, validity, and reliability, data analysis, or multiple target audiences. (Stubbs et al., 2012)

The number of students participating in a specific program influences the possibility to obtain statistically significant results. Generally, the larger the sample size, the more convincing the results, especially with quantitative methods such as questionnaires in pre- and post-test settings or with comparison groups. For smaller sample sizes, results are more likely to be less convincing. (Stubbs et al., 2012)

For data collection and analysis a transparent procedure is key to rigorous evaluation (Stubbs et al., 2012). Ensuring high accuracy of test instruments by checking for validity and reliability of the instrument in data collection and using both descriptive and inferential statistics to analyze the data are important parts of this procedure (Stubbs et al., 2012).

The collection of demographic data of the participants in the evaluation study (again mostly students, but possibly also teachers, parents, political stakeholders, etc.) allows the researchers to compare impacts of the program on different target groups such as boys and girls, students with different backgrounds, etc. (Stubbs et al., 2012)

The rigorous evaluation also involves the selection of appropriate evaluation and measurement methods based on factors as, for example, the stage of development and number of participants of the program or the length of the program (Stubbs et al., 2012).

For programs in the initial stages, qualitative measures such as interviews or observations provide good feedback on the technology use or design of the program and its curriculum. With programs evolving iteratively, the focus of evaluations tends to shift from technology and curriculum evaluation towards the evaluation of outcome and impact regarding students' learning, attitudes, etc. Accordingly, with a rising number of participants, measurement methods shift from qualitative to quantitative. Established programs, which have been conducted for multiple years or are replicated at different locations, should evaluate long term impact, or compare the program at different locations, respectively. Especially longitudinal studies are a particular challenge for evaluation studies in educational robotics since it is very hard to track students in an out-of-school setting and self-selection over multiple years. (Stubbs et al., 2012)

The length of the program also affects the design of the evaluation study. The length may vary from half or one-day activities to program duration up to nearly a whole year. Depending on the length, measurement methods also vary from qualitative measures for short course activities to quantitative measures for longer programs. (Stubbs et al., 2012)

Finally, Stubbs et al. (2012) suggest the use of multiple methods in evaluation studies of educational robotics programs, since administering multiple methods will produce richer (i.e. complementary) data to analyze.

9 Overview of the research questions and the study design

9.1 Research questions

In the previous chapters of this thesis, engineering design skills have been discussed as one form of problem solving skills in STEM education and the use of educational robotics to foster these skills, especially in the setting of competitions. Moreover, the review of the literature of research studies, evaluations, and impact analyses revealed a major lack of evidence on the impact of educational robotics on students' learning. That is the reason why this thesis aims at contributing to this research gap by providing an empirical study on students' learning of problem solving skills through participation in the WRO, a popular international educational robotics competition for students aged six to 19 years.

For the empirical part of this thesis, the following three research questions[32], which lead to the respective hypotheses, are formulated:

1. Research question: Can students improve their problem solving skills through participation in an educational robotics competition such as the World Robot Olympiad?

Hypothesis 1a: Students can improve their problem solving skills through participation in the educational robotics competition.

Since the students' overall skill development in the WRO can also be influenced by other variables, the skill development will be further examined concerning specific subgroups.

Hypothesis 1b-f: There are no differences in their skill development for different subgroups such as

b) category (Regular, Open, and Football category)
c) age group (Starter, Elementary, Junior, and Senior)
d) experience (in number of prior participations)
e) gender (boys only, girls only, and mixed teams)
f) success (in % of points achieved at the regional competition)

Rationale: In search of appropriate ways of teaching problem solving skills to students in STEM education, Passey (2017), for example, poses the question of whether constructivist (and constructionist) forms of pedagogies are suitable for the learning of these skills. Even though many studies have already investigated this question (e.g. Eguchi (2017)), criticism emerged in the educational robotics community that there is a lack of systematic quantitative research on the

[32] Another research question regarding students' opinion on relevant skills for the 21st century job market, which was also conducted in the context of the evaluation study of the WRO in 2019, was already reported in chapter 6 (p. 49). This incoherent structure was selected in favor of the argumentative structure in the context of the model of educational reconstruction as research framework.

impact of educational robotics on students learning (Alimisis, 2013). As a consequence, instead of focusing on descriptive and small-scale studies in the form of experience reports by teachers, the educational robotics community is required to conduct more evaluation studies using more sophisticated methodological approaches.

2. Research question: Can students learn a systematic engineering design process by using sophisticated problem solving strategies through their participation in an educational robotics competition such as the World Robot Olympiad?

Hypothesis 2a: Teams apply different problem solving strategies.

Hypothesis 2b: Successful teams prefer more sophisticated problem solving strategies compared to less successful teams.

Rationale: Following the summative assessment of students' problem solving skills in the first research question, one might ask *how* skill development regarding students' problem solving skills through participation in the WRO might come about (formative assessment). In their systematic review about the use of educational robotics as *computational manipulatives* in STEM education, Sullivan & Heffernan (2016) propose a continuum for the learning of problem solving strategies ranging from simple trial-and-error to more sophisticated strategies. Accordingly, since the aim of the WRO is to foster engineering design skills, successful teams in the WRO are expected to prefer more sophisticated problem solving strategies compared to their less successful counterparts.

3. Research question: What kind of assistance (i.e. teacher interventions) do team coaches (have to) provide to their students in an educational robotics competition such as the World Robot Olympiad as a student-centered, collaborative, and problem-based setting?

Hypothesis 3a: Team coaches use different types of teacher interventions.

Hypothesis 3b: There are differences regarding the types of intervention for the subgroups

a) age group (Elementary, Junior, and Senior)
b) success (in % of points achieved at the regional competition)

Rationale: In their study on students' learning through participation in the FLL, Kaloti-Hallak et al. (2015a) name the teaching pedagogy (in company with the competitive nature of the activities, the unstable nature of the design of the robots, and the curricular position of the activities) as an important factor influencing students' learning (including the learning of problem solving). They noted a shift from teacher-centered towards student-centered pedagogy (Kaloti-Hallak et al., 2015a). Consequently, the role of the teacher in the student-centered pedagogy changes. In a student-centered, collaborative, and problem-based setting, the teacher provides assistance and intervenes using different types of intervention, which Leiß and Wiegand (2005)

categorize as *regarding the organization*, *affective*, *regarding the content*, and *metacognitive* (or *strategic*).
Referring to the development of students' problem solving skills, the metacognitive type is of special interest. Because of the more complex tasks for older age groups, they are expected to receive a higher degree of metacognitive support. Similarly, successful teams are expected to receive a higher degree of metacognitive support due to more sophisticated problem solving approaches, which they are thought to use to increase their performance.
To answer these three research questions, an empirical investigation was conducted in the setting of the WRO. The study design will be described in the following section.

9.2 Study design

The empirical part of this thesis was conducted throughout the seasons of 2018 and 2019 of the WRO in Germany. It is composed of three studies, some of which were part of a larger impact evaluation study of the WRO in 2019[33]. Fig. 16 (p. 77) and 17 (p. 77) present the study design in reference to the schedule of a season of the WRO.

To give a short overview, the three studies will be explained roughly in this chapter. A more detailed description follows in the corresponding chapters.

1. **Study on students' learning of problem solving skills**: This study focuses on the students' learning (or development of) problem solving skills through participation in the WRO. It compares the problem solving skills of the students (as rated by their team coaches) *before* and *after* their participation.
   As illustrated in Fig. 17 (p. 77), this study was part of the impact evaluation study of the WRO in 2019. This impact evaluation study consisted of two partial studies.
   - The first partial study investigated students' learning of 21st century skills (digital literacy, teamwork/collaboration, communication, *and problem solving*) using questionnaires with the team coaches (N = 413 of 683 participating teams in the WRO in Germany in 2019) (Pöhner et al., 2020b).
   - The second partial study focused on the students' (i.e. the former participants in the educational robotics competition) self-concept and interest in STEM (N = 62 former participants of the WRO in Germany) (Pöhner & Hennecke, 2019a). According to the theory of career decision making by Gottfredson (1981), they are important indicators of students' career choices. The second partial study also comprised a questionnaire study. Whereas the investigation of students' learning of problem solving skills was part of the first partial study, an excerpt of

[33] This impact evaluation study was conducted in collaboration with the organization TECHNIK BEGEISTERT e.V., the organizers of WRO Germany and financially supported by the foundation Dr. Hans-Riegel-Stiftung. The results of this study can be found online: www.tb-ev.de/wirkung (last accessed: 29th February 2020) and a short summary of the main results of this evaluation study is available in appendix A (or in Pöhner et al. (2020a)).

this second partial study was presented in chapter 6 (p. 49) regarding the students' opinion on the relevance of problem solving skills for the 21st century job market.

2. **Study on students' use of problem solving strategies**: The second study within this thesis deals with the students' use of problem solving strategies in the WRO. It consists of two parts. The first part is a (qualitative) diary study, in which a couple of teams were asked to monitor their working processes to identify problem solving strategies in the educational robotics competition. They kept the diary throughout the months before the regional competitions of the WRO in 2018, starting in mid-January and continuing until the teams' respective regional competitions (as indicated in Fig. 16, p. 77). (Pöhner & Hennecke, 2018b)
   After the national final of the WRO in 2018, team coaches of teams in the Regular category were asked to participate in the second part of this study ((quantitative) questionnaire study) and to rate which strategy (as resulting from the diary study) they considered more promising to succeed in the educational robotics competition (N = 57).
3. **Study on teaching pedagogy**: The third study presents a change of perspective. Whereas in the previous studies on students' learning of problem solving skills and on their use of problem solving strategies the focus was on the students, the focus of this third study is on the team coaches. It investigates how team coaches provide assistance to their students during their learning process (especially regarding the learning of problem solving skills) (N = 57) (Pöhner & Hennecke, 2018c). The questions regarding the teaching pedagogy were incorporated in the same questionnaire study, which was used at the end (in the second part) of the study on the students' use of problem solving strategies. (see Fig. 16, p. 77).

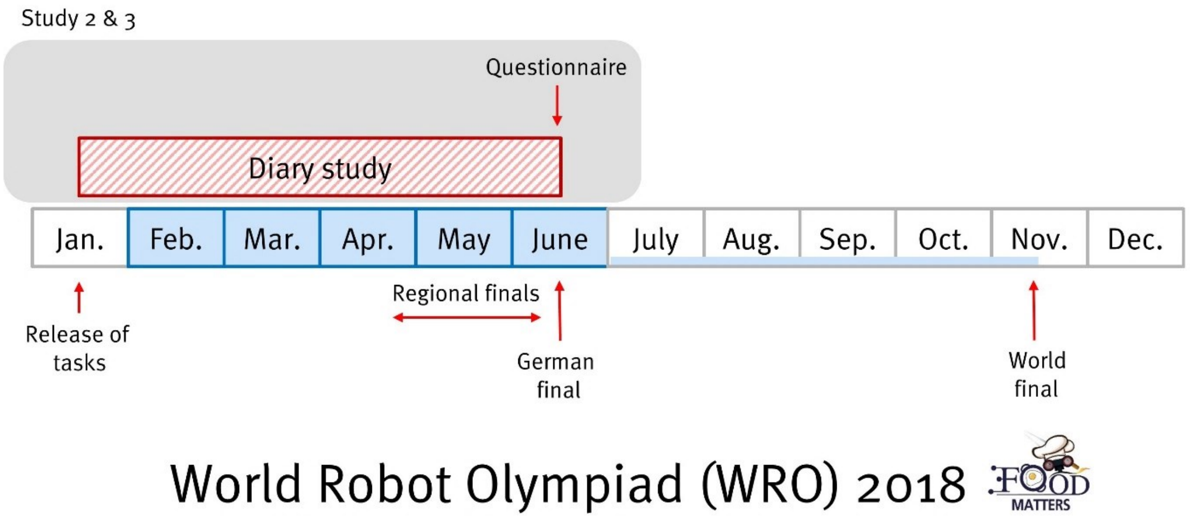


Figure 16: Study design in reference to the schedule of the season of the World Robot Olympiad in 2018.

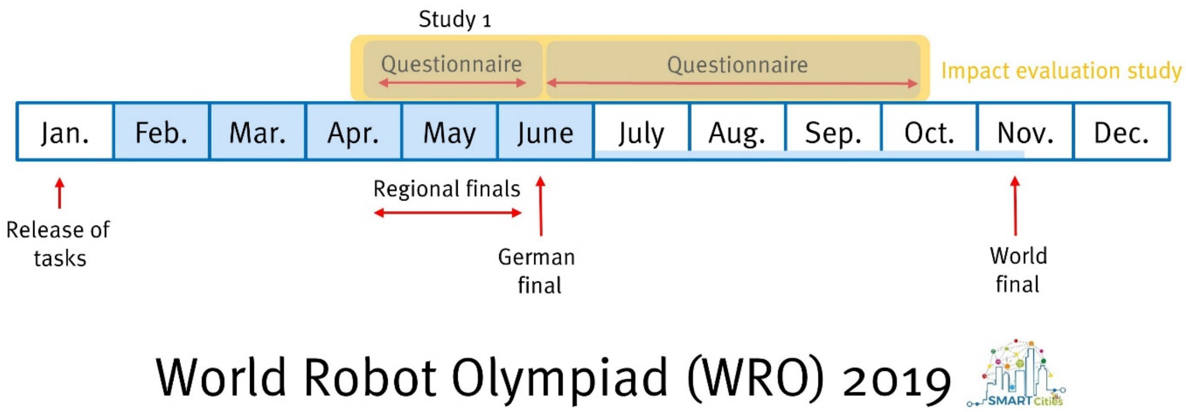


Figure 17: Study design in reference to the schedule of the season of the World Robot Olympiad in 2019.

As shown in the description of the three studies above, they were numbered according to the corresponding research questions. Thus, the chronological structure (as illustrated in Fig. 16 and 17) of the studies is not coherent with their argumentative structure. In the following, each study will be presented (following the argumentative structure) in a separate chapter (chapters 10 to 12). Each chapter will present information on the study's motivation in the introductory section, data collection (study design and instruments) and analysis, and results. Regardless, before the studies will be presented in the following chapters, section 9.3 (p. 78) will introduce example tasks of the Junior age group of the Regular category of the WRO in 2018 and 2019 to familiarise the reader with the educational robotics competition as setting of the empirical part of this thesis.

9.3 Example tasks of the World Robot Olympiad of 2018 and 2019

The overall theme of the WRO in 2018 was *Food matters*. This theme dealt with one of the big problems of today's world, which is the way to grow, share, and consume food with a growing population in the world and problems such as world hunger and climate change, which are connected to it. This theme was about to explore the ways technology can support humans in fighting these problems. In the Junior age group (13 to 15 years) of the Regular category, for example, the task *Precision farming* investigated the use of robots, drones, etc. to produce more food more efficiently. Teams had to build and program a robot, which can plant different colored seedlings in different fields depending on the soil quality of the fields (Fig. 18). (World Robot Olympiad, n.d.–l)

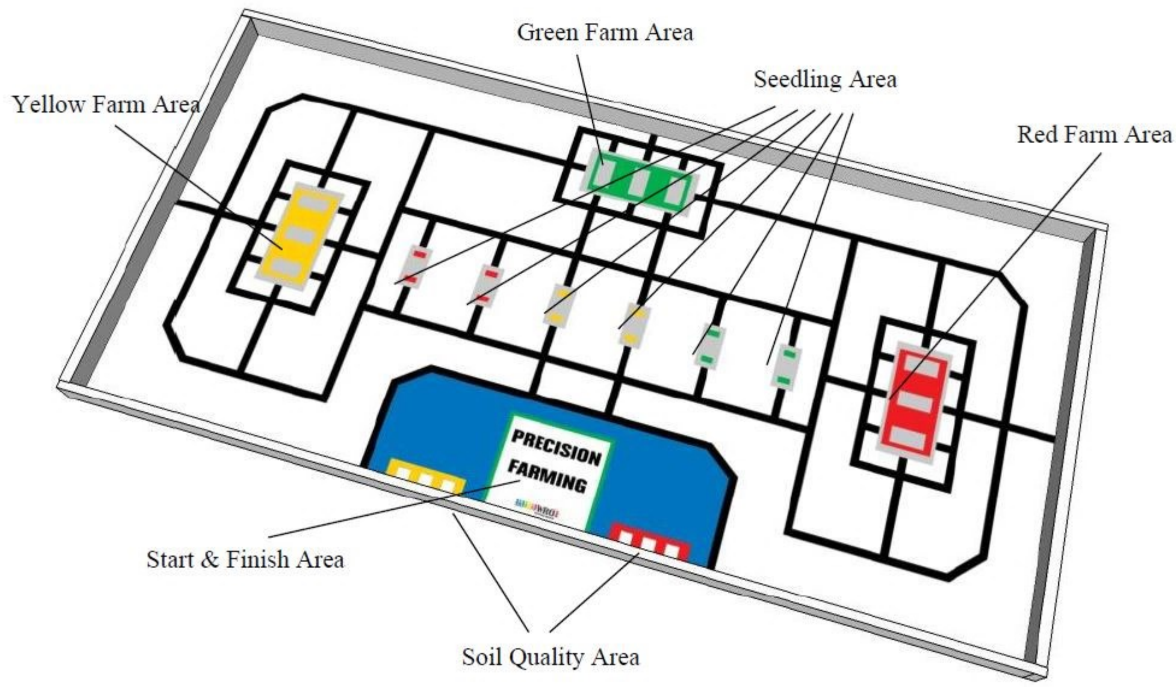


Figure 18: WRO tournament table for the 2018 season (Food matters) for the Junior age group in the Regular Category (Precision farming) with a description of the components. (World Robot Olympiad, n.d.–l)

The task of the robot was to collect the green, red, and yellow seedlings from the seedling area and plant them in the corresponding farm areas. The soil quality was indicated by black and white LEGO blocks, which were positioned in the soil quality area. The seedlings and the soil quality blocks would change randomly throughout the competition. An example setup to illustrate this task is available in Fig. 19. In this example, the color code in the soil quality area indicates that in the yellow farm are the field #1 is of bad soil quality, and #2 and #3 are of good soil quality. In the red farm area, fields #4 and #5 are of good soil quality and #6 is of bad soil quality. The seedlings need to be planted accordingly. The fields in the green farm area are all of good soil quality and seedlings can be planted in any field. (World Robot Olympiad, n.d.–l)

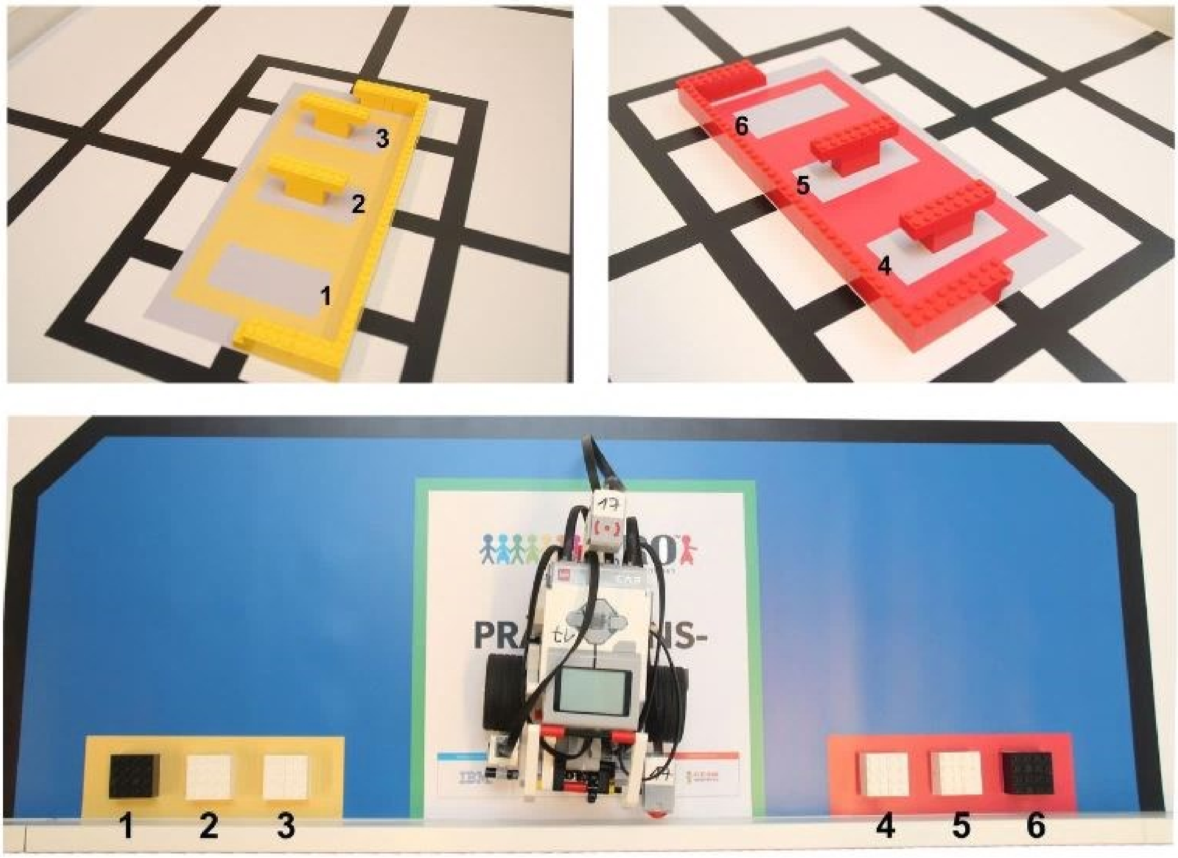


Figure 19: Example setup of the task Precision farming to illustrate the color coding of the soil quality for the farm areas. (World Robot Olympiad, n.d.–l)

In 2019, the overall theme of the WRO was *Smart cities*. This year's theme dealt with the ongoing process of digitalization in today's everyday life in the city. This includes developments such as, for example, green energy, innovative concepts to safe energy, and smarter traffic systems. In the Junior age group of the Regular category, teams focused on the theme *Smart lightning*.

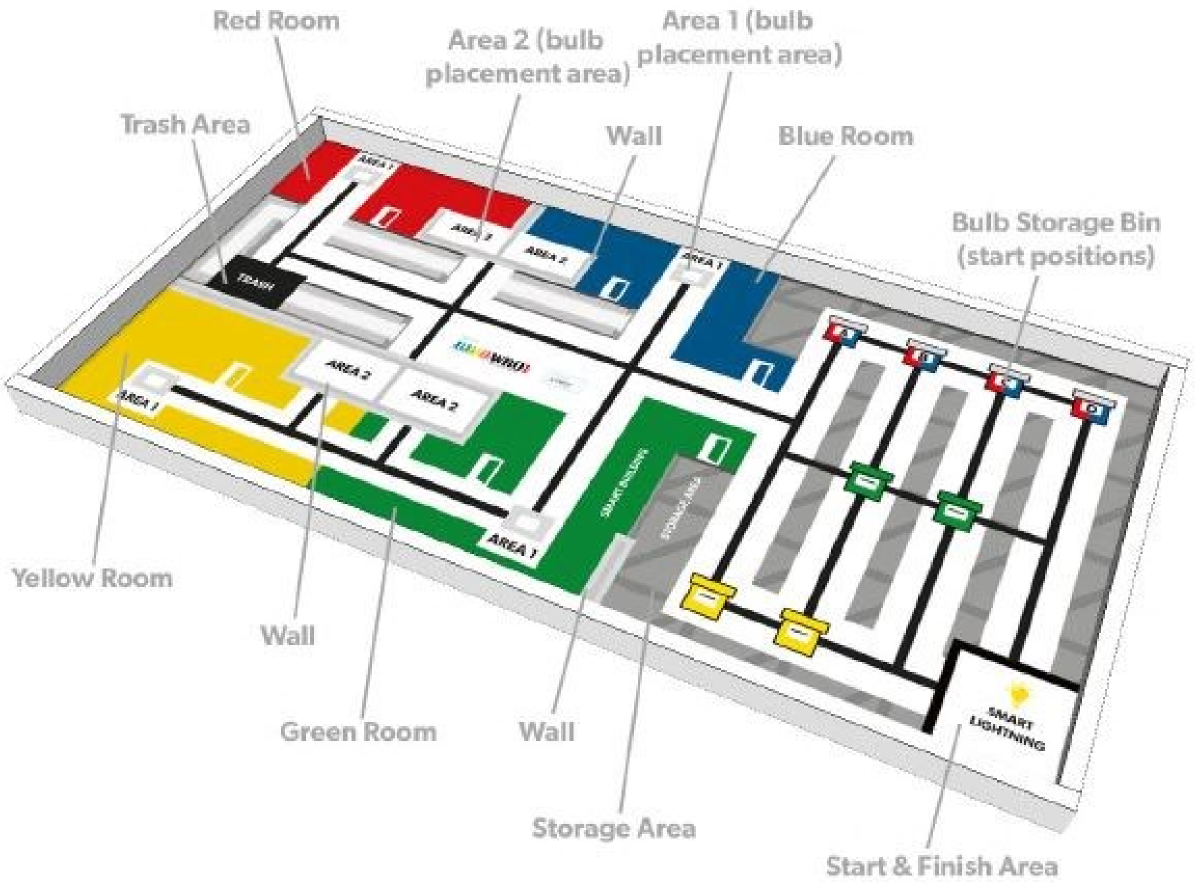


Figure 20: WRO tournament table for the 2019 season (Smart Cities) for the Junior age group in the Regular Category (Smart Lightning) with a description of the components. (World Robot Olympiad, n.d.–l)

To save energy, smart homes include intelligent systems, which work without human interaction and automate many aspects of our life. The teams had to build a robot, which modernizes a lightning system by replacing old light bulbs with new smart light bulbs. The robot would take new smart light bulbs from the storage area and deliver them to the different rooms (red, blue, green, and yellow). Old light bulbs had to be brought to the trash area. In this task, the position of the old and new light bulbs and the rooms, which they had to be delivered to, would change randomly through the competition. An example setup to illustrate this task is available in Fig. 21 (p. 81). In this example, an old black light bulb was placed in a yellow bulb placement area (area 1). Thus, one yellow and two green light bulbs were placed randomly on the corresponding bulb storage bins (above). Similarly, one old black light bulb was placed in a blue bulb placement area (area 1). Thus, one blue and two red light bulbs were placed randomly on the corresponding bulb storage bins (below). Whereas the yellow and green light bulbs have fixed bulb storage bins, the red and blue light bulbs share four bulb storage bins and their position can vary among those four bins. (World Robot Olympiad, n.d.–l)

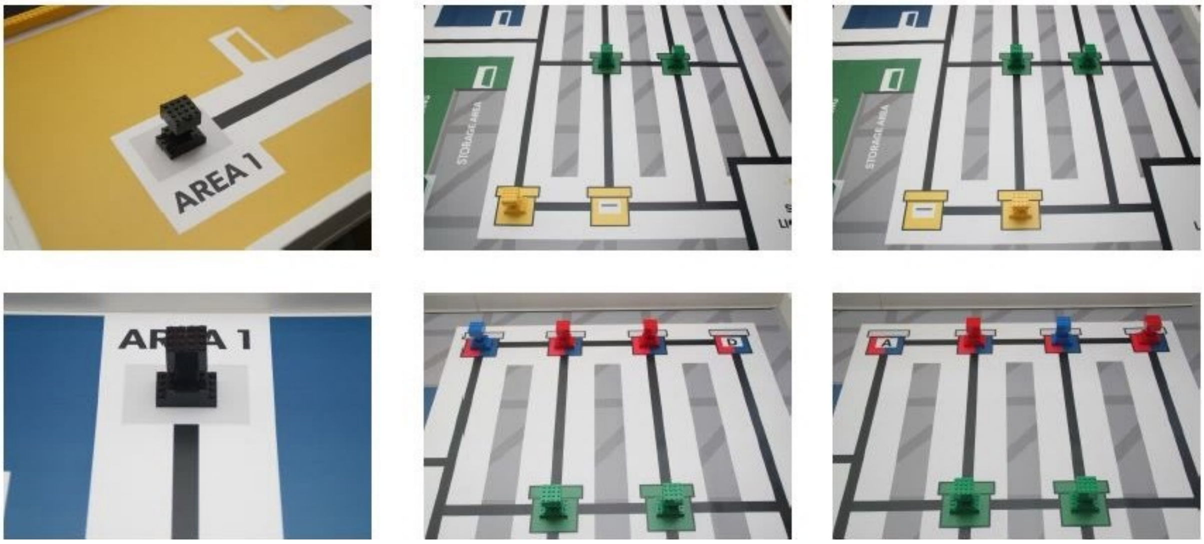


Figure 21: Example setup of the task Smart lightning to illustrate the color coding of the different colored light bulbs. (World Robot Olympiad, n.d.–l)

These two tasks work as examples for the Junior age group of the Regular category of the WRO. The main differences of the age groups in the Regular category reside in the robot's ability to react to dynamic situations. Whereas the Elementary age group (mostly) consists of static situations (e.g. with fixed paths the robot needs to drive), the Junior and Senior age group include randomized elements (e.g. color coding, which can vary (Fig. 19, p. 79 and 21, p. 81) and influence the robot's behavior) to create dynamic situations.

More information on the tasks of the WRO in 2018 and 2019 for the different categories and age groups can be found online: https://wro-association.org/competition/previous-challenges (last accessed 9th July 2020).

10 Development of students' problem solving skills

10.1 Introduction

This first study aimed to investigate the development of students' problem solving skills through participation in a season of the WRO. It was conducted in the context of the impact evaluation study of WRO Germany in 2019.

In addition to the overall impact of the WRO on students' problem solving skills, this study examines various characteristics, which are likely to influence (or moderate) the students' skill development. These variables include team- (or input-) (experience, gender), program- (category, age group), or output- (success) characteristics.

10.2 Data collection

10.2.1 Study design

This study comprises a quasi-experimental design study with pre- and post-test using then-test data (i.e. pre-test data, which is collected in retrospect). Cohen et al. (2017) describe this type of study as the one-group pre-test post-test (pre-experimental).

The team coaches of the participating teams in the WRO were asked to externally assess students' skill level regarding their problem solving skills *before (pre) and after (post)* the WRO season of 2019 through a paper-and-pencil questionnaire. The study took place at the 33 regional competitions of WRO Germany, starting on 4th May 2019 in Leonberg and Trier, and continued until the last regional competition on 8th June 2019 in Menden (Sauerland) (Fig. 17, p. 77).

A typical regional competition day of WRO Germany consists of multiple rounds of preparation and competition. During the preparation rounds, students work autonomously on their robots to improve them for the next round of the competition. During these rounds, the team coaches usually gather for meetings or particular events for team coaches, which have been organized by the local organizers of the regional competitions. In 2019, the local organizers advised the team coaches to allocate time for the completion of the questionnaire of the WRO's impact evaluation study.

Unfortunately, this type of quasi-experimental design lacks control for extraneous variables (Cohen et al., 2017). Consequently, the attribution of differences in pre- and post-test values cannot be justified because other variables may infer the results (Cohen et al., 2017). Usually, control (or comparison) groups are used to check for extraneous variables in experimental research designs (Cohen et al., 2017). Whereas the experimental group experiences an intervention, the control group does not (Cohen et al., 2017). Regardless, the degree of control for extraneous variables from experiments in, for example, chemistry and physics cannot be attained in educational settings. Moreover, Stubbs et al. (2012) state that control groups are used less frequently in evaluations of educational robotics competitions due to the logistical problems involved. They argue that, especially in self-selecting programs, it is difficult to find an appropriate comparison group since the participants are more likely to be interested in STEM fields than those who do not participate (Stubbs et al., 2012).

Another point of criticism of this study design addresses the use of then-test data, i.e. pretest-data, which is collected in retrospect. The use of then-test data increased in popularity in recent years in the field of program evaluations as an alternative to traditional pre-test data. Collecting pre-test data in retrospect does not only provide pragmatic advantages (reduction of data collection dates) but can also alleviate the *response shift bias*. The response shift bias describes the lack of knowledge to judge the initial level of functioning (i.e. problem solving skills). After the intervention, study participants are more likely to be able to judge appropriately. However, advocates of traditional pre-test data name the *desire by participants to show a learning effect* and *threats to validity due to insufficient reflection of information* as disadvantages. (Allen & Nimon, 2007)

All in all, the advantages of the then-test data outweighed its disadvantages in this study.

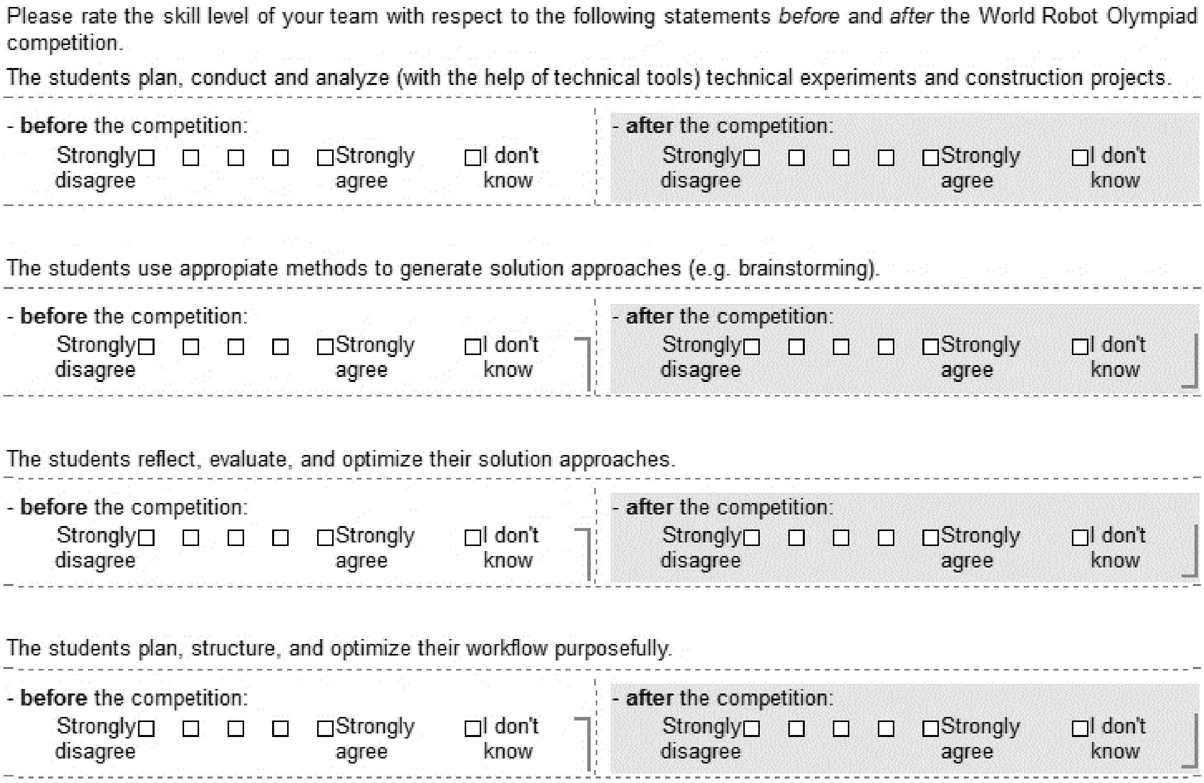
10.2.2 Instruments

To measure students' problem solving skills (in terms of their engineering design skills) a scale with multiple items was constructed. These items describe an operational definition of the students' problem solving skills.

The scale was part of the questionnaire in the impact evaluation study of WRO Germany in 2019. The use of multiple items for measuring a specific abstract concept is described as *operationalization* and describes the way this (latent) concept is represented in the corresponding scale (Haden, 2019b; Johnson & Christensen, 2020). In case of the lack of an existing scale for the concept to be investigated, a new scale has to be developed. Finding appropriate items for this scale can be achieved through different methods such as, for example, expert interviews or a literature review (Haden, 2019b; Johnson & Christensen, 2020).

For this study, new items were identified through the use of a literature review of the lesson plans of LEGO education[34]. LEGO education analyzed the educational standards (process- and content standards) of STEM subjects of different states in Germany (and other countries) and linked them to activities of their lesson plans. Engineering design skills were described as *practices* in the process standards of the analysis and the following items were selected to be incorporated in the scale for this study:

[34] More information on the lesson plans of LEGO education can be found online (in German): https://education.lego.com/de-de/lessons (last accessed 22nd May 2020). On the new and restructured website, the lesson plans are edited, and the educational standards can be found in the teacher support rubric.



Please rate the skill level of your team with respect to the following statements *before* and *after* the World Robot Olympiad competition.

The students plan, conduct and analyze (with the help of technical tools) technical experiments and construction projects.

- **before** the competition: Strongly disagree □ □ □ □ □ Strongly agree □ I don't know
- **after** the competition: Strongly disagree □ □ □ □ □ Strongly agree □ I don't know

The students use appropiate methods to generate solution approaches (e.g. brainstorming).

- **before** the competition: Strongly disagree □ □ □ □ □ Strongly agree □ I don't know
- **after** the competition: Strongly disagree □ □ □ □ □ Strongly agree □ I don't know

The students reflect, evaluate, and optimize their solution approaches.

- **before** the competition: Strongly disagree □ □ □ □ □ Strongly agree □ I don't know
- **after** the competition: Strongly disagree □ □ □ □ □ Strongly agree □ I don't know

The students plan, structure, and optimize their workflow purposefully.

- **before** the competition: Strongly disagree □ □ □ □ □ Strongly agree □ I don't know
- **after** the competition: Strongly disagree □ □ □ □ □ Strongly agree □ I don't know

Figure 22: Items (P1 to P4) of the problem solving scale of the questionnaire in the impact evaluation study of WRO Germany in 2019[35] (translated from the German version).

The items used a 5-point Likert scale (strongly disagree – strongly agree) to assess the team coaches' rating.

To ensure high accuracy of the measurement instrument, Stubbs et al. (2012) recommend checking for the instrument's reliability and validity when evaluating educational robotics competitions. Whereas *reliability* refers to the stability and consistency of an instrument, *validity* refers to its accuracy of the inferences (Johnson & Christensen, 2020).

The reliability of an instrument can be stated as *Cronbach's alpha*. It measures the internal consistency of the instrument and is an alternative to other measures of reliability such as, for example, *the test-retest-reliability* or the *parallel-test-reliability* (Johnson & Christensen, 2020). The problem solving scale of the questionnaire in the impact evaluation study of WRO Germany showed an acceptable value of $\alpha = .768$. All four items were included in the scale since the column *Cronbach's alpha if item deleted* did not show any possible improvement.

[35] The software *EvaSys* (https://en.evasys.de/main/home.html) was used for this study.

Table 7: Results of the reliability analysis (Cronbach's alpha) of the problem solving scale of the questionnaire in the impact evaluation study of WRO Germany in 2019.

Scale		Corrected item-total correlation	Cronbach's alpha if item deleted	Cronbach's alpha
Problem solving (engineering design)	P1	.506	.748	.768
	P2	.636	.468	
	P3	.540	.732	
	P4	.613	.691	

The validity (unidimensionality, construct validity) of an instrument is calculated by *exploratory factor analysis (EFA)* (using principal component analysis (PCA)) (Johnson & Christensen, 2020). The results of the EFA indicate that the scale is valid to measure students' problem solving skills (fulfilling the requirements of the factor analysis with KMO > .7 and a significant Barlett's-test; accounting for 59.72 % of the total variance and all factor loadings > .7).

Table 8: Results of the validity analysis (exploratory factor analysis) of the problem solving scale of the questionnaire in the impact evaluation study of WRO Germany in 2019.

Scale		Component	Cumulative %	KMO	p-value
Problem solving (engineering design)	P1	.819	59.72	.776	< .001
	P2	.805			
	P3	.746			
	P4	.716			

For the analysis of subgroups, the questionnaire study also included questions on the teams' background characteristics such as category (Regular, Open, and Football category), age group (Starter, Elementary, Junior, and Senior), experience (in number of prior participations) and gender (boys only, girls only, and mixed teams). In contrast, the teams' success (in % of points achieved at the regional competition) was gathered after the regional competition through the competition's website.

10.3 Data analysis

In this study, the Wilcoxon-, the Kruskal-Wallis-test, and correlation analyses were used[36]. Whereas the Wilcoxon-test is a non-parametric test to compare two related samples, the Kruskal-Wallis-test is a non-parametric test to investigate differences in two or more independent samples (Cohen et al., 2017). The Wilcoxon-test was used to examine the skill development of students' problem solving skills before and after the WRO competition. The Kruskal-Wallis-

[36] The software *SPSS* (https://www.ibm.com/analytics/spss-statistics-software) was used for the statistical analysis of this study.

test and the correlation analysis were used to compare the subgroups of category, age group, experience, gender, and success.

To control the pre-test-values when comparing different subgroups (using the Kruskal-Wallis-test and the correlation analyses), the difference between pre- and post-test-values (of individual teams) was not calculated as simple difference score (i.e. *absolute gain*: post score – pre score) but as *normalized (or relative)* gain (g) as defined by Hake (1998):

$$\text{Hake's g} = \frac{\text{post score} - \text{pre score}}{\text{max score} - \text{pre score}}$$

pre score = result of the pre-test (i.e. then-test)
post score = result of the post-test
max score = maximum value of the Likert-scale

The normalized gain can take values between zero and one. The advantage of this normalized gain is that the student's pre-test-values are explicitly considered. The normalized gain considers that gains a more likely to appear (i.e. to be assessed by the team coaches) at the lower end rather than at the upper end of the scale. Thus, students, who achieve a gain of one point on the scale from 3 to 4 will receive a higher normalized gain score than students, who achieve a gain of one point on the scale from 1 to 2 (both in comparison to an absolute gain of one point on the scale):

$$\text{Hake's g} = \frac{4-3}{5-3} = \frac{1}{2} = 50\%, \qquad \text{Hake's g} = \frac{2-1}{5-1} = \frac{1}{4} = 25\%$$

In this way, the comparison of students from different subgroups (e.g. age groups) is much fairer since their prior knowledge is explicitly considered.

10.4 Results

10.4.1 Sample description

A total of 683 teams participated in the season of 2019 *Smart Cities* of WRO Germany. The response rate for this study is 60 % (413 of 683 participating teams). This corresponds to 1053 students. 90 of 270 missing responses result from regional competitions, who did not send back any responses. This indicates an organizational problem of the competition organizers of the respective regional competition.

The following description of the sample of this study will provide information about background characteristics of the sample, especially regarding the subgroups, which will later be analyzed for differences in their skill development (e.g. category or age group).

In summary, the response rate for the categories of the WRO is 61 % (350 of 573 participating teams) for the Regular category, 40% (17 of 43 participating teams) for the Football category, and 69 % (46 of 67 participating teams) for the Open category.

Concerning the category, 85 % (350 of 413 teams) participated in the Regular category, 11 % (46 of 413 teams) in the Open category, and 4 % (17 of 413 teams) in the Football category. This roughly parallels the distribution of teams in the WRO in general.

Fig. 23 presents the distribution of participating teams per category and age group:

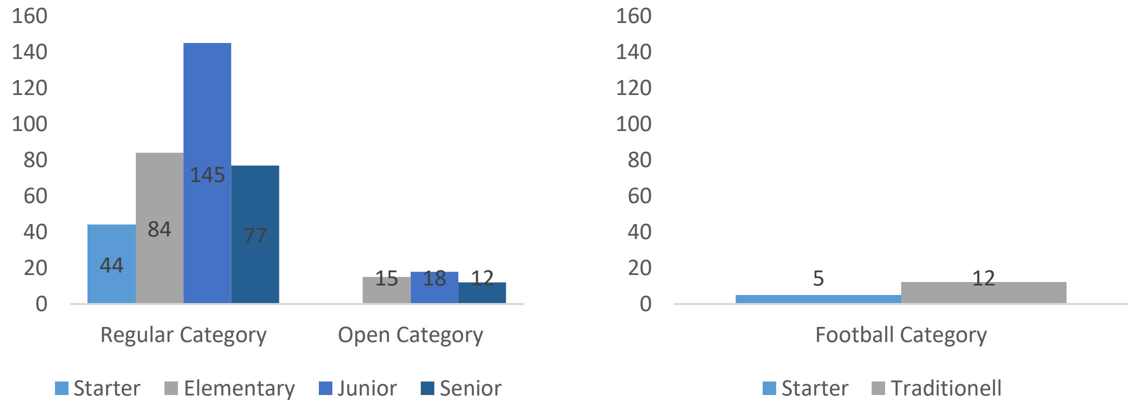


Figure 23: Participating teams per category and age group for the Regular and Open category (left) and Football category (right).

The distribution of participating teams regarding their experience (i.e. prior participations in WRO Germany) is shown in Fig. 24:

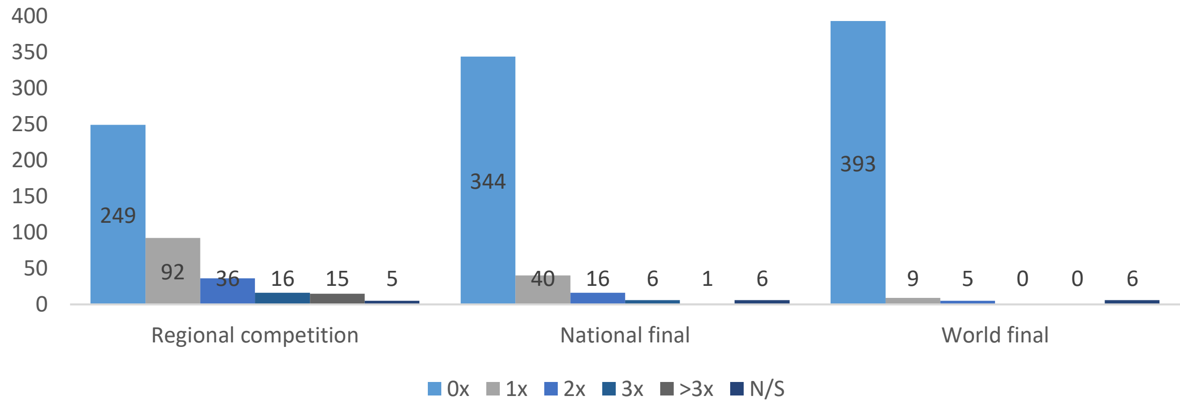


Figure 24: Participating teams regarding their experience with WRO Germany.

Fig. 25 presents the distribution of participating students regarding their gender.

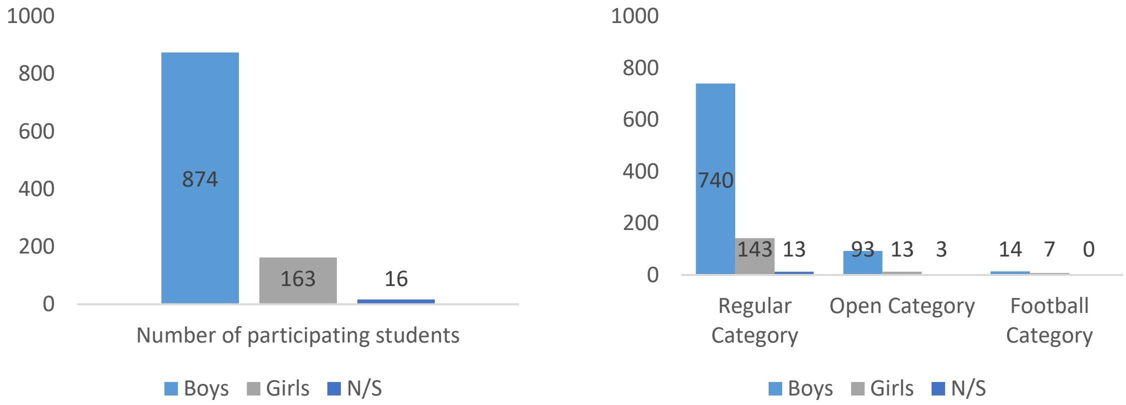


Figure 25: Participating teams regarding their gender.

The description of the sample shows that most teams participate in the Regular category, have little to some experience, and that the majority of participants are boys.

10.4.2 Overall analysis

1. Research question: Can students improve their problem solving skills through participation in an educational robotics competition such as the World Robot Olympiad?

Hypothesis 1a: Students can improve their problem solving skills through participation in the educational robotics competition.

The overall results show a significant increase in students' problem solving skills before and after the competition (Median pre = 2.5, Median post = 3.25; Wilcoxon-test: z = -15.065, p < .001, N = 361). This corresponds to an effect size of r = 0.79, which resembles a large effect.

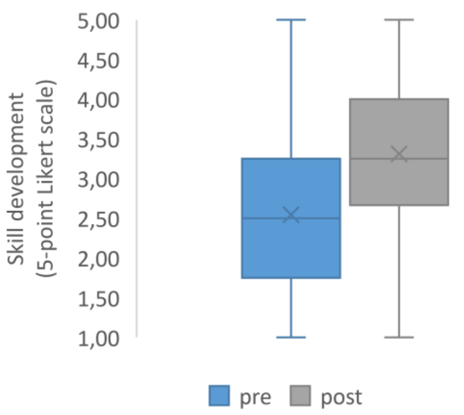


Figure 26: Skill development of students' problem solving skills as boxplot.

Accordingly, this hypothesis can be confirmed. Students can develop their problem solving skills through participation in the WRO as an example of an educational robotics competition.

10.4.3 Analysis of subgroups

In addition to the overall results, the skill development of students' problem solving skills was compared for the subgroups *category, age group, experience, gender,* and *experience*, since they are considered as moderating variables in this study. Consequently, the corresponding hypotheses sounded as follows:

Hypothesis 1b-f: There are no differences in their skill development for different subgroups such as

- b) category (Regular, Open, and Football category)
- c) age group (Starter, Elementary, Junior, and Senior)
- d) experience (in number of prior participations)
- e) gender (boys only, girls only, and mixed teams)
- f) success (in % of points achieved at the regional competition)

The skill development for these subgroups was compared using the normalized gain (Hake's g) as described in section 10.3 (p. 85).

Regarding the category (1b), the results show no significant differences between the categories Regular, Open, and Football for the development of students' problem solving skills (middle ranks[37]: Regular category = 178.92 *(N* = 314), Open category = 203.11 *(N* = 35), Football category = 170.88 *(N* = 12); Kruskal-Wallis-test: $\chi^2(2) = 1.815$, $p = .403$) (Fig. 27).

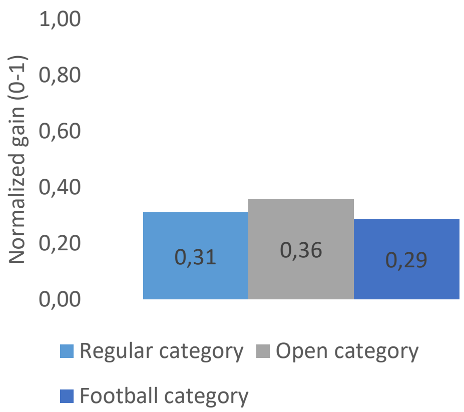


Figure 27: Differences in students' skill development of problem solving skills regarding the category as bar chart.

Similarly, no significant differences have been found for the other subgroups (1c-f). The results of the Kruskal-Wallis-tests are presented in Tab. 9 and 11. Whereas the Kruskal-Wallis-test was

[37] The middle rank, which is used to describe to scores of the teams in the comparison of different subgroups, is a basic measure for many non-parametric statistical tests (e.g. Wilcoxon or Kruskal-Wallis-test). In general, ranking is a process of data transformation of, for example, ordinal values, in which they are replaced by their rank when the data is sorted. To calculate the middle rank, the sum of ranks is divided by the number of elements in the subgroup.

used to compare the teams and their age groups and gender, correlation analysis was used to find commonalities between the teams and their experience and success (Tab. 10 and 12).

Table 9: Results of the Kruskal-Wallis-test to compare the teams' skill development and their age groups

	Middle rank				**Kruskal-Wallis χ^2**	***N***				***p***
	Starter	Elementary	Junior	Senior						
Test statistics	127.86	148.95	154.26	162.83	3.931	36	83	118	65	.269

Table 10: Results of the correlation analysis to find commonalities of the teams' skill development and their experience

	Correlation coefficient (Spearman's rho)	***p***	***N***
Test statistics	.095	.079	346

Table 11: Results of the Kruskal-Wallis-test to compare the teams' skill development and their gender

	Middle rank			**Kruskal-Wallis χ^2**	***N***			***p***
	Boys only	Girls only	Mixed teams					
Test statistics	177.39	151.72	176.38	1.37	273	24	73	.504

Table 12: Results of the correlation analysis to find commonalities of the teams' skill development and their success

	Correlation coefficient (Spearman's rho)	***p***	***N***
Test statistics	.053	.323	350

Even though the use of the normalized gain (Hake's g) to compare subgroups regarding the development of students' problem solving skills in this educational robotics competition shows positive results in terms of the absence of moderating variables of students' learning, the investigation of the prior knowledge (i.e. pre-values in the questionnaire) seems promising to examine the students' skills at entry-level. In summary, we find the following statistically significant differences:

- Category: teams in the Regular category show a lower prior knowledge than teams in the Open and Football category (middle ranks: Regular category = 175.10 (*N* = 317), Open category = 231.96 (*N* = 36), Football category = 281.12 (*N* = 17); Kruskal-Wallis-test: $\chi^2(2) = 23.526$, $p < .001$).
- Age group: teams in younger age groups (Starter, Elementary) show lower prior knowledge than older teams (Junior, Senior) (middle ranks: Starter = 139.85 (*N* = 43),

Elementary = 135.98 (N = 92), Junior = 189.56 (N = 141) , Senior = 224.39 (N = 77); Kruskal-Wallis-test: $\chi^2(3) = 39.946, p < .001$).

- Gender: teams, who consist only of girls, show lower prior knowledge than teams, who consist only of boys or boys and girls (middle ranks: Boys only = 196.04 (N = 273), Girls only = 136.60 (N = 24), Mixed teams = 162.16 (N = 73); Kruskal-Wallis-test: $\chi^2(2) = 11.214, p = .004$).

Additionally, statistically significant correlations were found for the students' prior knowledge concerning their experience ($r_{Spearman} = .297$, $p < .001$, $N = 366$) and success ($r_{Spearman} = .121$, $p = .002$, $N = 370$).

To conclude, it can be stated that students can foster their problem solving skills through participation in the WRO independent of input-, program-, and output characteristics, which do not moderate students' learning. Thus, this educational robotics competition is successful in implementing a learning setting to develop their 21st century skills. Every student participating in this program can foster his or her skills and, hence, the program is equally effective.

These results support the existing literature on the positive impact of educational robotics (competitions) on students' learning of problem solving skills. For example, Melchior (2013) stated in the evaluation report of the FLL season of 2012/13 that 93 % of the team coaches in the FLL reported an increase in their problem solving skills. Moreover, as already indicated in section 4.3 (p. 31), Benitti and Spolaor (2017) mentioned problem solving (together with teamwork) as the most frequently researched skills to be developed through educational robotics. Regardless, prior research is mostly associated with small-scale studies or with the lack of an elaborated or transparent research methodology (Benitti & Spolaor, 2017).

From an educational policy perspective, it is very interesting to see that especially the students' (or teams') input variables (experience and gender) do not moderate their learning. Following the phrase of the *leaky pipeline* as an analogy for the decrease in students' (especially girls') interest and self-concept towards STEM (Taskinen & Lazarides, 2020), Witherspoon et al. (2016) report that they found a higher-level involvement for girls (in programming) in an entry-level educational robotics competition and a lower-level involvement in higher levels of the competitions because of this decline in (programming) interest. This is problematic because the results of this study indicate that indeed educational robotics competition can provide a learning environment, which is equally effective for all genders. Consequently, one of the main reasons for this decline is of course not the limited capabilities of girls but their competition with male students for the team coach's attention, the lack of female role models, and, while growing up, the greater pressure from peers, parents, and mentors and societal expectations to adopt specific gender roles (Witherspoon et al., 2016).

Additionally, Melchior (2013) reports that girls in the FLL show greater gains in their learning than program participants as a whole. Nonetheless, in this study, using the normalized gain, which controls for girls' lower prior knowledge, no significant differences were found.

Despite the positive results of this first study, they do not clarify *how* an increase in students' problem solving skills comes about. To gain deeper insights into the students' actual working process in educational robotics competitions, qualitative analysis is necessary. Hence, the second study comprises an investigation of the use of students' problem solving skills to develop solutions in the educational robotics competition.

11 Students' use of different problems solving strategies

11.1 Introduction

The first study of this thesis indicated that educational robotics competitions can provide a learning setting for students to foster their problem solving skills. Regardless, qualitative data is necessary for further analysis of students' learning, especially when analyzing STEM *skills* or *practices* rather than *concepts*, as Bresciani et al. (2010) indicate:

> *Each primary type of quantitative data contributes unique and valuable perspectives about student learning to the outcomes-based assessment process. When used in combination, a complete or holistic picture of student learning is created. (Bresciani et al., 2010)*

In the context of educational robotics, Benitti and Spolaor (2017) state that evaluation of educational robotics should include quantitative *and* qualitative analysis. Their systematic review of educational robotics revealed that only 25 % of the reviewed studies used both types of analysis (Benitti & Spolaor, 2017). Anwar et al. (2019) concur by saying that future research designs which utilize different methods of analysis would be useful. Additionally, for educational robotics (competitions), Stubbs et al. (2012) suggest the use of multiple methods in evaluation studies of educational robotics programs, since administering multiple methods will produce richer (i.e. complementary) data to analyze.

In their systematic review of qualitative and mixed-method studies, Sullivan and Heffernan (2016) describe educational robotics as *computational manipulatives*. Whereas *manipulatives*, in general, are entities, which scaffold students' learning in a specific domain, *computational manipulatives* have computing capabilities. Educational robotics, for example, are built and programmed by students to interact with the environment. They can be used for either learning about a domain (i.e. robotics) (first-order-use) or the understanding of scientific concepts in other domains (second-order-use). Regarding the first-order-use, engineering design is one fundamental practice of robotics and is an important scientific activity, which is similar (but not equal to) scientific inquiry (section 3.3, p. 23). Moreover, it is a way to teach general problem solving skills and science process skills. (Sullivan & Heffernan, 2016)

From the results of their systematic review, Sullivan and Heffernan (2016) conclude a learning progression for students' learning of reasoning in educational robotics, which comprises the following levels: *sequencing, causal inference, conditional reasoning,* and *system thinking*.

The learning progression starts with simple sequencing, which describes the students' ability to put items (i.e. programming steps) in a specific order to construct simple educational robotics programs and continues with the investigation of cause-and-effect principles. The progression continues towards reasoning abilities (causal inference and conditional reasoning) and an advanced understanding of systems (system thinking). Whereas causal inference describes the investigation of the discrepancy of the expected in contrast to the presented behavior (structure-behavior-function) and the construction of abstract rules or explanations for the behavior of the robot, conditional reasoning depicts the students' ability to understand simple input-process-output loops (with one input variable). Lastly, advanced system thinking includes the understanding of multivariate phenomena. Students, who are capable of conditional reasoning but not system thinking, might understand the need to control variables in engineering design but are not able to use multivariate data. (Katehi et al., 2009; Sullivan & Heffernan, 2016)

This learning progression aligns with the development of problem solving strategies. Sullivan and Heffernan (2016) argue that students start with simple trial-and-error strategies and continue to move towards more sophisticated strategies to solve educational robotics problems. In this context, trial-and-error strategies are precursors of conditional reasoning, and more sophisticated strategies are associated with their reasoning ability (Sullivan & Heffernan, 2016). All in all, they conclude a continuum of problem solving strategies from simple trial-and-error to more sophisticated strategies (Barak & Zadok, 2009; Bilotta et al., 2009; Huang et al., 2013; Sullivan & Heffernan, 2016).

This study aims to investigate the problem solving strategies of teams, who participate in the WRO, as an example of an educational robotics competition, and to place them within the continuum of problem solving strategies. Moreover, since the aim of the WRO is to foster engineering design skills, successful teams in the WRO are expected to display more sophisticated problem solving strategies than their less successful counterparts.

11.2 Data collection

11.2.1 Study design

This study uses a mixed-method design. Mayring (2001) describes the level of study design as one possibility to integrate quantitative and qualitative methods. In this case, results from a qualitative (case) study are tested through a quantitative (questionnaire) study (Mayring, 2001).

The qualitative study (the first part in the mixed-method design) comprises a case study with self-selecting teams of the Regular category of the WRO in 2018. The participating teams were asked to keep a diary to monitor their working processes throughout the months before the regional competitions of the WRO in 2018, starting in mid-January and continuing until the teams' respective regional competitions (diary method) (Fig. 16, p. 77).

In general, case studies (as part of qualitative, naturalistic research) are "[…] an investigation into a specific instance or phenomenon in its real-life context" (Cohen et al., 2017). They are often used to gain in-depth insights into a specific case to understand distinctive underlying phenomena. Different types of case studies include descriptive, explanatory, and exploratory case studies. In contrast to *descriptive* (i.e. providing narrative accounts) or *explanatory* (i.e.

testing theories) case studies, *exploratory case studies* can be used to generate hypotheses, which can later be tested in quantitative studies and, thus, function as pilots of other (quantitative) studies, especially in cases without any previously existing theories. Regardless, critics argue that case studies often lack control and are unsystematic. Thus, they are difficult to make inferences from and lack generalizability. However, researchers claim that for case studies generalizability is more likely to be understood in terms of *analytical generalizability* rather than *statistical generalizability*. Whereas statistical generalizability describes the reasoning from a sample to a population, analytical generalizability does not care about a representative result but focuses on the expansion of theory. Case studies allow researchers to understand similar (or – as in this study – different) cases to find explanations for specific situations and actions. In this study, the case studies are used to identify *how* students can develop their problem solving skills through their participation in this educational robotics competition. (Cohen et al., 2017; Yin, 2014)

As Cohen et al. (2017) and Yin (2014) indicate, exploratory case studies are used to generate hypotheses, which can function as a pilot to other (quantitative) studies. In the quantitative study (the second part in the mixed-method design), the problem solving strategies of different teams, which resulted from the qualitative diary study, were presented to the team coaches of teams from the Regular category of the WRO via an online questionnaire after the national final of the WRO in 2018. They were asked to rate which strategy they considered more promising to succeed in the educational robotics competition. Their rating together with their demographic data allowed to identify, which strategies are preferred by differently successful teams in this educational robotics competition.

11.2.2 Instruments

Case study

Case studies use a variety of different instruments such as, for example, documents (e.g. reports, diaries, notes, etc.), interviews, observations, and artifacts (e.g. pictures, student projects, programming exercises, etc.) (Cohen et al., 2017; Yin, 2014). According to Rahimi et al. (2018), these are *intermediate products*, which are the outputs of the joint making and learning cycle in design-based activities and can be used for formative assessment. In this study, a team diary (i.e. protocol, test report) was used to monitor the team's working process.

This (online[38]) diary was semi-structured and focusing on the teams' working process concerning their problem solving process in the educational robotics competition.

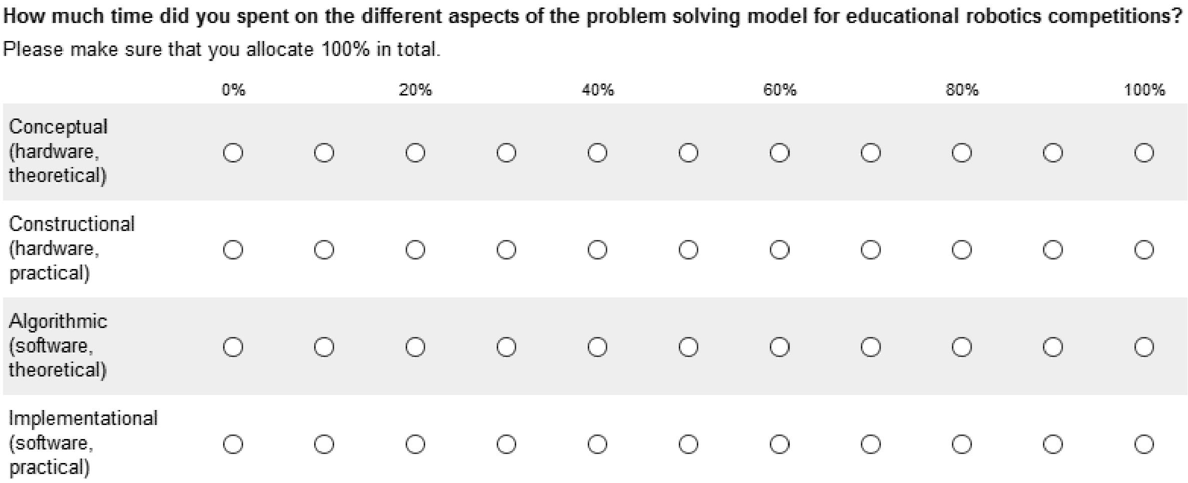
The structure of the diary is based on a problem solving process model, which was derived from a literature review. As already mentioned in section 3.2.3 (p. 21) and 3.2.4 (p. 22), the

[38] The software *SosciSurvey* (https://www.soscisurvey.de/) was used for the online diary and the questionnaire study.

engineering design cycle comprises the phases *identifying the problem, generating ideas how to solve the problem* (e.g. brainstorming), *building and testing multiple prototypes, evaluation of prototypes* (with specifications and constraints in mind and including trade-offs to balance conflicting constraints (*optimization*)) (Katehi et al., 2009). Focusing especially on educational robotics as computational manipulatives, Sullivan and Heffernan (2016) propose a model, which they call the *troubleshooting cycle*: *diagnosis* (observation, evaluation, hypothesis generation), *revision* (manipulation, computation, estimation, and control of variables), and *retest* (hypothesis testing, observation, evaluation and hypothesis generation). Another even more detailed model is provided by Bilotta et al. (2009) and includes the building/constructing of the robot on the one hand and the programming of the robot on the other hand. They included the following phases into their model: *planning and building the artifact, behavioral programming (divided into basic and sensor programming),* and *checking*. The advantage of this model is the inclusion of the building/constructing of the educational robot. Especially in educational robotics competitions as a long-term learning activity, the building/constructing of the educational robot is a very important part of the solution. This involves the planning of the construction and the actual building of the construction. Thus, the model, which was used for the diary in this case study, does not only incorporate the building/constructing (hardware) and programming (software) of the robot as tasks but splits these into a theoretical and practical dimension. All in all, the model consists of the following aspects:

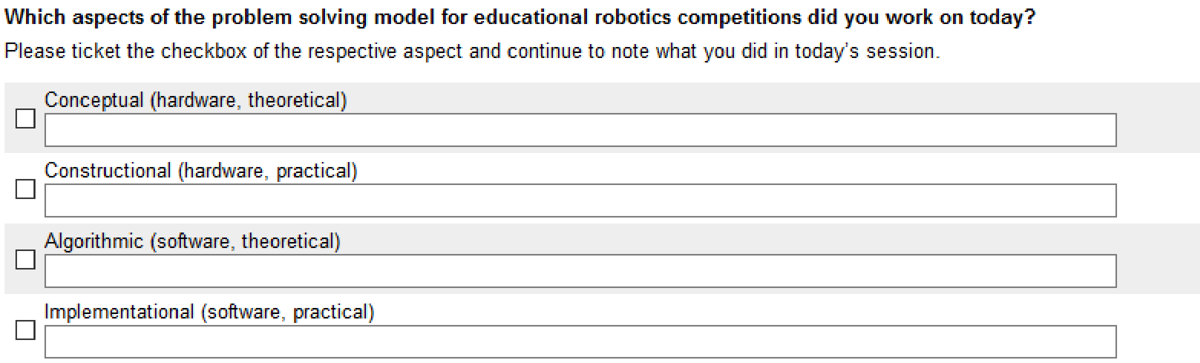
- *Conceptual*: Conceptual aspects describe issues with the general design of the robot (hardware, theoretical)
- *Algorithmic*: Algorithmic aspects describe issues with the development of algorithms or solution approaches of the given problem (software, theoretical)
- *Constructional*: Constructional aspects describe issues with the construction of the robot (hardware, practical)
- *Implementational*: Implementational aspects describe issues with the implementation within a programming language (software, practical) (Pöhner & Hennecke, 2018b)

This model worked as a structure for the diary and the team coaches were encouraged to monitor their working processes concerning this model. For each session of work, they were asked to write down the amount of time they spent (in % of the session) for each aspect (Fig. 28) and add notes, which describe what they did (Fig. 29).


How much time did you spent on the different aspects of the problem solving model for educational robotics competitions?
Please make sure that you allocate 100% in total.

	0%		20%		40%		60%		80%		100%
Conceptual (hardware, theoretical)	○	○	○	○	○	○	○	○	○	○	○
Constructional (hardware, practical)	○	○	○	○	○	○	○	○	○	○	○
Algorithmic (software, theoretical)	○	○	○	○	○	○	○	○	○	○	○
Implementational (software, practical)	○	○	○	○	○	○	○	○	○	○	○

Figure 28: Item from the teams' diary regarding the amount of time they spent (in % of the session) for each aspect of the problem solving model for educational robotics competition (translated from the German version).


Which aspects of the problem solving model for educational robotics competitions did you work on today?
Please ticket the checkbox of the respective aspect and continue to note what you did in today's session.

☐ Conceptual (hardware, theoretical)
☐ Constructional (hardware, practical)
☐ Algorithmic (software, theoretical)
☐ Implementational (software, practical)

Figure 29: Item from the teams' diary regarding the notes of what they did in each session (translated from the German version).

Questionnaire

The problem solving strategies, which resulted from the case study (Fig. 31, p. 101 and 32, p. 101), were used as a basis for the questionnaire study. After the national final of the WRO in 2018, team coaches of teams in the Regular category were asked to participate in this study and to rate which strategy they considered more promising to succeed in the educational robotics competition. They were not given any specific name of a problem solving strategy, but its visual representation (in terms of a line chart of the trends of the amount of time, which the teams spent on each of the four aspects of our problem solving model). The team coaches' rating was prompted with a 6-point Likert scale (very unsuccessful – very successful).

11.3 Data analysis

In his guide on case study research, Yin (2014) argues that the analysis of case studies is difficult because of the lack of universal analytical techniques. One of his suggestions, which is suitable for this study, is the use of the cross-case-synthesis, which allows us to compare multiple cases. It usually uses a category system to contrast multiple cases. (Yin, 2014)

This study applied frequency analysis and qualitative content analysis as analytical methods in the cross-case-synthesis. Frequency analysis compares multiple cases based on a numeric characteristic (Mayring, 2010). Here, the amount of time, which the teams spent on the different aspects of the problem solving model during their preparation for their regional competition of the educational robotics competition was compared for different teams. This included the relative amount of time for each aspect of the problem solving model on the one hand and the amount of time spent over time on the other hand.

Qualitative content analysis is a method to analyze textual data. One type of qualitative content analysis is to structure and organize the material with the help of a predefined category system (deductive building of categories). All text elements, which fit a category of the category system, will be systematically extracted from the textual data. (Mayring, 2010)

In this study, the notes of the team coaches' regarding their working processes throughout the preparation for their regional competition were analyzed using the structural type of qualitative content analysis. This analysis aimed to identify complementary material to support the results from the frequency analysis and help to identify problem solving strategies.

In the subsequent questionnaire study, inferential statistics (Kruskal-Wallis-test) were used to analyze the data (Cohen et al., 2017). The overall aim is to answer the research question, as mentioned in section 9.2 (p. 75), regarding promising problem solving strategies for teams participating in educational robotics competitions.

11.4 Results

11.4.1 Sample description

In the qualitative case study (the first part in the mixed-method design) 15 teams participated initially and eight teams continued until the end (53 %). The sample can be described as follows:

Table 13: Sample description of the participating teams in the case study and reasons for in- or exclusion in the analysis using purposive, extreme sampling.

Team	**Age group**	**Result at the regional competition of the WRO in 2018**		**Reasons for in- or exclusion in the analysis (using purposive, extreme sampling)**
		Points (in total)	Points (in %)	
Team #1	Elementary	35 (of 340)	10 %	These teams were excluded from the analysis because they did not fulfull the inclusion criteria (i.e., no team from either end of the continuum available).
Team #2	Elementary	50 (of 340)	15 %	
Team #3	**Junior**	**105 (of 360)**	**29 %**	**This team was selected as a prototype for a *less successful* team.**
Team #4	Junior	120 (of 360)	35 %	This team was excluded from the analysis because team #5 was selected as moderately successful team due to its higher number of points.
Team #5	**Junior**	**140 (of 360)**	**41 %**	**This team was selected as a prototype for a *moderately successful* team.**
Team #6	**Junior**	**360 (of 360)**	**100 %**	**This team was selected as a prototype for a *successful* team.**
Team #7	Senior	120 (of 380)	32 %	These teams were excluded from the analysis because did they not fulfull the inclusion criteria (i.e., no team from either end of the continuum available).
Team #8	Senior	125 (of 380)	33 %	

To identify promising problem solving strategies, the teams were selected using a purposive, extreme sampling. Purposive sampling describes a form of non-probability sampling, in which some cases are selected because of their typicality or possession of particular characteristics, which are of interest in terms of the corresponding research question (Cohen et al., 2017). In extreme sampling, the cases are picked from either end of a continuum to provide the most diverse examples of a particular issue (little success – great success) (Cohen et al., 2017). In this case, to be able to compare (or rather contrast) teams appropiately, one criterion for inclusion in the analysis was that they are from the same age group (which means that they worked on the same task in the educational robotics competiton). Moreover, within one age group there should be teams from either end of the continuum to be included.

In the regional competitions of this educational robotics competition, the teams compete in four rounds and the best two scores are summed up as a total score. Two of the selected teams are #3 (prototype for a less successful team) and #6 (prototype for a successful team). They achieved a total score of 105 (29 %) and 360 (100 %) points, respectively. Moreover, a third team (#5, 140 points, 41 %) was included in the analysis as a prototype for a moderately successful team to be contrasted with the other two teams.

In the quantitative questionnaire study (the second part in the mixed-method design) a total of 57 team coaches participated. Regarding the age group, 19 were from the Elementary age group, 23 from the Junior age group, and 15 from the Senior age group. Their average result from the regional competition of the WRO in 2018 is 33 %.

11.4.2 Case study

Frequency analysis

2. Research question: Can students learn a systematic engineering design process by using sophisticated problem solving strategies through their participation in an educational robotics competition such as the World Robot Olympiad?

Hypothesis 2a: Teams apply different problem solving strategies.

During their preparation for their regional competition, the teams invested a lot of time in building and programming their robot. Team #3 (prototype for a less successful team) recorded a total of 28 sessions with an average of 2 hours and 36 minutes per session. Team #6 (prototype for a successful team) recorded a total of 25 sessions with an average of 3 hours and 24 minutes.

Fig. 30 presents the amount of time teams #3 (left) and #6 (right) spent on the four aspects of the problem solving model:

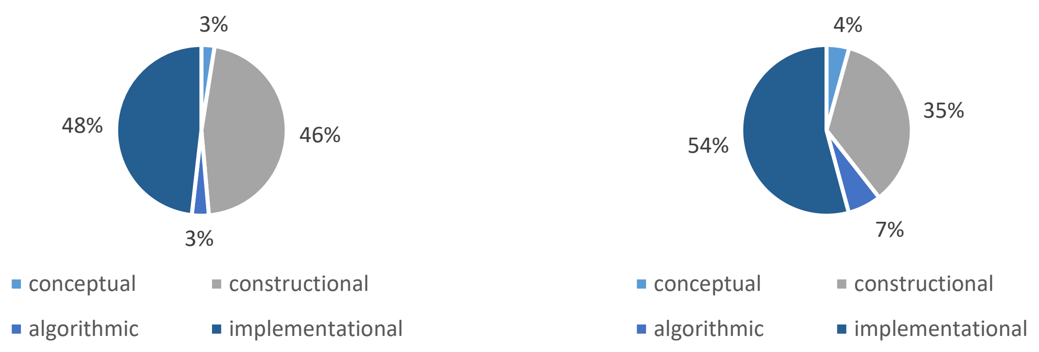


Figure 30: Time distribution of the teams' time (team #3 left, team #6 right) on the four aspects of the problem solving model.

The pie charts in Fig. 30 reveal that both teams spent most of their time on the practical aspects (constructional and implementational) and less on the theoretical aspects (conceptual and algorithmic). Moreover, team #3 spent less time on the implementational aspect and more time on the constructional aspect than team #6. Team #6 also spent more time on theoretical aspects (conceptual and algorithmic) than team #3.

Even greater differences than for the comparison of the mere amount of time, which teams spent on the four aspects of the problem solving model, can be observed when investigating the amount of time, which they spent on these aspects *over time* (Fig. 31 for team #3 and 32 for team #6):

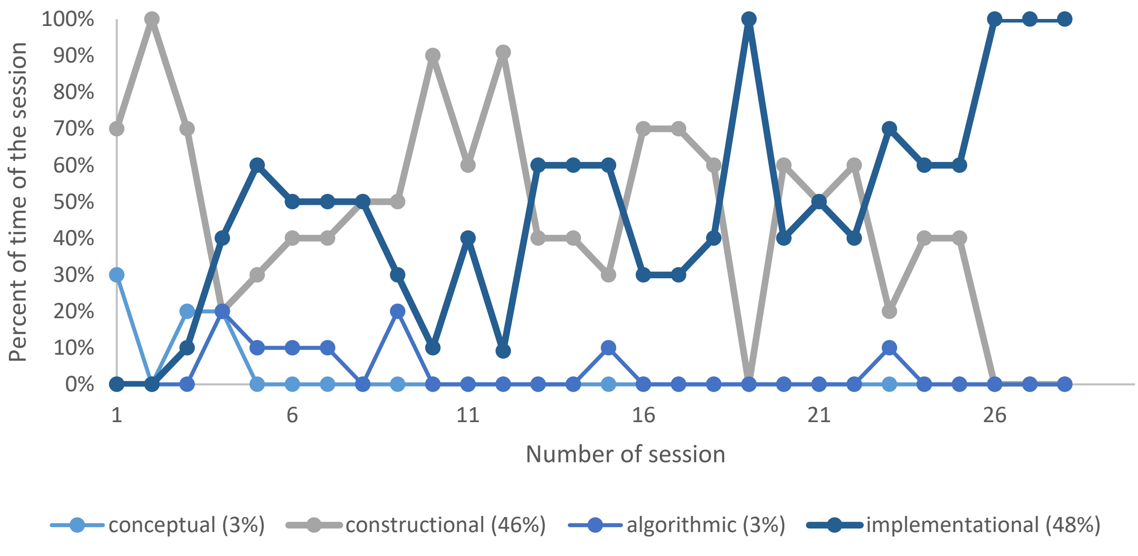


Figure 31: The working process of team #3.

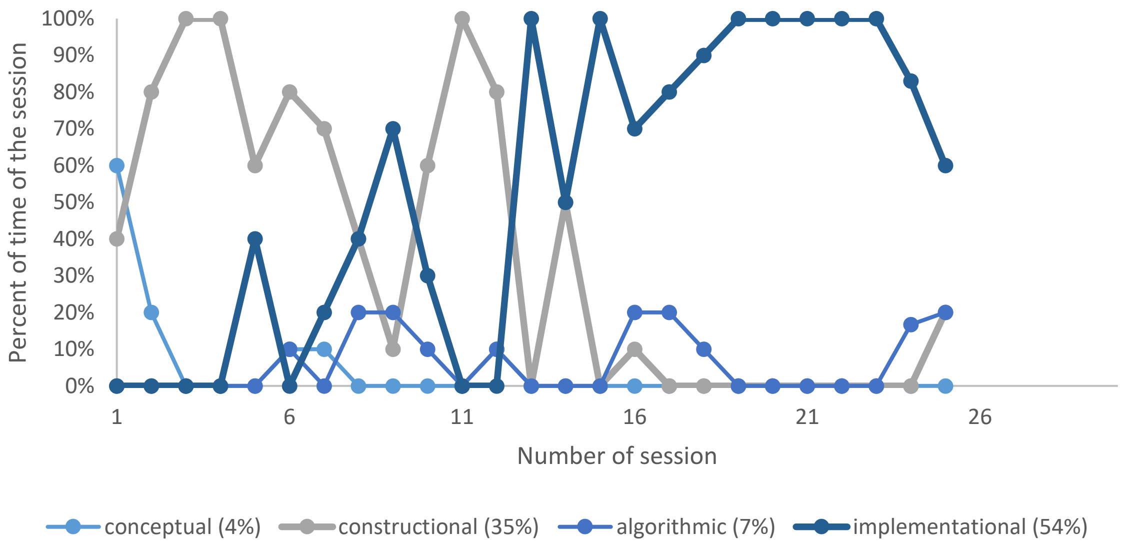


Figure 32: The working process of team #6.

As Fig. 31 and 32 show, the time progress of team #6 can roughly be divided into a hard- (session 1-12) and a software stage (session 13-25). In contrast, the time progress of team #3 cannot be divided into different stages as easily. Additionally, the time progress of team #3 displays a lot of overlaps of the constructional aspect (grey line) and the implementational (dark blue line). This indicates a lot of changes between the hard- and software stage during the development of a robot and stands in contrast to the time progress of team #6, which shows clear stages of hard- and software development.

Team #5 (prototype for a moderately successful team) invested a total of 22 sessions with an average of 2 hours and 46 minutes in the building and programming of a robot during the preperation for the educational robotics competition. The amount of time, which the team spent on the four aspects of the problem solving model, is distributed as follows:

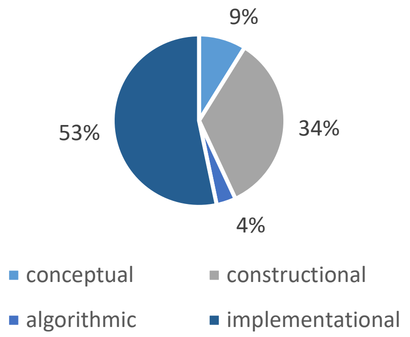


Figure 33 Time distribution of team #5 on the four aspects of the problem solving model.

The amount of time, which this team spent on these aspects *over time* is presented in Fig. 34:

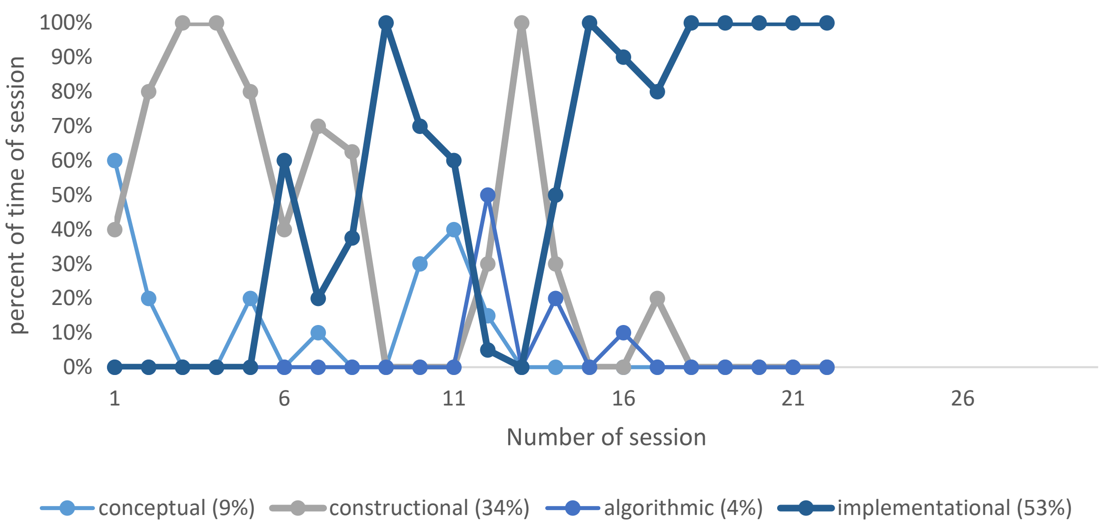


Figure 34: The working process of team #5.

In comparison to the working processes of teams #3 and #6, the working process of team #5 presents a combination of these. On the one hand, similar to team #6, the working process of team #5 can roughly be divided into a hard- (session 1-14) and a software stage (session 15-22). On the other hand, the working process in sessions 1-14 shows several overlaps of the constructional aspect (grey line) and the implementational (dark blue line), which indicates several changes between the hard- and software stage (similar to team #3). Thus, the working process of team #5 can be classified as a combination (or intermediate stage) of the working processes of teams #3 and #6. Regardless, even though the number of points, which team #5 achieved in the regional competition of the educational robotics competiton (140 of 360, 41 %), was closer to team #3 as prototype of a less successful team (105 of 360, 29 %), the overall working process of team #5 tends to be more similar to the one of team #6 as prototype of a successful team, indicating that the use of a specific problem solving strategy might not be the only variable influencing the teams' success.

Following the frequency analysis of the amount of time, which the teams spent on the different aspects of the problem solving model during their preparation for their regional competition of the educational robotics competition, qualitative content analysis was conducted to gain deeper insights into the teams' working processes. This analysis aimed to identify complementary material, which supports the results from the frequency analysis and helps to identify problem solving strategies.

Qualitative content analysis

In qualitative content analysis exist different techniques to analyze text documents. As mentioned in section 11.3 (p. 97), the structural type of qualitative content analysis describes the intention to organize the material with the help of a predefined category system. Hence, the text document can be searched for passages, which fit a category of the category system and case studies can be compared based on the number of passages, which have been found for each category (Mayring, 2010).[39]

In this study, the category system was built based on the concepts and skills of the engineering design cycle as introduced in section 3.3 (p. 23) (Katehi et al., 2009). These concepts and skills were then transformed into verbs/actions, which were searched for in the diaries of the three teams, which describe their activities during the preparation for the regional competition of the educational robotics competition. The verbs/actions, which define a category of the category system are:

- discussing, searching for alternatives, making trade-offs
- modeling, drawing, representing
- (predictively) analyzing
- testing, experimenting, evaluating
- optimizing

An example of a diary entry of team #6 for the first category is:

> *Discussing alternative solutions for a gripper arm module for the seedlings.*

---

[39] The software *MAXQDA* (https://www.maxqda.de/) was used for the qualitative content analysis of the teams' diaries.

Fig. 35 shows the (relative) number of passages, which have been identified for each category in the teams' diaries:

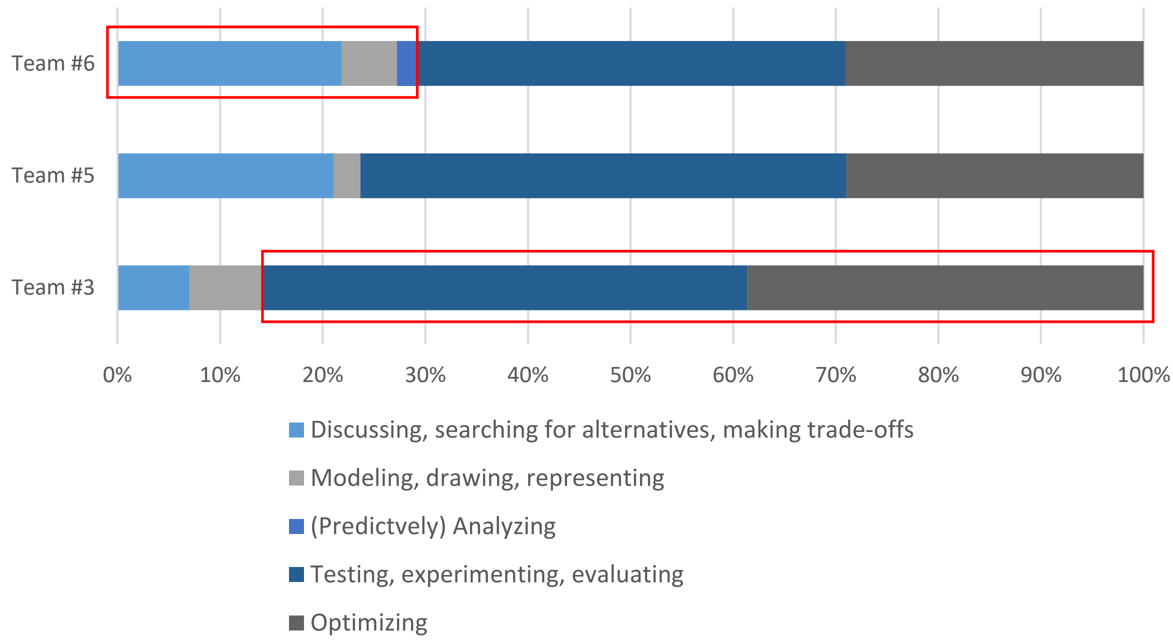


Figure 35: Results of the qualitative content analysis of the teams' diaries.

The qualitative content analysis shows that, even though the predominant activities for alle three teams are *testing, experimenting, evaluating* and *optimizing*, the distribution differs. Whereas the proportion of *testing, experimenting, evaluating* and *optimizing* activities is higher for team #3, the proportion of *discussing, searching for alternatives, making trade-offs* and *modeling, drawing, representing* activities is higher for team #6 (Fig. 34). Again, team #5 seems to be a combination of the other two teams.

Considering both the results of the frequency analysis of the teams' working process and the qualitative content analysis of the teams' diary entries, we conclude that, whereas team #6 proceeded in clear stages when developing a working robot prototype, team #3 always built new prototypes if the prior one failed. They followed a trial-and-error approach, which consisted of more testing, experimenting, evaluating, and optimizing whereas team #6 engaged in more planning activities. This is, for example, underlined by the use of a paper model (modeling, drawing, representing) of the robot to predictively analyze its behavior:

> *Building a paper model of the robot.*
>
> *Using the paper model to plan the robot's run.*

Thus, we labeled the problem solving strategy of team #6 as a *planning strategy* and the problem solving strategy of team #3 as a *testing strategy*.

Summary

Referring back to the literature, the results of this case study coincide with evidence from other studies. For example, Bilotta et al. (2009), who conducted an educational robotics workshop with university students (aged 19 to 21 years) for eleven weeks concluded the following strategies:

- *Strategy towards the problem*: Students using this strategy focus on task comprehension and analysis of the problem.
- *Strategy towards the solution*: Students using this strategy prefer testing and experimenting with their ideas many times without proper task comprehension and analysis. (Bilotta et al., 2009)

In their study, the students, who applied the first strategy, were more successful in their final task than students using the second one (Bilotta et al., 2009). This is in accordance with our results since the strategy towards the problem resembles our planning strategy and the strategy towards the solutions resembles our testing strategy. Moreover, Bilotta et al. (2009) ascribe the reason for the different outcomes to the use of the strategy towards the problems (testing strategy) as a rudimentary trial-and-error strategy, which students used since they could not benefit from higher-level problem solving strategies.

Trying to answer the questions of how students come up with inventive solutions to educational robotics problems, Barak and Zadok (2009) also determine two strategies (or heuristic searches). On the one hand, a combination of forward and backward reasoning to gradually come up with a solution (testing strategy) and, on the other hand, a planning strategy, which uses modeling, analogies, and abstractions (Barak & Zadok, 2009). Regardless, these strategies are not dichotomous but Sullivan and Heffernan (2016) argue that problem solving strategies evolve on a continuum from simple trial-and-error strategies to more sophisticated strategies.

All in all, both the literature and the results of this case study indicate the importance of more advanced problem solving strategies in educational robotics. Regardless, to test if the assertation that the planning strategy (as a more sophisticated problem solving strategy) is more likely to be associated with successful teams (in contrast to the testing strategy as a trial-and-error strategy), a questionnaire study was conducted with team coaches of teams from the Regular category of the WRO in 2018.

11.4.3 Questionnaire

Hypothesis 2b: Successful teams prefer more sophisticated problem solving strategies compared to less successful teams.

For the analysis of the team coaches' responses (N = 57) regarding their opinion of promising problem solving strategies, they were divided into three success groups based on their results from their regional competitions:

- teams with little success: < 33 % of points achieved at the regional competition (38 teams fall in this category)
- teams with some success: < 66 % of points achieved at the regional competition (10)
- teams with great success: > 66 % of points achieved at the regional competition (9)

As mentioned in section 11.2.2 (p. 95), they were asked to rate which strategy (testing or planning strategy) they considered more promising to succeed in the educational robotics competition based on its visual representation (Fig. 31, p. 101 and 32, p. 101). They were able to rate each strategy on a 6-point Likert scale (very unsuccessful – very successful).

Regarding the testing strategy, no significant differences were found (middle ranks: little success = 26.43 ($N = 38$), some success = 34.2 ($N = 10$), great success = 34.06 ($N = 9$); Kruskal-Wallis-test: $\chi^2(2) = 2.947$, $p = .229$).

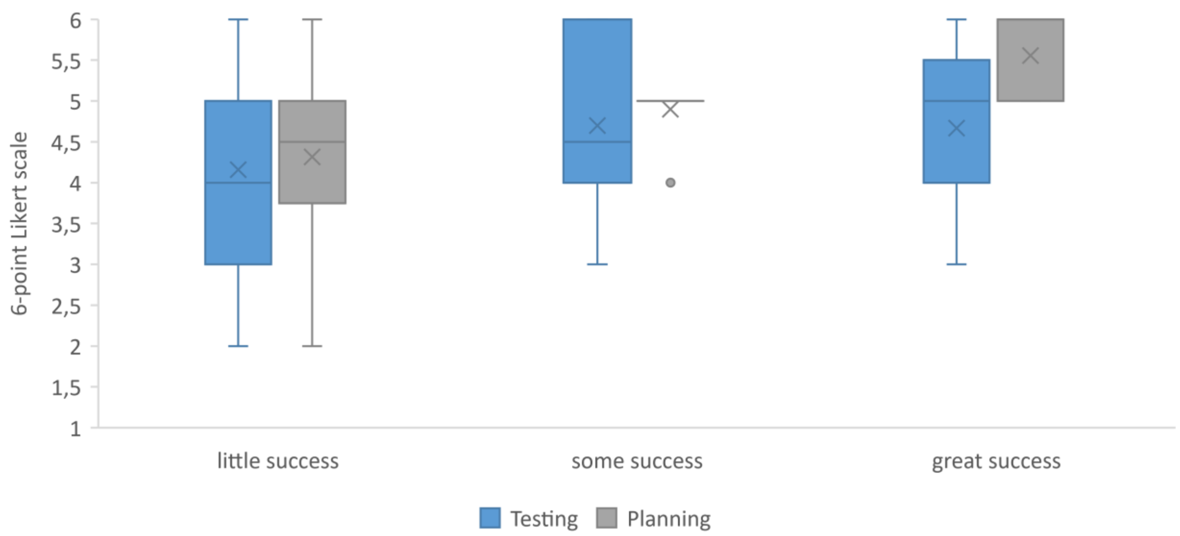


Figure 36: Team coaches' answers regarding the potential of the testing and planning strategy.

Regarding the planning strategy, a significant difference was found (middle ranks: little success = 24.09 ($N = 38$), some success = 33.0 ($N = 10$), great success = 45.28 ($N = 9$); Kruskal-Wallis-test: $\chi^2(2) = 14.674$, $p < .001$). To find out which success groups differ from each other, post-hoc-tests (Dunn-Bonferroni-tests) are necessary for the pairwise comparison of these skills (Cohen et al., 2017). These tests confirm a significant difference for the groups with little and great success (z = -3.722, p = .001). This corresponds to an effect size of r = 0.54, which resembles a large effect.

From these results, we can conclude that WRO is successful in implementing a learning setting, which fosters students' problem solving skills. Team coaches, especially the ones of successful teams in the educational robotics competition, acknowledge the relevance of sophisticated problem solving strategies to build and program a robot prototype.

Whereas the first and second research questions have identified the benefits of this educational robotics competition to foster students' problem solving skills through the use of sophisticated problem solving strategies, the third research question investigates the teacher's involvement in the students' learning process.

12 Teaching pedagogy

12.1 Introduction

A team in the WRO consists of two or three students and one team coach. In general, the task of the team coach is to prepare the students for their participation in the educational robotics competition. This includes many different aspects such as, for example:

- organize working conditions (e.g. classroom, materials)
- find sponsors and partners for funding
- communicate with competition organizers and parents of the students
- teach basics of building and programming a robot (e.g. using appropriate (online) materials
- provide support and guidance for students during their engineering design process (World Robot Olympiad, n.d.–b)

Even though the team coach is allowed to help students understand the basics of building and programming a robot and support them in their engineering design process, direct input in terms of pre-built robot models or programs is prohibited (World Robot Olympiad, n.d.–d). Regardless, the interaction between team coaches and students is vital in the educational robotics competition and influences students' learning and success to a great extent, as a study by Kaloti-Hallak et al. (2015a) shows. They investigated the effectiveness of robotics competitions on students' learning in CS. Despite the positive results regarding students' learning in the FLL, the authors identified different factors, which affect the learning process in an educational robotics competition and the teaching pedagogy was among those factors. They suggest that a teacher-centered pedagogy may not be effective in this context and propose a more student-centered pedagogy due to discovery learning, which takes place in this context. (Kaloti-Hallak et al., 2015a)

In this engineering design process, students use educational robotics as technically and computationally enhanced tangible object to explore their ideas (Eguchi, 2017). The teacher's task is to provide working conditions for the students to be able to conduct this exploration. Eleanour Duckworth (2005), a student of Jean Piaget, coins this *critical exploration*. Critical exploration denies direct teaching and argues for the teacher to facilitate the students' exploration process. She argues that

> *[critical exploration] has two levels of meaning: both exploration of the subject matter by the child (the subject or the learner) and exploration of the child's thinking by the adult (the researcher or the teacher). (Duckworth, 2005)*

The process of exploration on the side of the teacher results in different ways of teacher interventions in the students' learning process, depending on the individual problems of the students. Leiß and Wiegand (2005) differentiate between four types of teacher interventions in student-centered, collaborative, and problem-based learning settings. Moreover, depending on the teacher interventions, Leiß and Tropper (2014) define different types of teacher roles. They are summarized in Tab. 14.

Table 14: The teachers' role and types of interventions in student-centered, collaborative, and problem-based learning settings

Teachers' role	Type of intervention	Definition
Manager	Related to the organization	Interventions related to the organization include defining temporal deadlines, maintain discipline, etc.
	Affective	Affective interventions describe the regulation of emotional, especially motivational, aspects in the students' learning process
Expert	Related to the content	Interventions related to the content describe the explanation of relevant content of the subject (e.g. theories, concepts, etc.)
Behavioral model	Metacognitive	Metacognitive interventions define the setup of appropriate problem solving and interaction culture. The introduction of (meta-)cognitive strategies ease the students' learning process and they benefit from such strategies.

This study on the teaching pedagogy in educational robotics competitions aims to investigate the teachers' role and the types of interventions (as described above) used in the educational robotics competition (Pöhner & Hennecke, 2018c).

12.2 Data collection

12.2.1 Study design

As Fig. 16 in section 9.2 (p. 77) shows, this study was incorporated into the questionnaire study at the end of the WRO season in 2018. Participants were team coaches of teams from the Regular category of the WRO and the study was conducted via an online questionnaire after the national final of the WRO in 2018. It corresponds to the same questionnaire study as in chapter 11 (p. 93).

12.2.2 Instruments

To measure the team coaches' (degree of) support, they were asked to rate the degree of their support for each level of intervention on a 6-point Likert scale (very low – very high). A definition and examples of the different types of interventions (section 12.1, p. 108) were given before the questionnaire.

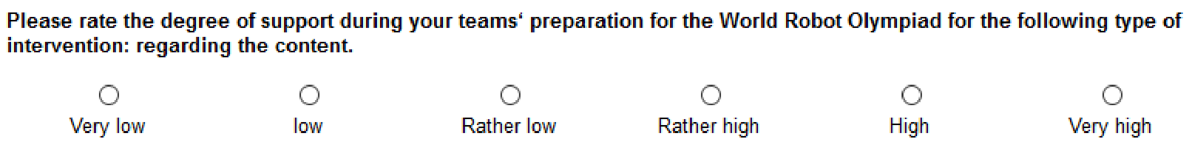


Figure 37: Example item from the questionnaire study regarding the teaching pedagogy during the WRO in Germany in 2018 [40] *(translated from the German version).*

12.3 Data analysis

In the study, the Friedman- and Kruskal-Wallis-test were used to analyze the data (Cohen et al., 2017). This study aimed to investigate overall differences regarding the types of interventions on the one hand and regarding the age group (Elementary, Junior, and Senior) and success (in % of points achieved at the regional competition) of the teams on the other hand.

12.4 Results

12.4.1 Sample description

A total of 57 team coaches participated in this study. Regarding the age group, 19 were from the Elementary age group, 23 from the Junior age group, and 15 from the Senior age group. Their average result from the regional competition of the WRO in 2018 is 33 %.

12.4.2 Overall analysis

3. Research question: What kind of assistance (i.e. teacher interventions) do team coaches (have to) provide to their students in an educational robotics competition such as the World Robot Olympiad as a student-centered, collaborative, and problem-based setting?

Hypothesis 3a: Team coaches use different types of teacher interventions.

[40] The software *SosciSurvey* (https://www.soscisurvey.de/) was used for the questionnaire study.

Fig. 38 displays the boxplot of the answers of the team coaches regarding the support for each type of intervention.

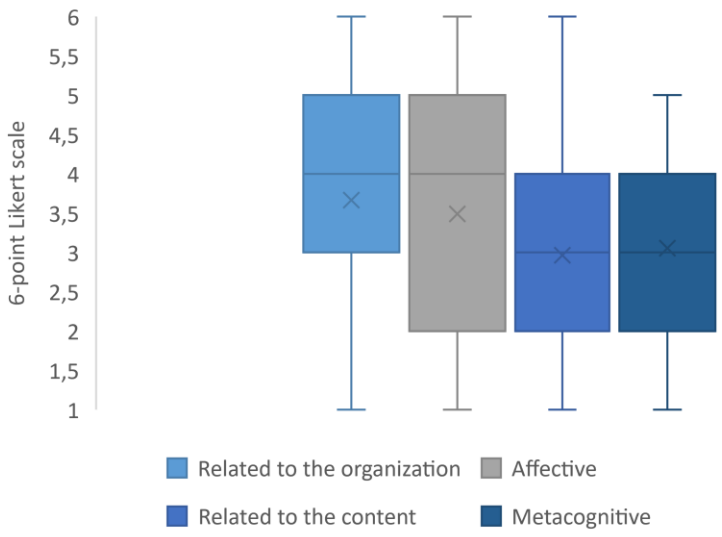


Figure 38: Boxplot of the answers of the team coaches regarding the support for each level of intervention.

The Friedman-test reveals a significant difference between the team coaches' answers for the different types of intervention. ($\chi^2(3) = 16.254$, $p = .001$, $N = 57$).

Table 15: Descriptive statistics from the Friedman-test

	N	Mean value	Standard derivation	Median	Middle rank
Related to the organization	57	3.67	1.504	4.00	2.92
Affective	57	3.49	1.16	4.00	2.69
Related to the content	57	2.96	1.336	3.00	2.15
Metacognitive	57	3.05	0.990	3.00	2.24

To find out which types of interventions differ from each other, post-hoc-tests (Dunn-Bonferroni-tests) are necessary for the pairwise comparison of these types (Cohen et al., 2017). Tab. 16 presents a cross matrix of all four types of intervention and the results of the post-hoc-tests.

Table 16: Results from the post-hoc-tests (pairwise comparison) displaying the test statistics (z), statistical significance (p) and the effect size (correlation coefficient r) (ns = not significant)

	Related to the organization	**Affective**	**Related to the content**	**Metacognitive**
Related to the organization				
Affective	z = 0.943 p = .346 r = ns			
Related to the content	z = 3.192 p = .001 r = 0.42	z = 2.249 p = .025 r = ns		
Metacognitive	z = 2.289 p = .005 r = 0.30	z = 1.886 p = .059 r = ns	z = -0.363 p = .717 r = ns	

The results from the post-hoc-test show the types of interventions differ significantly, especially the types *related to the organization (and affective)* and *related to the content* and *metacognitive* (with medium to large effect sizes ($0.30 \leq r \leq 0.42$)). Whereas the types *related to the organization* and *affective* received higher values, the other types received lower ones.

12.4.3 Analysis of subgroups

Hypothesis 3b: There are differences regarding the types of intervention for the subgroups

a) age group (Elementary, Junior, and Senior)
b) success (in % of points achieved at the regional competition)

In addition to the overall results, we investigated the age group (Elementary, Junior, and Senior) and success (in % of points achieved at the regional competition) of teams regarding the different types of interventions by their team coaches.

Fig. 38 presents the team coaches' answers to the different types of interventions for each age group.

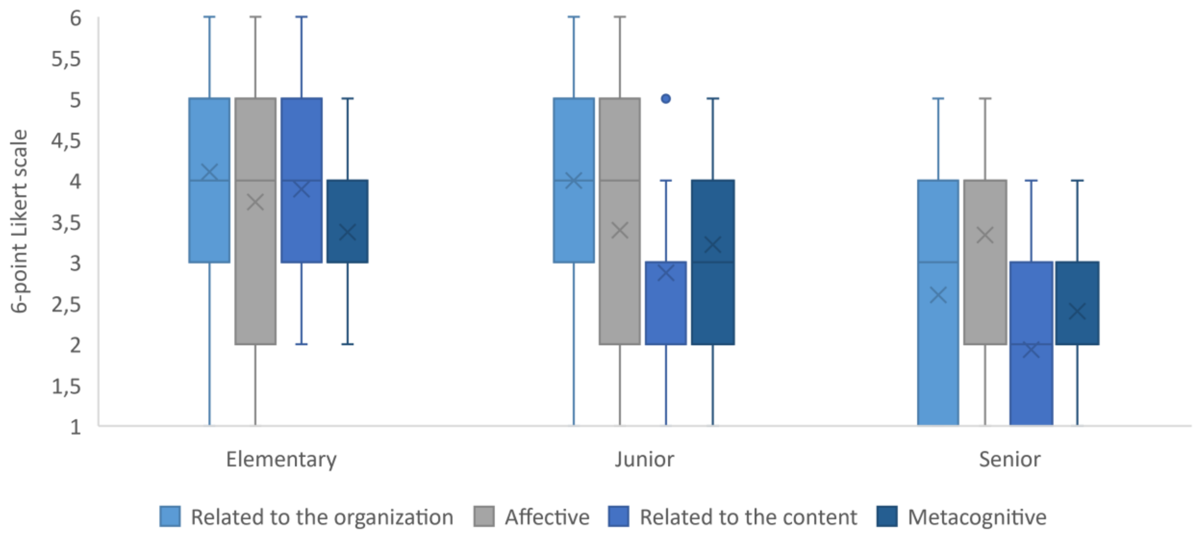


Figure 39: Team coaches' answers to the different types of interventions for each age group.

In general, an overall decline from younger to older age groups is visible. The greatest decline can be found for the type *related to the content* and the smallest decline for the *affective* type of intervention.

The Kruskal-Wallis-test approves the significant decrease among the age group for the types of interventions *related to the organization, related to the content,* and *metacognitive* (Tab. 17). Post-hoc-tests (Dunn-Bonferroni-tests) revealed a significant difference between these three types of interventions with effect sizes of $0.497 < r < 0.72$.

Table 17: Results of the Kruskal-Wallis-test to compare the different types of interventions for each age groups

	Middle rank			**Kruskal-Wallis χ^2**	***N***			***p***
	Elementary	Junior	Senior					
Test statistics (related to the organization)	33.76	32.52	17.57	10.221	19	23	15	.005
Test statistics (affective)	31.74	27.87	27.27	0.823	19	23	15	.669
Test statistics (related to the content)	39.92	28.15	16.45	17.744	19	23	15	< .001
Test statistics (metacogni-tive)	34.47	31.50	18.23	9.712	19	23	15	.006

Regarding the learning of problem solving skills, contrary to prior expectations, the metacognitive type of intervention also decreases.

The second subgroup to be investigated aims at the success of the different teams. Similar to the questionnaire study in section 11.4.3 (p. 106), the teams were divided into three success groups based on their results from their regional competitions:

- teams with little success: < 33 % of points achieved at the regional competition (38 teams fall in this category)
- teams with some success: < 66 % of points achieved at the regional competition (10)
- teams with great success: > 66 % of points achieved at the regional competition (9)

Since the sample is the same as in this study, the number of teams is equal as well.

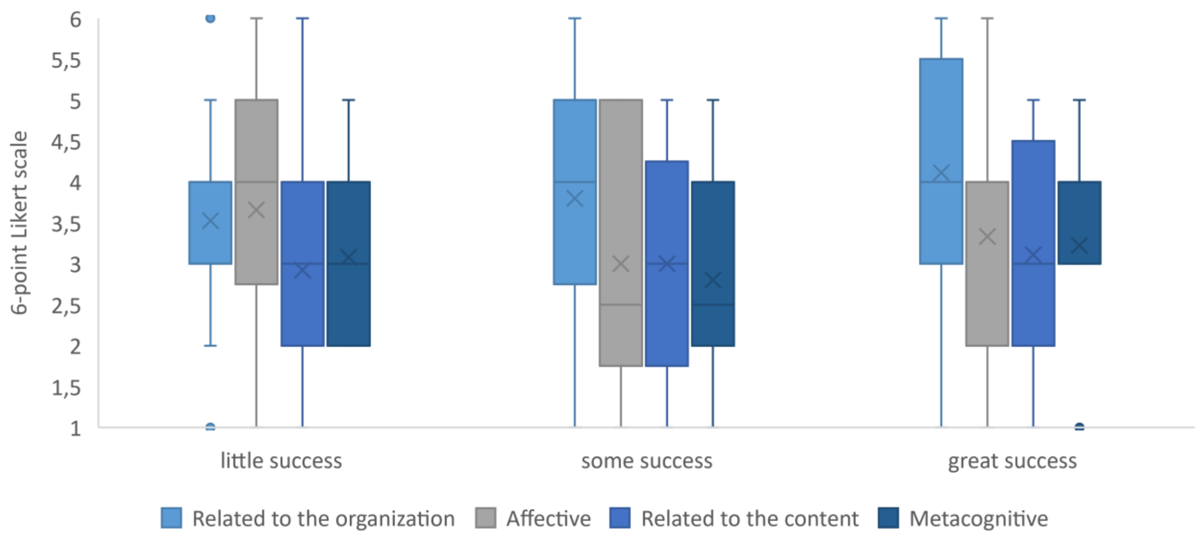


Figure 40: Team coaches' answers to the different types of interventions for the three success groups.

A Kruskal-Wallis-test revealed no significant differences for the three success groups.

In summary, the team coaches in this educational robotics competition use different types of interventions to support their students throughout the preparation for the competition. It is positive to note that there is an overall decline in the support in older age groups, especially regarding the type of intervention *related to the content*. Of course, younger students need more help with building and programming the robot and the general idea of the engineering design process, but it decreases the older they get. Contrary to prior expectations, the metacognitive type of intervention does not increase for a) age groups and b) success groups. One the one hand, this is surprising because of the more complex tasks for older age groups and more sophisticated problem solving approaches of successful teams, but, on the other hand, students seem to master the problem solving culture of the tasks in the educational robotics competition and do not require this type of intervention by their team coaches. Lastly, the affective type of intervention is the only type of intervention, which is consistent for all age groups.

These results underline the teacher's role as manager of the students' learning process in the educational robotics competition and as a guide in their engineering design process, where students use educational robotics as technically and computationally enhanced tangible objects to explore their ideas (Eguchi, 2017). Moreover, Eguchi (2016a) argues that this collaborative learning setting is well aligned with Vygotsky's idea of the *zone of proximal development*, where learning does not only occur through the teacher's scaffolding and guidance but also through the interaction with peers:

[This] is what we call the zone of proximal development. It is the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers. (Vygotskij, 1978, p. 86)

13 Conclusion

13.1 Summary of results

All in all, this thesis tried to contribute to the research gap regarding the lack of *systematic* evaluation of the use of educational robotics (Alimisis, 2013), as formulated in the motivation of this thesis. Despite many published research articles dealing with the investigation of the impact of educational robotics on students' learning using *descriptive* reports by teachers (in terms of anecdotal experience reports) achieving positive outcomes with individual, small-scale studies (Benitti, 2012), the focus of this thesis was to provide more (methodologically) sophisticated research on this topic. Hence, it was following the call by Alimisis (2013) for more rigorous (quantitative) research, which is necessary to validate the impact of educational robotics.

In the beginning, the aim was to increase understanding of engineering design skills as one form of (general) problem solving skills in STEM education. Thus, different perspectives on problem solving skills from different STEM disciplines were contrasted and engineering design skills were inferred from this overview. Educational robotics was then introduced as a hands-on learning tool or *computational manipulative* (Sullivan & Heffernan, 2016) to foster these skills in the context of competitions as a goal-oriented approach to educational robotics (Eguchi, 2010).

Based on this theoretical work, this thesis presented an empirical investigation on students' learning of problem solving skills (in terms of engineering design skills) through participation in the World Robot Olympiad (WRO), a popular international educational robotics competition. This investigation was composed of three studies, some of which were part of a larger impact evaluation study of the WRO in 2019. The empirical part of this thesis tried to answer the following three research questions (with the corresponding hypothesis):

1. Research question: Can students improve their problem solving skills through participation in an educational robotics competition such as the World Robot Olympiad?

Hypothesis 1a: Students can improve their problem solving through participation in the educational robotics competition.

Hypothesis 1b-f: There are no differences in their skill development for different subgroups such as

- b) category (Regular, Open, and Football category)
- c) age group (Starter, Elementary, Junior, and Senior)
- d) experience (in number of prior participations)
- e) gender (boys only, girls only, and mixed teams)
- f) success (in % of points achieved at the regional competition)

2. Research question: Can students learn a systematic engineering design process by using sophisticated problem solving strategies through their participation in an educational robotics competition such as the World Robot Olympiad?

Hypothesis 2a: Teams apply different problem solving strategies.

Hypothesis 2b: Successful teams prefer more sophisticated problem solving strategies compared to less successful teams.

3. Research question: What kind of assistance (i.e. teacher interventions) do team coaches (have to) provide to their students in an educational robotics competition such as the World Robot Olympiad as a student-centered, collaborative, and problem-based setting?

Hypothesis 3a: Team coaches use different types of teacher interventions.

Hypothesis 3b: There are differences regarding the types of intervention for the subgroups

a) age group (Elementary, Junior, and Senior)
b) success (in % of points achieved at the regional competition)

The main results of the empirical part of this thesis are consolidated in the following:

- Students can foster their problem solving skills through participation in the WRO (N = 413 of 683 participating teams in the WRO in Germany in 2019). The effect size of r = 0.79 corresponds to a large effect. (RQ1)
- The investigated team- (or input-) (experience, gender), program- (category, age group), or output- (success) characteristics do not moderate students' learning in the educational robotics competitions (using Hake's g as normalized gain), which makes the competition equally effective. (RQ1)
- In contrast to the summative assessment of problem solving skills above, the second study investigated *how* this skill development comes about (formative assessment). A case study with three teams in the WRO revealed different problem solving strategies for differently successful teams (planning vs. testing strategy). A follow-up questionnaire (N = 57) tested the assertion that the planning strategy (as a more sophisticated problem solving strategy) is more likely to be associated with successful teams (in contrast to the testing strategy as a trial-and-error strategy) and concluded that successful teams rate a planning strategy as more promising to succeed in the educational robotics competition than a testing strategy. This effect (r = 0.54) was large. (RQ2)
- Regarding the teaching pedagogy (N = 57), all types of intervention (related to the organization, related to the content, and metacognitive) – except the affective type – decrease from the Elementary to Senior age group in the WRO. This was a medium to a large effect ($0.30 \leq r \leq 0.42$). The affective type of interventions remains consistent

throughout all age groups, underlining the team coach's role as manager and guide (instead of instructor) in the students' learning process. (RQ3)

- There are no significant differences in the types of interventions regarding the success of teams. This includes the metacognitive type, which was expected to increase for age groups and success. Regardless, students seem to master the problem solving culture of the tasks in the educational robotics competition and do not require this type of intervention by their team coaches. (RQ3)

All in all, these results are well aligned with existing research in the field and, hence, reinforcing the positive impact of educational robotics on students' learning, especially on problem solving skills (in terms of engineering design skills). The importance of problem solving skills has already been found in prior research studies showing those skills as one of the most frequently investigated ones (Benitti & Spolaor, 2017; Souza et al., 2018). Regardless, the setting of competitions as a goal-oriented approach to educational robotics (Eguchi, 2010) is of particular interest when aiming at fostering students' learning. Following the idea of the STEM pipeline as described by, for example, Mead et al. (2012), the length of the educational robotics program plays an important role in the impact level of educational robotics on the students (Nugent et al., 2016). Whereas shorter programs aim at the affective level, longer programs focus on the promotion of students' learning (cognitive level) (Nugent et al., 2016). Thus, educational robotics competitions with clear goals and duration of multiple months provide a very valuable setting to foster students' learning sustainably.

13.2 Methodological issues with the evaluation study

Even though some points of criticism regarding the methodology of the empirical part of this thesis have already been discussed in the corresponding chapters, this section will provide a summary of these points together with further issues for each of the three presented studies.

The first study (chapter 10, p. 82) investigated the development of students' problem solving skills through participation in an educational robotics competition. It used a quasi-experimental design study with pre- and post-test using then-test data (pre-experimental: the one-group pre-test post-test (Cohen et al., 2017)). The applied quasi-experimental design lacks the control for extraneous variables and, consequently, attribution of differences in pre- and post-test values cannot be justified because other variables may infer the results (Cohen et al., 2017). The use of control (or comparison) groups would have solved this problem, but finding an appropriate control group is difficult in self-selecting programs as this competition because of the participants' likelihood to be more interested in STEM fields than those who do not participate (Stubbs et al., 2012). Moreover, control groups are used less frequently in evaluations of educational robotics competitions due to the logistical problems involved (Stubbs et al., 2012).

The use of then-test data is another point of criticism in this study. Then-test data describes pre-test data, which is collected in retrospect, and increased in popularity in recent years in the field of program evaluations. The reason for this is pragmatic advantages (reduction of data collection dates) and the alleviation of the *response shift bias*. Regardless, advocates of traditional pre-test data name the *desire by participants to show a learning effect* and *threats to validity due to insufficient reflection of information* as disadvantages (Allen & Nimon, 2007). In this study, the reduction of data collection dates and the alleviation of the response shift bias was valued higher than the disadvantages of this way of data collection. Following Allen and Nimon (2007), Little et al. (2020) conclude from a comparison of traditional pre- and post-test data with then-test data that then-test data is a both practically and psychometrically sound alternative to the traditional pre- and post-test, especially regarding constructs such as, for example, beliefs, preferences, and conceptions to attitudes, skills, and values.

Thirdly, the team coaches of the participating teams in the WRO were asked to externally assess students' skill level regarding their problem solving skills *before (pre) and after (post)* the WRO season of 2019 through a paper-and-pencil questionnaire. Using student data would have been another approach to collect information about their problem solving skills, but due to logistical problems, this type of data collection was dismissed. Stubbs et al. (2012) consider asking teachers about their perceptions of students' learning a useful method to gain information. Regardless, more effective methods would have been to directly assess students' learning of problem solving skills (e.g. through quizzes or tasks, which the students have to solve) or self-reports (i.e. perceptions) by students of their learning (Stubbs et al., 2012). These methods could have led to more accurate data, but teacher perceptions can be helpful, especially when other methods are not feasible (Stubbs et al., 2012). Moreover, since most of the team coaches participating in this competition are teachers (76 % of the participating teams in the evaluation study of WRO Germany in 2019 are school teams (Pöhner & Hennecke, 2020)) the assessment of students' learning is part of their daily work and, thus, they were considered to be able to judge the students' learning appropriately. This is acknowledged by, for example, Wang et al. (2016), who examined the con- and divergence of students' and teachers' reports on students' (cognitive, behavioral, emotional, and social) engagement in mathematics and science. They conclude that students' and teachers' reports are strongly correlated regarding the cognitive and behavioral domain (and weakly correlated for the emotional and social domain) (Wang et al., 2016). Thus, teachers have a valuable insight into students' cognitive efforts and their manifestation in the classroom, whereas their reports on affective (and social) variables are less reliable (Wang et al., 2016). Consequently, the use of teacher data to assess students' learning in the cognitive domain of problem solving skills seems reliable.

In the second study (chapter 11, p. 93), the use of different problem solving strategies and their relationship with success in the educational robotics competition was examined. It used a mixed-method design and integrated qualitative (exploratory case study) and quantitative (questionnaire study) in this study on the design level in terms of a generalization model (Cohen et al., 2017; Mayring, 2001; Yin, 2014). Within the case study, team diaries (as a chronological series of questionnaires) were used to monitor the teams' working process. An alternative to team diaries would have been videography. Even though videography could have provided more granular and objective data, this study settled for team diaries because of the logistical problems involved with videography and the interest in longer time frames (i.e. a session during the preparation for the educational robotics competition) (Cohen et al., 2017). Regardless, videography can be a valuable method of data collection when examining shorter time frames with higher granularity.

Another point of criticism addresses sampling within the case study. The case study used purposive sampling (N = 3) in terms of extreme sampling. Out of the eight teams (out of 15 teams at the beginning), who continued their team diary until the end, two were selected based on their result from the regional competition of the WRO (the best and worst team were selected) (from the same age group). Moreover, a third team was selected to additionally contrast the other two teams. In case study research, using extreme cases is one of the two most used sampling techniques (apart from typical case sampling) (Cohen et al., 2017).

The third study (chapter 12, p. 108) dealt with the teaching pedagogy in educational robotics competitions. A point of criticism regarding this study focuses on the operational definition of the teaching pedagogy. In this case, a model of teacher interventions by Leiß and Wiegand (2005) (and the corresponding teacher roles (Leiß & Tropper, 2014)) was used and identified four different types of teacher interventions (related to the organization, affective, related to the content, metacognitive). The team coaches were asked to assess the degree of their support for each level of intervention on a 6-point Likert scale (very low – very high). Instead of using these types of interventions as items in the questionnaire study, further operational definitions of these types would have been possible. For example, the taxonomy of problems occurring during robotics activities by Schulz and Pinkwart (2017) would have provided a more detailed definition of problems (related to the content), dividing the problems into problems concerning *the hardware, software, environment,* and *mathematics and physics knowledge*.

Overall, the results of this thesis have to be interpreted with care because of the extracurricular position of educational robotics competitions. As self-selecting programs, the students participating in these activities are not a sample of the general student population but more likely a positive selection thereof. Thus, the results, which are deducted from studies on educational robotics competitions, can hardly be generalized to the whole student population (Benitti & Spolaor, 2017). As a consequence, more research is necessary to investigate the use of educational robotics to foster students' learning in the regular STEM classroom (Benitti & Spolaor, 2017).

Moreover, other areas of future research can be identified and an excerpt from those will be presented in the final section to conclude this thesis.

13.3 Ideas for future research

13.3.1 Further empirical evidence

The demand for more empirical data on the benefits of educational robotics, which has already been expressed by, for example, Alimisis (2013) continues to be important. Even though this thesis provided another piece in the puzzle of impact analysis on educational robotics, there are still many different areas, which require further evaluation (section 4.5, p. 39).

Focusing on educational robotics competitions, in particular, they highly differ regarding their effort and scope of impact evaluation studies (section 7.3, p. 64). Even though competitions such as the RCJ still lack sophisticated impact evaluation, the FLL and WRO already provide these. In the next step, more comparative studies are necessary to be able to judge the impact of each program. Following the evaluation design process for educational robotics by Stubbs et al. (2012), a comparison of educational robotics competition evaluation studies could focus on methodology, e.g. formative vs. summative evaluation, target audience, impact category, or evaluation and measurement methods on the one hand and results on the other hand. The publication of evaluation results in scientific publications and on the competition's website provides a valuable resource for researchers to use as a basis for comparative analysis. For example, the organization FIRST (*F*or *I*nspiration and *R*ecognition of *S*cience and *T*echnology) accompanies its programs with different evaluation studies to measure its impact and provides information and results about these studies in their resource library[41]. WRO Germany also published information on the results of their evaluation study of 2019 on their website[42]. Using these resources for a meta-analysis would give a broad view of the impact evaluation of the programs on students' learning. Thus, it could help to foster the understanding of the role of educational robotics competitions as out-of-school learning settings for STEM education.

In this thesis, problem solving skills (in terms of engineering design skills) have been examined as part of 21st century skills. Other skills related to 21st century learning (e.g. communication and collaboration) (section 2.2, p. 8) could be investigated further. Pöhner et al. (2020b) already concluded from the impact evaluation study of WRO Germany in 2019 that the educational robotics competition is beneficial for developing these skills, but following the approach of this

[41] The results of multiple evaluation studies on the programs can be found in FIRST's resource library here: https://www.firstinspires.org/resource-library/first-impact (last accessed 7th August 2020)

[42] The results of the evaluation study WRO Germany can be found here: www.tb-ev.de/wirkung (last accessed 7th August 2020)

thesis further research could identify *how* this happens during the students' participation in the competition.

Another idea for further research in the field of impact evaluation of educational robotics competitions is the investigation of the long term effects of educational robotics competitions on students' career choices (Stubbs et al., 2012). Following the idea of the STEM pipeline as an analogy for sustainable development in STEM education, the programs follow primary (affective) and secondary (cognitive) goals (Mead et al., 2012; Nugent et al., 2015). Tertiary goals would be to influence students' career choices towards STEM. This influence would usually be investigated through longitudinal studies. Regardless, longitudinal studies are a great challenge for educational robotics programs since it is very hard to track students in an out-of-school setting and self-selection over multiple years. (Stubbs et al., 2012). FIRST's longitudinal study serves as a positive example and resembles a multiple-year longitudinal study with around 1200 students to evaluate this long-term impact (Melchior et al., 2018). Other studies focusing on students' career choices used the students' self-concept and interest (among others) as predictors of their career choices (according to occupational psychology) to examine this influence (Pöhner & Hennecke, 2019a). In general, more longitudinal studies are necessary to provide valid information about the program's influence on students' career choices.

Diversity and broadening participation was also identified as a relevant idea for future research (Anwar et al., 2019). Again, following the STEM pipeline as displayed in Fig. 7 (p. 37), this includes the diverse backgrounds and contexts of the participating students. These comprise the students' personal attributes but also the different stakeholders involved in their education (i.e. educators, peers, family). For example, Chiang et al. (2020) investigated the different perspectives on the benefits of participation in the WRO (in China) of the participating students, their teachers, and their parents. They conclude that students especially value their cognitive and affective development and cooperation within the team (Chiang et al., 2020). The teachers focus on the communication within and team and the parents appreciate the comprehensive development of their children and the impact of participation in the educational robotics competition on their school learning and future (Chiang et al., 2020).

13.3.2 Engineering design and its role in integrated STEM education

Besides further empirical evidence, educational robotics (competitions) can be investigated using different theoretical lenses. One example is engineering design (through educational robotics) in integrated STEM education. The claim for an integrated approach of STEM education derives from the complexity of today's world's challenges such as, for example, *climate change, overpopulation,* or *resource management.* To fully comprehend these problems knowledge and skills from different STEM domains are necessary (Kelley & Knowles, 2016). Kenney and Odell (2014, p. 246) define STEM education as

> *[…] a meta-discipline, an integrated effort that removes the traditional barriers between these subjects, and instead focuses on innovation and the applied process of designing solution to complex contextual problems using current tools and technologies. Engaging students in high quality STEM education requires programs to include rigorous curriculum, instruction, and assessment, integrate technology and engineering into the science and mathematics curriculum, and also promotes scientific inquiry and the engineering design process.*

The focus of integrated STEM education according to the conceptual framework by Kelley and Knowles (2016) is *situated STEM learning*, which argues that the application of new knowledge and skills is as important as the learning thereof. Moreover, engineering design and scientific inquiry function as entry point to integrated STEM education (Kelley & Knowles, 2016). The use of engineering design as an entry point to situated STEM learning allows students to build upon their experiences and foster their science and mathematics knowledge and skills through a design process:

> *Engineering and technology provide a context in which students can test their own developing scientific knowledge and apply it to practical problems; doing so enhances their understanding of science - and, for many, their interest in science - as they recognize the interplay among science, engineering, and technology. We are convinced that the engagement in the practices of engineering design is as much a part of learning science as engagement in the practices of science. (Brown et al., 1989, p. 12)*

With annual changing themes, most educational robotics competitions aim at providing a situated STEM learning context for their participants. For example, in 2019, the season theme of the WRO was *Smart cities*. The tasks in the educational robotics competition focused on how technology might change our everyday life in terms of innovations to reduce energy consumption, smart traffic systems, etc. Unfortunately, the impact evaluation study of WRO Germany showed that 56,5 % of the team coaches (of all categories) agree that participation in the educational robotics competition contributes little to students' learning about the season theme. Regardless, for the Open category, only 19,6 % of the team coaches agree. Thus, the Open category provides a valuable learning setting for integrated STEM education using engineering design (focusing on a global challenge regarding the season theme) as an entry point (in contrast to the Regular category). (Pöhner & Hennecke, 2020)

13.3.3 Engineering design and playful learning

Another possible theoretical lens for the research in the field of educational robotics is its connection with playful learning. Playful learning (or *learning through play*) refers back to the way children in early childhood make sense of the world around them. In early childhood, knowledge construction happens based on the children's prior knowledge by manipulating artifacts of their environment and observing their behavior (Eguchi, 2017).

Zosh et al. (2018) defined play as a spectrum ranging from *free play* to *playful instruction*. Whereas free play includes no specific learning goal and is neither directed nor initiated by an adult, playful construction has a learning goal, is initiated by the child, and direct by the adult. Even though each type of play will foster the learning process of the children to some degree, especially *guided play* – as an intermediate type of play, which has a learning goal, is initiated by the adult but directed by the child – receives an elevated position with the spectrum of play since it particularly addresses the following characteristics of play, which are also essential for STEM learning: *active, minds-on thinking, engagement, meaning-making, joy,* and *iteration*. (Zosh et al., 2018)

Engineering design is reflected in the characteristic *iteration* in guided play. In guided play settings, children can explore these artifacts in a secure space of exploration to test their hypotheses and construct new knowledge, as Piaget (1964, p. 176) argues:

> *Knowledge is not a copy of reality. To know an object, to know an event, is not simply to look at it and make a mental copy or image of it. To know an object is to act on it. To know is to modify, to transform the object, and to understand the process of this transformation, and as a consequence to understand the way the object is constructed.*

All in all, this section provided a selection of ideas for future research. These comprise suggestions for further empirical investigation of the benefits of educational robotics on the one hand and the use of other theoretical perspectives on the other hand. They are starting points for future research, since there is still a lot of research necessary to identify the full potential of educational robotics in students' learning and demystify this technology, as this quote by Papert and Harel (1991, p. 9) indicates:

> *Building and playing with castles of sand, families of dolls, houses of Lego, and collections of cards provide images of activities which are well rooted in contemporary cultures and which plausibly enter into learning processes that go beyond specific narrow skills. I do not believe that anyone fully understands what gives these activities their quality of "learning-richness". But this does not prevent one from taking them as models in benefiting from the presence of new technologies to expand the scope of activities with that quality.*

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Appendix

Appendix A: Summary of the impact evaluation study of WRO Germany in 2019

Executive summary of the evaluation study of the World Robot Olympiad in Germany during the 2019-20 season "SMART Cities"

1. Introduction

The World Robot Olympiad (WRO)[1] is an international educational robotics competition with the aim to get students aged 6 to 9 years enthusiastic about science, technology, engineering, and mathematics (STEM). In teams of 2 or 3, the students assemble, design and program robots to accomplish tasks, which are associated with real-world problems regarding annually changing tasks (e.g. "SMART Cities" in 2019). Each team is accompanied by a team coach. Teams use *LEGO* robotics kits to build their robots (in the categories Regular and Football) or develop a robot model using also other robotics kits such as *RaspberryPi* or *Arduino* (in the Open category). Starting at regional competitions, where the teams compete against each other in the respective categories for the first time, they can qualify for advanced rounds of the competition, i.e. the national final or even the world final, which takes place in different countries each year (e.g. in Győr, Hungary in 2019).

The overall aim of the WRO is to tackle the lack of specialists in technological industries. Thus, on the one hand, the WRO aims at sparking the students' interest in STEM, and, on the other hand, it wants to foster the skills they need for their future working life. This addresses especially *21st century skills*. This phrase describes skills, which are indispensable for a future, which is shaped by an increasing digitalization, automation, and globalization. Examples of 21st century skills are advanced communication, collaboration, and problem solving skills as wells as digital literacy.

Beneath the international organization of the WRO Association, the competition is organized by national partners. In Germany, The WRO is organized by the organization TECHNIK BEGEISTERT e.V. Since the organization started their work in 2012, the number of participants in WRO Germany has been growing continuously, from 32 teams in 2012 to 683 teams in 2019 (Regular Category: 573 teams, Football Category: 43 teams, Open Category: 67 teams). 693 teams correspond to 2298 students, who participated in WRO Germany in 2019. Moreover, further surveys show that WRO Germany even reached up to 4138 students through their programs in 2019. For example, students participate in educational robotics afterschool-classes but did not yet participate in the WRO Germany competition itself. Apart from the number of participating teams, the number of regional competitions has also been growing continuously, from 2 regional competitions in 2012 to 34 in 2019.

This ongoing trend is a first indicator that WRO Germany is a promising educational program. Regardless, to measure the impact of the WRO, the organizers of the WRO in Germany, the organization TECHNIK BEGEISTERT e.V., conducted an evaluation study in cooperation with

[1] Further information on the WRO can be found online here:
International: https://wro-association.org/home, Germany: https://www.worldrobotolympiad.de/

the University of Würzburg during the season of 2019-2020 "SMART Cities". Even though WRO Germany has been collecting feedback by participants via online surveys regularly in recent years[2], no scientific program evaluation has been conducted yet. This evaluation is necessary to measure the impact of the program on, for example, students' skill development and career choices in the field of STEM.

2. Research questions

The research questions for the evaluation study were the following:

1. **What is the impact of the WRO on students' skill development in terms of**
    a. **Building a robot (digital literacy)**
    b. **Programming a robot (digital literacy)**
    c. **Teamwork/collaboration**
    d. **Communication**
    e. **Problem solving?**
2. **What is the impact of the WRO on students' self-concept and interest regarding STEM[3] (as indicators of future career choices)?**

3. Study design and methodology

To answer these research questions, two studies have been designed (Fig. 1):

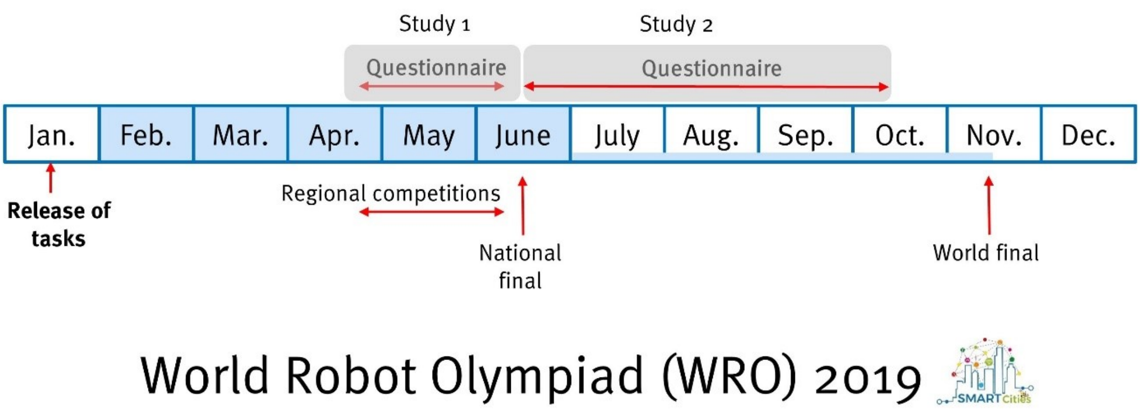


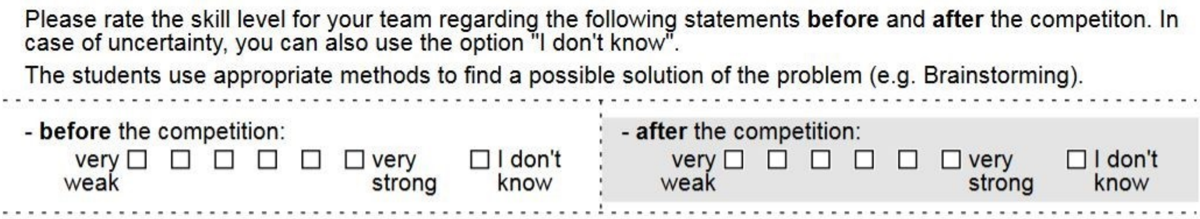
Figure 1: Study design of the evaluation study

The first study was a paper-pencil-questionnaire study at the teams' respective regional competitions with the team coaches. The study started at the first regional competition on 4th May 2019 (in Leonberg) and continued until the last regional competition on 8th June 2019 (in Menden (Sauerland)). In addition to general questions regarding demographic information or

[2] Selected results of these surveys can be found online in the annual reports by TECHNIK BEGEISTERT e.V. here (in German):
https://www.worldrobotolympiad.de/technik-begeistert-ev/transparenz

[3] Especially regarding Computer Science (CS) and technology.

questions on the current WRO season, the questionnaire asked the team coaches to externally assess students' skill development in a pre-post design (using "then-data", i.e. pre-values in retrospect). For each skill (e.g. problem solving), multiple questions were grouped as scales. One example question from the problem solving scale is available in Fig. 2.


Please rate the skill level for your team regarding the following statements **before** and **after** the competiton. In case of uncertainty, you can also use the option "I don't know".

The students use appropriate methods to find a possible solution of the problem (e.g. Brainstorming).

- **before** the competition: very weak ☐ ☐ ☐ ☐ ☐ ☐ very strong ☐ I don't know

- **after** the competition: very weak ☐ ☐ ☐ ☐ ☐ ☐ very strong ☐ I don't know

Figure 2: Example question from the problem solving scale

Using the pre- and post-values allowed the researchers to construct values for skill development.

The second study was conducted with former participants (alumni) of WRO Germany using an online questionnaire. Participation in this study happened on a self-selective basis and the data collection started on 25th June 2019 (first day of the national final in Germany) and continued until mid-September. This questionnaire study focused on the impact of the WRO on the alumni's career choices. Regardless, this impact was not measured directly but indirectly using the impact on their self-concept and interest regarding STEM as indicators of their future career choices. Self-concept and interest are regarded as relevant indicators for future career choices in occupational psychology.

Data analysis was conducted using descriptive and inferential statistical methods. To convey the meaning of the results from the inferential statistical analysis comprehensibly, effect sizes were used. In general, effect sizes are a measure of the strength of the impact of a trait (e.g. the WRO as educational program) on a variable (e.g. the students' problem solving skills). The higher the effect size, the higher the impact of the trait on the variable. To report effect sizes, multiple units are available. In this report, we use a unit called *Common Language Effect Size* (CLES). As the name indicates, this unit aims at reporting effect sizes in a non-technical way. CLES is the probability that a sample from one group (e.g. *after* the competition) is greater than a sample from another group (e.g. *before* the competition). Effect sizes, which are reported in the CLES unit, can be divided into small (>53%), medium (>58%), and large (>62%) effects.

4. Key findings

Key findings from the evaluation study are reported in the following.

4.1 Study 1

A total of 60% of teams (413 of 683) participated in this study. This corresponds to 1053 students.

Tab. 1 presents a summary of the five investigated skills with effect sizes (in CLES) and their interpretation.

Table 1: Summary of skill development with effect sizes (in CLES) and their interpretation

Skill	Effect size (CLES)	Interpretation
Building a robot	0,79	Large effect
Programming a robot	0,77	Large effect
Teamwork/collaboration	0,74	Large effect
Communication	0,74	Large effect
Problem solving	0,79	Large effect

The results show, for example, a positive skill development regarding the students' problem solving skills in 79% of the cases. On a positive note, both building and programming a robot as *hard skills* and teamwork/collaboration, communication, and problem solving skills as *soft skills* are influenced positively.

In addition to the comparison of pre- and post-values for all participants, further analysis was conducted to compare key subgroups.

- Category (Regular, Open und Football category)
- Age group (Starter, Elementary, Junior and Senior)
- Experience (number of participations at regional competitions of WRO Germany)
- Gender (all-boys, all-girls, and mixed teams)
- Success (percentage of solved tasks at the regional competition of WRO Germany)

When comparing different subgroups, they are compared based on their relative skill development (i.e. normalized gain, in contrast the absolute skill development). Using the relative values, skill development can be calculated excluding prior skill level.

- **Category**: The digital literacy skills (building and programming a robot) show the greatest impact in the Regular category compared to the Open category (CLES = 0,55 (building a robot) or 0,59 (programming a robot), i.e. small to medium effects) and the Football category (CLES = 0,57 (building a robot) or 0,56 (programming a robot), i.e. small effects). Communication skills are most influenced in the Open category (CLES = 0,56, i.e. small effects). Regarding the category, CLES is the probability that a sample from one group (e.g. Regular category) is greater than a sample from another group (e.g. Open category). The interpretation of CLES is similar for the comparison of the following subgroup comparisons.
- **Age group:** The comparison of different age groups does not show any differences regarding the relative skill development of participants. Regardless, differences can be observed in the prior skill level. Younger age groups (Starter and Elementary) show a

lower prior skill level than older age groups (Junior and Senior) (CLES = 0,58-0,62, i.e. medium effects).

- **Experience:** Similar to the comparison of different age groups, differently experienced teams do not show any differences regarding the relative skill development but in their prior skill level. Less experienced teams show a lower prior skill level than more experienced ones (CLES = 0,54-0,64, i.e. small to large effects).
- **Gender:** To compare the teams based on their gender, the teams were divided into all-boys, all-girls, and mixed teams. Again, they do not show any differences regarding the relative skill development but in their prior skill level. Teams with a higher proportion of boys, i.e. all-boys teams or teams with mostly boys, show a higher prior skill level compared to their female counterparts regarding their digital literacy skills (building and programming a robot) and problem solving skills (CLES = 0,55-0,59, i.e. small to medium effects). No differences were found for teamwork/collaboration and communication skills.
- **Success:** Differently successful teams differ in terms of their skill development of communication skills (CLES = 0,57, i.e. small effects). Regarding their prior skill level, more successful teams show higher values for their problem solving skills (CLES = 0,54, i.e. small effects).

4.2 Study 2

62 former participants (alumni) participated in the second study.

The results of the descriptive analysis of the second study show that alumni rate problem solving skills as significantly higher than the other investigated skills regarding the skills' relevance for their future working life. They rate problem solving skills as 15% more important than the average of the other skills. Subsequently, teamwork/collaboration skills are rated as 14% and communication skills as 12% more important than the average of the other skills. All in all, especially the relevance of soft skills is emphasized.

Moreover, they rate the influence of the WRO on general school motivation as rather weak to neutral (average of 3,4 of 7). The school motivation regarding STEM is rated as rather high to high (average of 5,2 of 7) by contrast.

In occupational psychology, the self-concept, i.e. the collection of beliefs about personal traits, skills, etc., and interest regarding STEM are important indicators of future career choices in the field. Interests are developed in reference to boundaries, which are defined by the self-concept, and career decision making happens within these boundaries. The inferential statistical data analysis shows a great positive impact on the alumni's self-concept (CLES = 0,81, i.e. large effect) and interest (CLES = 0,84, i.e. large effect) regarding STEM. Thus, the WRO influences the career choices of participants indirectly by having a great impact on their self-concept and interest regarding STEM as indicators for future career choices.

5. Conclusion

In summary, the WRO proves to have a great impact on students' learning and future career choices. On the one hand, WRO positively influences the (former) students' self-concept and interest regarding STEM as indicators for future career choices and, on the other hand, the students' skill development of 21st century skills in terms of digital literacy skills (building and programming a robot), teamwork/collaboration, communication, and problem solving skills. More interestingly, the first study indicates that there is no *ceiling effect* in the students' skill development and students can develop their skills independent of their age, experience, gender, or success.

Appendix B: Questionnaire study (chapter 6)

EvaSys	WRO Alumni	Electric Paper

Universität Würzburg
Institut für Informatik
Didaktik der Informatik

Alumnifragebogen im Rahmen des

Bitte so markieren: Bitte verwenden Sie einen Kugelschreiber oder nicht zu starken Filzstift. Dieser Fragebogen wird maschinell erfasst.
Korrektur: Bitte beachten Sie im Interesse einer optimalen Datenerfassung die links gegebenen Hinweise beim Ausfüllen.

Alumni

Liebe/r Teilnehmer/in,

es freut uns, dass du dich entschieden hast, an unserer Befragung teilzunehmen. Diese Befragung richtet sich an ehemalige Teilnehmer (Alumni) der World Robot Olympiad. Wir untersuchen, welchen Einfluss die Teilnahme an der World Robot Olympiad auf den weiteren schulischen bzw. beruflichen Werdegang der ehemaligen Teilnehmer hat.

Die Teilnahme an der Befragung dauert **ca.10-12 Minuten** und ist selbstverständlich **freiwillig**.

Deine Angaben werden nach den Richtlinien der DSGVO streng vertraulich behandelt und können zu keinem Zeitpunkt mit deiner Person in Verbindung gebracht werden. Die Ergebnisse werden nur in anonymisierter Form im Rahmen eines Projektes ausgewertet und dargestellt. Weitere Informationen zur DSVGO und dem Datenschutz an der JMU Würzburg kannst du unter folgendem Link nachlesen:

https://www.uni-wuerzburg.de/universitaet/datenschutzbeauftragter/dsgvo/

Bitte beachte beim Ausfüllen stets die Hinweise im Fragetext. Darüber hinaus möchten wir dich bitten, zur Navigation durch den Fragebogen ausschließlich die „Weiter“- und „Zurück“-Buttons unten auf der Seite zu nutzen (bei der Verwendung der „Vor-/Zurück-Buttons“ in der Symbolleiste deines Browsers kann es zu Komplikationen im Ablauf der Befragung kommen). Bitte klicke nun auf „Weiter“, um mit die Umfrage zu starten. Herzlichen Dank!

Ansprechpartner:
Nicolai Pöhner
Didaktik der Informatik
Universität Würzburg
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Bei Fragen zum Datenschutz wende dich bitte an unseren Datenschutzbeauftragten unter der E-Mail datenschutz@uni-wuerzburg.de.

Alumni [Fortsetzung]

Demografische Daten:

Wie alt bist du?
- ☐ 18-19 ☐ 20-21 ☐ 22-23
- ☐ 24-26 ☐ 27-28 ☐ 29-30
- ☐ Älter als 30 ☐ keine Angabe

Welches Geschlecht hast du?
- ☐ männlich ☐ weiblich ☐ divers
- ☐ keine Angabe

In welchem Bundesland bist du zur Schule gegangen? (Bei mehreren bitte das Bundesland angeben, in dem du den größten Anteil deiner Schulzeit zur Schule gegangen bist.)
- ☐ Baden-Württemberg ☐ Bayern ☐ Berlin
- ☐ Brandenburg ☐ Bremen ☐ Hamburg
- ☐ Hessen ☐ Mecklenburg-Vorpommern ☐ Niedersachsen
- ☐ Nordrhein-Westfalen ☐ Rheinland-Pfalz ☐ Saarland
- ☐ Sachsen ☐ Sachsen-Anhalt ☐ Schleswig-Holstein
- ☐ Thüringen ☐ Ausland

Was ist dein höchster Bildungsabschluss?
- ☐ Hauptschulabschluss ☐ Realschulabschluss (Mittlere Reife) ☐ Gymnasium (Abitur bzw. Hochschulreife)
- ☐ Abgeschlossene Ausbildung ☐ Fachhochschulreife ☐ Hochschulabschluss (Bachelor)
- ☐ Hochschulabschluss (Master) ☐ Hochschulabschluss (Sonstige) ☐ Hochschulabschluss (Promotion)
- ☐ Sonstige

Alumni [Fortsetzung]

Erfahrung:

In welcher Kategorie der World Robot Olympiad (Regular, Football, Open) hast du wie oft teilgenommen?

Regular Category	0 ☐	☐	☐	☐	☐	☐	☐ >5	☐ keine Angabe
Football Category	0 ☐	☐	☐	☐	☐	☐	☐ >5	☐ keine Angabe
Open Category	0 ☐	☐	☐	☐	☐	☐	☐ >5	☐ keine Angabe

In welchem Jahr war deine erstmalige Teilnahme an der World Robot Olympiad?

☐ vor 2012 ☐ 2012 ☐ 2013
☐ 2014 ☐ 2015 ☐ 2016
☐ 2017 ☐ 2018

Wie oft hast du an weiterführenden Wettbewerben der World Robot Olympiad (Deutschland- bzw. Weltfinale) teilgenommen?

Deutschlandfinale	0 ☐	☐	☐	☐	☐	☐	☐ >5	☐ keine Angabe
Weltfinale	0 ☐	☐	☐	☐	☐	☐	☐ >5	☐ keine Angabe

Wer hat dich dazu bewegt, an der World Robot Olympiad teilzunehmen? (Es können mehrere Möglichkeiten angekreuzt werden)

☐ Freunde ☐ Lehrer ☐ Eltern
☐ Eigenes Interesse ☐ Sonstiges

Alumni [Fortsetzung]

Schulischer und beruflicher Werdegang

Was machst du aktuell beruflich?

- ☐ Schule
- ☐ Studium
- ☐ Berufsausbildung
- ☐ Berufstätigkeit
- ☐ Sonstiges

Alumni [Fortsetzung]

Frage			
Auf welche Art Schule gehst du?	☐ Berufsbildende Schule	☐ Gesamtschule	☐ Gymnasium
	☐ Realschule	☐ Sonstiges	
Welchen Schulzweig hast du gewählt?	☐ Mathematisch, naturwissensc-haftlich und technologisch	☐ Wirtschaftswis-senschaftlich	☐ Sozialwissens-chaftlich
	☐ Sprachlich	☐ Humanistisch	☐ Musisch
	☐ Sonstiges		

Alumni [Fortsetzung]

Welches Fach- bzw. Fachrichtung studierst du?

- ☐ Medizin und Gesundheitswesen
- ☐ Gesellschafts- und Sozialwissens-chaften
- ☐ Ingenieurwisse-nschaften
- ☐ Sprache, Kultur und Medien
- ☐ Recht und Wirtschaft
- ☐ Naturwissensc-haften, Mathematik und Informatik
- ☐ Lehramtsstudi-engänge

Du hast Naturwissenschaften, Mathematik und Informatik angegeben. Gib bitte hier den genauen Namen deines Studiengangs an.

Du hast Ingenieurwissenschaften angegeben. Gib bitte hier den genauen Namen deines Studiengangs an.

Du hast Lehramtstudiengänge angegeben. Gib die Fächerkombination an, die du studierst.

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Alumni [Fortsetzung]

In welcher Branche absolvierst du deine Ausbildung?

- ☐ Instudie und Handel
- ☐ Handwerk
- ☐ Landwirtschaft
- ☐ Öffentlicher Dienst
- ☐ Freier Beruf (z.B. Steuerfachange-stellte(r), Medizinische Fachangestellte (r))
- ☐ Hauswirtschaft
- ☐ Sonstiges

Gib die Bezeichnung für deine Berufsausbildung an.

Alumni [Fortsetzung]

In welcher Branche arbeitest du?

- ☐ Instudie und Handel
- ☐ Handwerk
- ☐ Landwirtschaft
- ☐ Öffentlicher Dienst
- ☐ Freier Beruf (z.B. Steuerfachange-stellte(r), Medizinische Fachangestellte (r))
- ☐ Hauswirtschaft
- ☐ Sonstiges

Gib die Bezeichnung deines Berufs an.

Alumni [Fortsetzung]

Was machst du aktuell beruflich?

MUSTER

Alumni [Fortsetzung]

Frage									
Wie stark hat dich die World Robot Olympiad in der Wahl deiner Laufbahn in Schule, Studium oder Beruf beeinflusst?	sehr schwach ☐	☐	☐	☐	☐	☐	☐ sehr stark	☐ keine Angabe

Wieviel hast du aus einzelnen Bereichen der World Robot Olympiad mitgenommen, das dich in Schule, Studium oder Beruf weiterbringt?

Bereich								
Bauen eines Roboters	sehr wenig ☐	☐	☐	☐	☐	☐	☐ sehr viel	☐ keine Angabe
Programmieren eines Roboters	sehr wenig ☐	☐	☐	☐	☐	☐	☐ sehr viel	☐ keine Angabe
Teamwork	sehr wenig ☐	☐	☐	☐	☐	☐	☐ sehr viel	☐ keine Angabe
Kommunikationsfähigkeit	sehr wenig ☐	☐	☐	☐	☐	☐	☐ sehr viel	☐ keine Angabe
Problemlösefähigkeit und Arbeitsweise	sehr wenig ☐	☐	☐	☐	☐	☐	☐ sehr viel	☐ keine Angabe

Hast du während deiner Schulzeit neben der World Robot Olympiad auch an anderen Förderungprogrammen im MINT-Bereich teilgenommen? (Es können mehrere Möglichkeiten angekreuzt werden)

- ☐ Ja, bei der FIRST LEGO League
- ☐ Ja, beim RoboCup
- ☐ Ja, bei Jugend forscht
- ☐ Ja, bei Informatikwettbewerben (z.B. Informatikbiber)
- ☐ Ja, bei Mathematikwettbewerben (z.B. Känguru)
- ☐ Ja, bei anderen Förderprogrammen, die hier nicht aufgelistet sind
- ☐ Nein

Aussage								
Meine Teilnahme an der World Robot Olympiad hat mich motiviert, in der Schule besser zu werden.	sehr schwach ☐	☐	☐	☐	☐	☐	☐ sehr stark	☐ keine Angabe
Meine Teilnahme an der World Robot Olympiad hat mich motiviert, in Informatik und Technik besser zu werden.	sehr schwach ☐	☐	☐	☐	☐	☐	☐ sehr stark	☐ keine Angabe

Alumni [Fortsetzung]

Selbstkonzept

Beantworte die folgenden Aussagen bitte im Vergleich zu deiner Zeit vor der World Robot Olympiad (früher).

Seit meiner Zeit bei der World Robot Olympiad...

... fühle ich mich in Informatik und Technik ...	weniger begabt als früher ☐	☐	☐	☐	☐ begabter als früher	☐ keine Angabe
... fällt mir das Lernen von neuen Themen in Informatik und Technik ...	leichter als früher ☐	☐	☐	☐	☐ schwerer als früher	☐ keine Angabe
... komme ich mit Aufgaben in Informatik und Technik ...	schlechter zurecht als früher ☐	☐	☐	☐	☐ besser zurecht als früher	☐ keine Angabe
... fällt mir das Lösen von Problem in Informatik und Technik ...	leichter als früher ☐	☐	☐	☐	☐ schwerer als früher	☐ keine Angabe
... kann ich in Informatik und Technik ...	weniger als früher ☐	☐	☐	☐	☐ mehr als früher	☐ keine Angabe

Alumni [Fortsetzung]

Interesse

Beantworte die folgenden Aussagen bitte im Vergleich zu deiner Zeit vor der World Robot Olympiad (früher).

Seit meiner Zeit bei der World Robot Olympiad...

... wirkt sich die Beschäftigung mit bestimmten Themen aus dem Bereich Informatik und Technik positiver auf meine Stimmung aus als früher.	trifft gar nicht zu ☐	☐	☐	☐	☐ trifft völlig zu	☐ keine Angabe
... beschäftige ich mich, unabhängig von Schule, Studium oder Beruf und wenn ich genügend Zeit habe, intensiver mit Themen aus Informatik und Technik als früher.	trifft gar nicht zu ☐	☐	☐	☐	☐ trifft völlig zu	☐ keine Angabe
... gehört die Beschäftigung mit Inhalten und Problemen aus Informatik und Technik stärker zu meinen Lieblingstätigkeiten als früher.	trifft gar nicht zu ☐	☐	☐	☐	☐ trifft völlig zu	☐ keine Angabe
... hat die Beschäftigung mit Themen aus Informatik und Technik mehr mit Selbstverwirklichung zu tun als früher.	trifft gar nicht zu ☐	☐	☐	☐	☐ trifft völlig zu	☐ keine Angabe
... macht es mir mehr Spaß als früher, über Inhalte und Themen aus Informatik und Technik zu reden.	trifft gar nicht zu ☐	☐	☐	☐	☐ trifft völlig zu	☐ keine Angabe
... schmökere ich im Buchladen, Bibliothek oder Internet lieber in Büchern, Zeitschriften oder auf Webseiten, die über Themen aus Informatik und Technik berichten, als früher.	trifft gar nicht zu ☐	☐	☐	☐	☐ trifft völlig zu	☐ keine Angabe
... ist es für mich von größerer persönlicher Bedeutung als früher, im Bereich Informatik und / oder Technik studieren bzw. arbeiten zu können.	trifft gar nicht zu ☐	☐	☐	☐	☐ trifft völlig zu	☐ keine Angabe
... messe ich Inhalten und Themen aus Informatik und Technik im Vergleich zu anderen Dingen, die mir sehr wichtig sind (z.B. Hobbies, Freunde) eine eher höhere Bedeutung zu als früher.	trifft gar nicht zu ☐	☐	☐	☐	☐ trifft völlig zu	☐ keine Angabe
... sind mir Themen und Inhalte aus Informatik und Technik wichtiger als früher.	trifft gar nicht zu ☐	☐	☐	☐	☐ trifft völlig zu	☐ keine Angabe

Alumni [Fortsetzung]

Aktuelles Engagement bei der World Robot Olympiad

Weißt du, dass man sich als Alumni bei der World Robot Olympiad einbringen kann?
- ☐ Ja
- ☐ Nein

Wenn du dich bei der WRO einbringen möchtest, schaue doch mal auf die Internetseite zum Thema Mitmachen bei der WRO. Du wirst nach der Umfrage auf diese Seite weitergeleitet.

Bist du als Alumni noch bei der World Robot Olympiad aktiv?
- ☐ Ja
- ☐ Nein

In welcher Form bist du als Alumni bei der World Robot Olympiad aktiv?
- ☐ Coach
- ☐ Jury bzw. Schiedsrichter
- ☐ Mitgliedschaft im Verein TECHNIK BEGEISTERT e.V.
- ☐ Organisator von Regionalwettbewerben bzw. Wettbewerbspartner
- ☐ Sonstiges

Warum bist du als Alumni nicht mehr bei der World Robot Olympiad aktiv?
- ☐ Fehlendes Interesse
- ☐ Fehlende Zeit
- ☐ Fehlendes Wissen, wie ich mich engagieren kann
- ☐ Sonstiges

MUSTER

Appendix C: Questionnaire study (chapter 10)

EvaSys	Fragebogen Evaluationsprojekt WRO (Regular)	Electric Paper

Universität Würzburg
Institut für Informatik
Didaktik der Informatik

Bitte so markieren: ☐ ☒ ☐ ☐ ☐
Korrektur: ☐ ■ ☐ ☒ ☐

Einleitung

Liebe Team-Coaches,

während dieser Saison der "World Robot Olympiad" wird ein umfrangreiches Evaluationsprojekt durchgeführt. Dabei interessiert uns, was die Teilnehmerinnen und Teilnehmer bei dem Wettbewerb lernen, wie sie sich durch die WRO entwickeln und wie sich ihre Einstellung zu Robotik, Informatik und technischen Themen verändert. Zudem hilft uns das Evaluationsprojekt die Qualität der WRO zu messen und darauf aufbauend weiterzuentwickeln.
Dabei sind wir auf Ihre Unterstützung angewiesen. Das Ausfüllen des Fragebogens ist selbstverständlich **freiwillig**, Sie tragen damit aber einen großen Teil zu einem gelungenen Evaluationsprojekt bei. Die Beantwortung des Fragebogens nimmt in etwa **10 - 15 Minuten** in Anspruch.
Nach dem Ausfüllen des Fragebogens legen Sie die Blätter bitte in den zugehörigen Umschlag und kleben diesen zu.

Weitere Informationen zum Evaluationsprojekt finden Sie auf unserer Webseite unter Saison 2019 > Evaluation. Die Ergebnisse des Evaluationsprojekts werden nach Auswertung der Fragebögen mit Ihnen geteilt.

Vielen Dank für Ihre Teilnahme!

Demografische Daten

In welcher Alterklasse nimmt Ihr Team teil? (Regular)

☐ Regular (Starter) ☐ Regular (Elementary) ☐ Regular (Junior)
☐ Regular (Senior)

Welchem Typ Institution bzw. Organisation gehört Ihr Team an?

☐ Schule ☐ Privat ☐ Kooperation mit Organisation, Universität, etc.
☐ Sonstiges

Aus welchem Bundesland kommen Sie?

☐ Baden-Württemberg ☐ Bayern ☐ Berlin
☐ Brandenburg ☐ Bremen ☐ Hamburg
☐ Hessen ☐ Mecklenburg-Vorpommern ☐ Niedersachsen
☐ Nordrhein-Westfalen ☐ Rheinland-Pfalz ☐ Saarland
☐ Sachsen ☐ Sachsen-Anhalt ☐ Schleswig-Holstein
☐ Thüringen ☐ Ausland

MUSTER

Demografische Daten [Fortsetzung]

Welche Schulart besuchen die Schülerinnen und Schüler Ihres Teams? (Bitte geben Sie die Schulart und die dazugehörige Anzahl an) (Bei "Sonstiges" können Sie die Schulart genauer angeben und im Klammern die Anzahl der Schülerinnen und Schüler z.B. Fachoberschule (2))

Gesamtschule	0 ☐	☐	☐	☐ 3
Grundschule	0 ☐	☐	☐	☐ 3
Gymnasium	0 ☐	☐	☐	☐ 3
Mittelschule	0 ☐	☐	☐	☐ 3
Realschule	0 ☐	☐	☐	☐ 3

Sonstiges

Wieviele Jungen bzw. Mächen sind in Ihrem Team?

Mädchen	0 ☐	☐	☐	☐ 3
Jungen	0 ☐	☐	☐	☐ 3

Wie oft hat Ihr Team (in dieser bzw. ähnlicher Besetzung) bereits an der World Robot Olympiad teilgenommen (in Anzahl der Saisons)? 0 ☐ ☐ ☐ ☐ ☐ ☐ ☐ >6

Dabei hat sich Ihr Team wie oft für weitere Runden (z.B. Deutschland- und Weltfinale) qualifiziert:

2. Runde (Deutschlandfinale)	0 ☐	☐	☐	☐	☐	☐ >6
3. Runde (Weltfinale)	0 ☐	☐	☐	☐	☐	☐ >6

Wie oft hat Ihr Team (in dieser bzw. ähnlicher Besetzung) bereits an anderen Roboterwettbewerben (z.B. FIRST LEGO League, RoboCup) teilgenommen? 0 ☐ ☐ ☐ ☐ ☐ ☐ ☐ >6

Dabei hat sich Ihr Team wie oft für weitere Runden (z.B. Deutschland- und Weltfinale) qualifiziert:

2. Runde	0 ☐	☐	☐	☐	☐	☐ >6
3. Runde	0 ☐	☐	☐	☐	☐	☐ >6

Wie oft haben Sie als Coach bereits an der World Robot Olympiad teilgenommen? 0 ☐ ☐ ☐ ☐ ☐ ☐ ☐ >6

Dabei haben Sie sich wie oft für weitere Runden (z.B. Deutschland- und Weltfinale) qualifiziert:

2. Runde (Deutschlandfinale)	0 ☐	☐	☐	☐	☐	☐ >6
3. Runde (Weltfinale)	0 ☐	☐	☐	☐	☐	☐ >6

Wie oft haben Sie als Coach bereits an anderen Roboterwettbewerben (z.B. FIRST LEGO League, RoboCup) teilgenommen? 0 ☐ ☐ ☐ ☐ ☐ ☐ ☐ >6

Dabei haben Sie sich wie oft für weitere Runden (z.B. Deutschland- und Weltfinale) qualifiziert:

2. Runde	0 ☐	☐	☐	☐	☐	☐ >6
3. Runde	0 ☐	☐	☐	☐	☐	☐ >6

EvaSys	Fragebogen Evaluationsprojekt WRO (Regular)	Electric Paper

Aktuelle Saison

Wie hat Ihrem Team das diesjährige Motto "Smart Citites" zugesagt?
Gar nicht zugesagt ☐ ☐ ☐ ☐ ☐ Sehr zugesagt

Wie gut gelungen ist Ihrer Meinung nach die Umsetzung des diesjährigen Mottos "Smart Cities" in den Aufgaben Ihrer Kategorie?
Gar nicht gelungen ☐ ☐ ☐ ☐ ☐ Sehr gut gelungen

Wie stark trägt Ihrer Meinung nach das Motto "Smart Cities" etwas dazu bei, dass die Schülerinnen und Schüler Ihres Teams etwas zu diesem Thema lernen?
Sehr schwach ☐ ☐ ☐ ☐ ☐ Sehr stark

Vorbereitungsphase

Wie viel Zeit hat Ihr Team durchschnittlich pro Woche in die Vorbereitung (mit Beginn am 15.01.2019 als Tag der Aufgabenveröffentlichung) auf den Regionalwettbewerb investiert?

☐ <2 Std. / Woche
☐ 2-4 Std./ Woche
☐ 4-6 Std. / Woche
☐ 6-8 Std. Woche
☐ >8 Std. / Woche

Wie sah die Rollenverteilung in Ihrem Team aus? (spezialisierte Rollen (z.B. ein Schüler baut, der andere programmiert) vs. allgemeine Rollen (jeder kennt sich mit allem aus))
Sehr spezialisiert ☐ ☐ ☐ ☐ ☐ Sehr allgemein

Ausgangslage

Wie stark werden Ihrer Meinung nach die folgenden Kompetenzen (bzw. Kompetenzbereiche) rein durch die schulische Bildung der Schülerinnen und Schüler Ihres Team gefördert?

Programmierung (z.B. im Informatikunterricht)	sehr schwach ☐	☐	☐	☐	☐ sehr stark	☐ weiß nicht
Bauen eines Roboters (z.B. im Physik- oder Technikunterricht)	sehr schwach ☐	☐	☐	☐	☐ sehr stark	☐ weiß nicht
Teamwork	sehr schwach ☐	☐	☐	☐	☐ sehr stark	☐ weiß nicht
Kommunikationsfähigkeit	sehr schwach ☐	☐	☐	☐	☐ sehr stark	☐ weiß nicht
Arbeitsweise und Problemlösefähigkeit	sehr schwach ☐	☐	☐	☐	☐ sehr stark	☐ weiß nicht

Bauen eines Roboters

Wie schätzen Sie die Kompetenz der Schülerinnen und Schüler Ihres Teams bzgl. einer Aussage **vor** und **nach** dem Wettbewerb ein (Skala: Kompetenz ist **nicht ausgeprägt** - Kompetenz ist **stark ausgeprägt**). Wenn Sie unsicher sind, können Sie bei einer Aussage auch **weiß nicht** ankreuzen.

Die Schülerinnen und Schüler bauen ein einfaches Schiebewerkzeug (z.B. LEGO-Balken als Schiebemechanismus)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler bauen ein anspruchsvolles Schiebewerkzeug (z.B. mit Auffängern an der Seite)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler bauen ein einfaches Greifwerkzeug (z.B. Heben und Öfffnen des Greifwerkzeugs mit zwei Motoren)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler bauen ein anspruchsvolles Greifwerkzeug (z.B. Heben und Öffnen des Greifwerkzeugs mit nur einem Motor)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler bauen ein einfaches Fahrgestell (z.B. ohne dabei auf stabile Fahreigenschaften besonders Rücksicht zu nehmen)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler bauen ein anspruchsvolles Fahrgestell (z.B. mit einem stabilen Rahmen für bessere Fahreigenschaften)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler setzen Sensoren auf einfache Art und Weise ein (z.B. sie nutzen Sensoren zielgerecht für eine Aufgabe)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

MUSTER

Bauen eines Roboters [Fortsetzung]

Die Schülerinnen und Schüler setzen Sensoren auf anspruchsvolle Art und Weise ein (z.B. sie nutzen einen Sensor, um mehrere Aufgaben zu lösen oder kombinieren mehrere Sensoren bei einer Aufgabe)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Programmieren eines Roboters

Welche Programmiersprache benutzt ihr Team?

☐ EV3-G / NXT-G (LEGO-Software)
☐ NEPO (Open Roberta Lab)
☐ Scratch 3
☐ LeJOS
☐ MonoBrick
☐ c4ev3
☐ EV3 Basic
☐ ROBOTC
☐ ev3dev (Go)
☐ ev3dev (Python)
☐ ev3dev (Java)
☐ ev3dev (C++)
☐ ev3dev (C)
☐ Sonstiges

Wieso hat ihr Team sich für diese Programmiersprache entschieden?

Wie schätzen Sie die Kompetenz der Schülerinnen und Schüler Ihres Teams bzgl. einer Aussage **vor** und **nach** dem Wettbewerb ein (Skala: Kompetenz ist **nicht ausgeprägt** - Kompetenz ist **stark ausgeprägt**). Wenn Sie unsicher sind, können Sie bei einer Aussage auch **weiß nicht** ankreuzen.

Falls ihr Team die LEGO-Programmierumgebung (oder eine andere visuelle Programmiersprache) benutzt, beantworten Sie bitte die folgenden beiden Fragen:

Die Schülerinnen und Schüler nutzen einfache Programmblöcke der LEGO-Programmierumgebung (z.B. Sensoren, Aktoren, Konstrollstrukturen)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler nutzen anspruchsvolle Programmblöcke der LEGO-Programmierumgebung (z.B. mathematische und logische Programmblöcke oder Felder)

- vor dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:
nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

EvaSys	Fragebogen Evaluationsprojekt WRO (Regular)	Electric Paper

Programmieren eines Roboters [Fortsetzung]

Falls Ihr Team eine textuelle Programmiersprache (z.B. LeJOS, MonoBrick) benutzt, beantworten Sie bitte die folgenden beiden Fragen:

Die Schülerinnen und Schüler nutzen einfache Programmbefehle (z.B. einfache Ansteuerung der Motoren, Sensoren und Konstrollstrukturen)

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

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Die Schülerinnen und Schüler nutzen anspruchsvolle Programmbefehle (z.B.DifferentialPilot bei LeJOS)

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

---

Ab hier gelten die Fragen wieder für alle:

Die Schülerinnen und Schüler programmieren einfache Algorithmen (z.B. einfacher Linienfolger ("Zick-Zack"), Fahren bis Linie)

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

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Die Schülerinnen und Schüler programmieren anspruchsvolle Algorithmen (z.B. Linienfolger mit P-Regler, Ausrichten an Linie)

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

---

Die Schülerinnen und Schüler setzen Algorithmen auf einfache Art und Weise zur Aufgabenlösung ein (z.B. sie bearbeiten sequentiell eine Aufgabe nach der anderen)

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

---

Die Schülerinnen und Schüler setzen Algortihmen auf anspruchsvolle Art und Weise zur Aufgabenlösung ein (z.B. sie bearbeiten (Teil-)Aufgaben parallel, sie optimieren die Aufgabenreihenfolge z.B. durch günstige Wegeplanung)

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Teamwork

Wie schätzen Sie die Kompetenz der Schülerinnen und Schüler Ihres Teams bzgl. einer Aussage **vor** und **nach** dem Wettbewerb ein (Skala: Kompetenz ist **nicht ausgeprägt** - Kompetenz ist **stark ausgeprägt**). Wenn Sie unsicher sind, können Sie bei einer Aussage auch **weiß nicht** ankreuzen.

Die Schülerinnen und Schüler handeln arbeitsteilig und tauschen Informationen untereinander aus

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

---

Die Schülerinnen und Schüler stellen eigene Standpunkte adressatengerecht dar und vertreten diese vor anderen

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

---

Die Schülerinnen und Schüler gehen respektvoll miteinander um und sehen sich als gleichberechtigte Teammitglieder an

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Kommunikation

Wie schätzen Sie die Kompetenz der Schülerinnen und Schüler Ihres Teams bzgl. einer Aussage **vor** und **nach** dem Wettbewerb ein (Skala: Kompetenz ist **nicht ausgeprägt** - Kompetenz ist **stark ausgeprägt**). Wenn Sie unsicher sind, können Sie bei einer Aussage auch **weiß nicht** ankreuzen.

Die Schülerinnen und Schüler präsentieren Sachverhalte, Informationen und Arbeitsergebnisse adressatengerecht und mediengestützt

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

---

Die Schülerinnen und Schüler erstellen technische Dokumentation Ihrer Arbeit (z.B. Skizzen, Entwurfspläne, Diagramme, etc.)

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

---

Die Schülerinnen und Schüler kommunizieren im fachlichen Austausch unter Verwendung korrekter Fachsprache

- vor dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb: nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Arbeitsweise und Problemlösefähigkeit

Wie schätzen Sie die Kompetenz der Schülerinnen und Schüler Ihres Teams bzgl. einer Aussage **vor** und **nach** dem Wettbewerb ein (Skala: Kompetenz ist **nicht ausgeprägt** - Kompetenz ist **stark ausgeprägt**). Wenn Sie unsicher sind, können Sie bei einer Aussage auch **weiß nicht** ankreuzen.

Die Schülerinnen und Schüler planen technische Experimente, Konstruktions- und Herstellungsaufgaben, führen diese durch und werten sie mithilfe von (technischen) Analysen aus

- vor dem Wettbewerb:

nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:

nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler wenden geeinete Methoden zur Gewinnung von Lösungsideen an (z.B. Brainstorming)

- vor dem Wettbewerb:

nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:

nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler reflektieren, prüfen und optimieren konstruktive Lösungen

- vor dem Wettbewerb:

nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:

nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Die Schülerinnen und Schüler planen, strukturieren und optimieren ihren Arbeitsablauf zielgerecht

- vor dem Wettbewerb:

nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

- nach dem Wettbewerb:

nicht ausgeprägt ☐ ☐ ☐ ☐ ☐ stark ausgeprägt ☐ weiß nicht

Appendix D: Team diary (chapter 11)

Sehr geehrte Damen und Herren,

In diesem Forschungsprojekt geht es um Erfolgsfaktoren bei Roboterwettbewerben. Zusammenfassend wollen wir der Frage nachgehen, worin sich verschiedene Teams unterscheiden (z.B. in deren Erfahrung, Motivation, etc. aber auch deren Arbeitsweisen) und wie diese Unterschiede sich auf deren Erfolg auswirken. Der vorliegende Fragebogen deckt dabei z.B. Fragen zu dem Zeitaufwand für verschiedene Aspekte (z.b. algorithmisch) sowie Ihrer Hilfe (als Coach) bezüglich dieser Aspekte und der Art der Hilfe (z.B. inhaltlich) ab. Dieser Fragebogen stellt einen einzelnen Eintrag in das Tagebuch dar und soll nach jeder Sitzung mit Ihrem Team ausgefüllt werden. Somit ergibt sich ein fortlaufendes Tagebuch zu Ihrer Arbeit.
Für Ihre Teilnahme möchte ich mich schon vorab herzlichst bei Ihnen bedanken. Bei Fragen stehe ich jederzeit telefonisch oder per E-Mail zur Verfügung.

Mit freundlichen Grüßen,
Nicolai Pöhner

Bitte geben Sie Ihren Teamnamen ein.

Weiter

Wie lange hat ihr Team dieses Mal an der Wettbewerbsaufgabe gearbeitet (in Minuten)?

Geben Sie dabei nur die Zeit an, die Ihr Team für die Wettbewerbsaufgabe aufgebracht hat.

Weiter

Nicolai Poehner, Didaktik der Informatik, Institut für Informatik, Julius-Maximilians-Universität Würzburg – 2018

Nun folgen einige Fragen zu Ihrem Zeitaufwand für die einzelnen Aspekte des Informatiksystems "Roboter".

Mit welchen Aspekten des Informatiksystems „Roboter“ haben Sie und Ihr Team sich heute beschäftigt?

- ☐ Konzeptionell (Hardware, theoretisch) ____________
- ☐ Bautechnisch (Hardware, praktisch) ____________
- ☐ Algorithmisch (Software, theoretisch) ____________
- ☐ Implementiertechnisch (Software, praktisch) ____________

Wieviel Zeit haben Sie und Ihr Team heute im Verhältnis für die einzelnen Aspekte aufgebracht?

Bitte achten Sie darauf, dass Sie insgesamt 100% vergeben.

	0%		20%		40%		60%		80%		100%
Konzeptionell (Hardware, theoretisch)	○	○	○	○	○	○	○	○	○	○	○
Bautechnisch (Hardware, praktisch)	○	○	○	○	○	○	○	○	○	○	○
Algorithmisch (Software, theoretisch)	○	○	○	○	○	○	○	○	○	○	○
Implementiertechnisch (Software, praktisch)	○	○	○	○	○	○	○	○	○	○	○

Weiter

Appendix E: Questionnaire study (chapter 11 and 12)

Wissenschaftliche Studie zu Roboterwettbewerben

Im Rahmen einer wissenschaftlichen Studie untersuchen wir Roboterwettbewerbe als außerschulisches Lernangebot für den Informatik- bzw. Technikunterricht. Der Schwerpunkt liegt dabei auf der Frage, wie Schülerinnen und Schüler durch die Teilnahme an diesen Roboterwettbewerben Problemlösen lernen können.

Diese Studie richtet sich an alle Coaches der Regular Category der World Robot Olympiad.

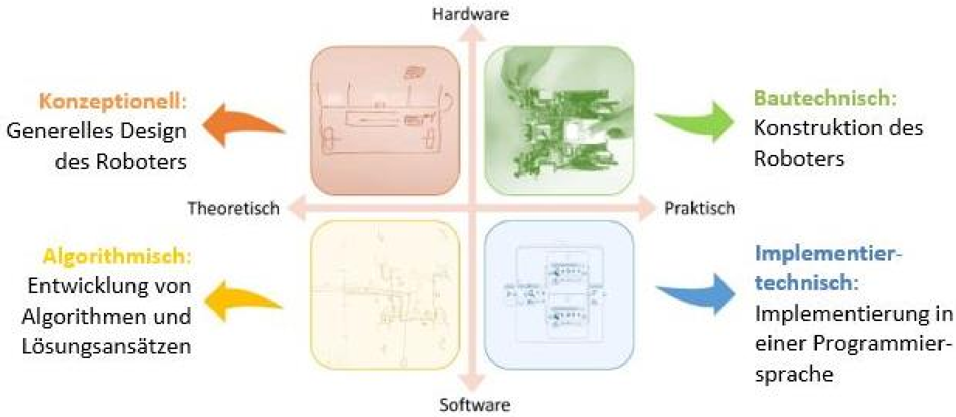
Weiter

Nicolai Poehner, Didaktik der Informatik, Institut für Informatik, Julius-Maximilians-Universität Würzburg – 2018

0% ausgefüllt

Problemlösestrategien und -prozesse:

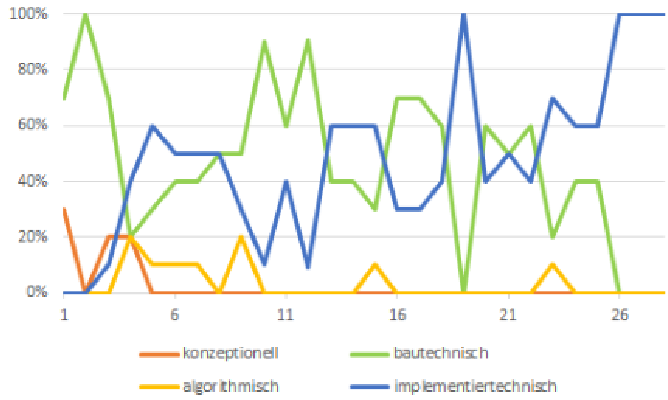
Um die Aufgaben der World Robot Olympiad angemessen zu lösen, müssen verschiedene Teilaufgaben erledigt werden. So muss der Roboter gebaut und programmiert werden, zudem müssen auch theoretische Überlegungen angestellt werden, wie die Konstruktion des Roboters bzw. die Programmierung aussehen soll (vgl. Abb.):



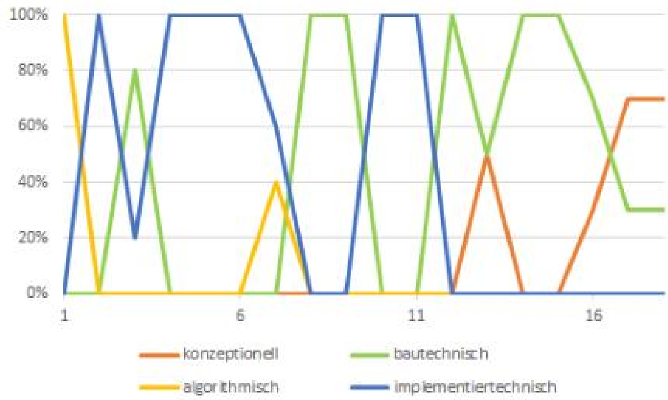
Um herauszufinden, wieviel Zeit einzelne Teams für diese vier Aspekte aufbringen, haben wir diese mithilfe eines Tagebuchs während der Vorbereitungsphase begleitet.

Nachfolgend sehen Sie hier drei Beispiele, die Arbeitsverläufe dreier Teams zeigen, die unterschiedlich erfolgreich bei ihren Regionalwettbewerben abgeschnitten haben. Sie sollen für jeden Arbeitsverlauf einschätzen, wie erfolgreich das Team beim Regionalwettbewerb wohl war.

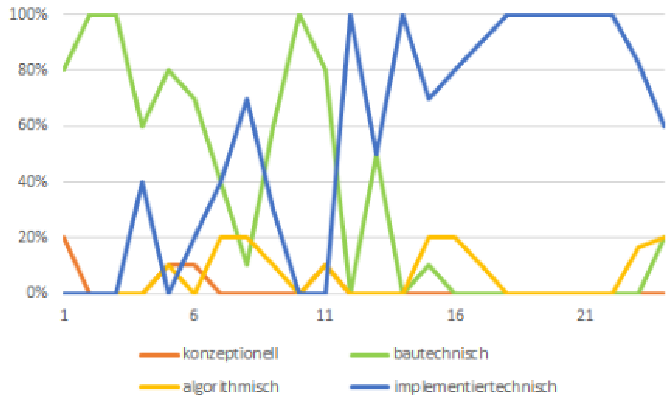
Wie erfolgreich schätzen Sie diese Teams aufgrund ihrer Arbeitsverläufe ein?



○ Sehr erfolglos ○ Erfolglos ○ Eher erfolglos ○ Eher erfolgreich ○ Erfolgreich ○ Sehr erfolgreich



○ Sehr erfolglos ○ Erfolglos ○ Eher erfolglos ○ Eher erfolgreich ○ Erfolgreich ○ Sehr erfolgreich



○ Sehr erfolglos ○ Erfolglos ○ Eher erfolglos ○ Eher erfolgreich ○ Erfolgreich ○ Sehr erfolgreich

Weiter

Hilfe des Coaches beim Problemlösen

Als Coach helfen Sie natürlich Ihrem Team immer wieder während der Vorbereitungsphase in verschiedener Art und Weise. Wir unterteilen die Hilfe dabei in folgende Kategorien:

- **Organisatorisch**: z.B. zeitliche Orientierung, Herstellung der Disziplin
- **Affektiv**: z.B. Schülerinnen und Schüler zu motivieren, weiterzuarbeiten
- **Inhaltich**: z.B. Erklärung von informatischen Konstrukten wie Schleifen, etc. (Programmierung) oder zur Funktionsweise von technischen Bauteilen wie Zahnrädern (Konstruktion)
- **Strategisch**: z.B. Erklärung des Sinns des Baus von Prototypen von Werkzeugen (metakognitive Ebene)

Wieviel organisatorische Hilfe haben Sie gegeben?

○ Sehr wenig ○ Wenig ○ Eher wenig ○ Eher viel ○ Viel ○ Sehr viel

Wieviel affektive Hilfe haben Sie gegeben?

○ Sehr wenig ○ Wenig ○ Eher wenig ○ Eher viel ○ Viel ○ Sehr viel

Wieviel inhaltliche Hilfe haben Sie gegeben?

○ Sehr wenig ○ Wenig ○ Eher wenig ○ Eher viel ○ Viel ○ Sehr viel

Wieviel strategische Hilfe haben Sie gegeben?

○ Sehr wenig ○ Wenig ○ Eher wenig ○ Eher viel ○ Viel ○ Sehr viel

Weiter

Selbstständigkeitserklärung

Hiermit erkläre ich, dass ich die eingereichte Doktorarbeit eigenständig, d.h. insbesondere selbständig und ohne Hilfe einer kommerziellen Promotionsberatung angefertigt und keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe.

Würzburg, 18.12.2020

Nicolai Pöhner