PERSPECTIVE

Action Research in Science Education: A twenty-year personal perspective

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Educational action research covers a broad range of strategies and methods to innovate the practice of education by a cyclical approach of implementing change and researching its effects for further improvement. By being a pragmatic and emancipatory approach, action research is done by or with teachers to meet their needs and problems in practice, and to contribute to their empowerment and continuing professional development. This paper opens up some perspectives on operating action research in domain-specific educational fields with a special focus on science education. It is based in personal experiences by the author from almost 20 years of applying action research in chemistry and science education.[1]

Models of action research in domain-specific science education research

Action research (AR) is a strategy connecting research and practice by making teachers to classroom researchers. It is suggested as one of the most promising strategies for classroom innovation, teacher continuing professional development, and lifelong learning, both by educational policy (European Commission, 2013; 2015; UNESCO, w.y.) and educational research in science education (Laudonia, Mamlok-Naaman, Abels & Eilks, 2018; Mamlok-Naaman, Eilks, Bodner & Hofstein, 2018).

A whole set of strategies has been suggested over time for how to do AR within science education (e.g. Burmeister & Eilks, 2013; Gilbert & Newberry, 2004; Mamlok-Naaman, Navon, Carmeli, & Hofstein, 2005; Marks & Eilks, 2010; Obaya, 2003; Scott & Driver, 1998; Towns, Kreke & Fields, 2000). A recent review by Laudonia et al. (2018) analyzed the different approaches to AR in science education. Their review identified that AR in science education mainly started from the

1990s onwards, when many examples of AR became recorded in the science education literature (e.g. Bencze & Hodson, 1999; Feldman, 1996; Parke & Coble, 1997). In their review, Laudonia et al. (2018) stated that the "various interpretations used when carrying out AR projects in science education are considerable". The same was suggested for the number of methodological approaches used. Concerning the fields of AR in science education Laudonia et al. (2018) identified three major areas: (1) AR for improving the curriculum and the pedagogy, (2) AR to inquire into students' cognition, and (3) AR for teachers' professional development. In all of the interpretations and fields of AR in science education there are, however, some joint features.

AR in science education is generally suggested as an inquiry done by or involving science teachers into their work by researching their classrooms. This is operated by a cyclical process of planning, action, observation, and reflection. The goals of any AR do not only encompass the generation of new knowledge, but rather they intend both to improve classroom practices based on evidence and to contribute to teachers' continuing professional development (Feldman, 1996; Feldman & Minstrel, 2000). Aside from the improvement of practice and continuing professional development, Eilks and Ralle (2002) suggested that AR should nevertheless seek to answer more general questions of educational practices and it should identify and validate strategies for educational innovation, which can be broadly applied.

The range of AR strategies in science education is broad. Eilks in 2014 described a range from:

- Initiatives for teacher in-service professional development based in educating them to operate individual, teacher-centred AR done within their own individual teaching practices (Mamlok-Naaman et al., 2004), via
- Intra- and inter-school AR networks focusing joint curriculum development without or with support of academic researchers (Gilbert & Newberry, 2004), toward
- AR networks involving teachers working in mutual and sustained cooperation with academic educational researchers (Eilks, 2014).

AR in science education ranges both from individualized to collaborative undertakings, but also from more teacher- to more research-centred starting points. This is the reason that already in the 1980s it was suggested to differentiate AR by the role the teachers play. Eilks (2014) and Laudonia et al. (2018), based on Grundy (1982) and Carr and Kemmis (1986), suggest to use a distinction of basically three modes of AR: technical, practical, and emancipatory (Table 1). These modes acknowledge the degree of teacher involvement and responsibility based in the questions of who makes decisions with regard to the content and methodology: the teachers or any external, accompanying persons. The corresponding range can be characterized as being facilitator-centred, interactive/collaborative, or teacher-centred. In the facilitator-centred approach, an external person is the driving force of the research, and teachers support the research by offering

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specific model in practice. In T. Stern, F. Rauch, A. Schuster & A. Townsend (eds.), *Action research, innovation and change* (pp. 156-176). London: Routledge 2014.

a field of practice, conduct the teaching, and provide data and feedback. In the interactive/collaborative mode, teachers and external persons jointly conduct the innovation and research process. In the teacher-centred approach, action is taken to enable the teachers to become self-standing, autonomous researchers in their field of practice. In the ideal of emancipatory AR, any external person only acts as a supporter of the research conducted by the teacher (Table 1).

Table 1. Potential characteristics of different modes of AR (adopted from Laudonia et al., 2018; based on Grundy, 1982)

	Technical (facilitator-centered) action research	Practical (interactive, collaborative, participatory) action research	Emancipatory (teacher-centered) action research
Research interest	Initiated from outside the classroom	Jointly negotiated by the teacher(s) and external expert(s)	Initiated by the teacher
Classroom action	Operated by the teacher(s)	Operated by the teacher(s)	Operated by the teacher
Data collection and evaluation	Mostly done by external accompanying facilitator(s)	Done either by the external person(s), teacher(s), or jointly together	Operated by the teacher
Implications for action	Suggested by an external facilitator	Jointly negotiated by the teacher(s) and external expert(s)	Decided by the teacher

Each of the three basic modes has its own benefits, strengths, but also weaknesses. On the one hand, emancipatory AR seem to be the most promising approach for empowering teachers to finally solve problems in their professional practice on their own. It has huge potential for helping teachers reduce deficits or enhance strengths in their practices and for contributing to their continuing professional development. It has, however, the biggest problems in sustained implementation and dissemination of findings (Mamlok-Naaman & Eilks, 2012). On the other hand, interactive AR might be most appropriate for developing innovations aiming at wide dissemination, e.g. altered curricula and new pedagogies (Eilks & Ralle, 2002, Eilks, 2014). If it is long-term, it has, however, limitations in the range of practice that can be involved (Mamlok-Naaman & Eilks, 2012). The third interpretation is technical AR. Here it must be stated that the question must be allowed to what extent this should be considered AR if the teachers' role is merely restricted to being just a supporter of external research. From my understanding, the teacher's role in AR should never become restricted to a purely technical form of support. If this were to become the case, it is suggested that one of the essential goals of AR, which is the empowerment of teachers, would be pushed so far into the background that the emancipatory expectations on AR by its relatedness to critical theory (Kemmis, 1993) might no longer be achievable.

The above discussed classification of AR modes was originally suggested as a structural model for differentiating types of AR by Grundy (1982):

> *"The differences in the relationship between the participants and the source and scope of the guiding 'idea' can be traced to the question of power. In technical action research it is the 'idea' which is the source of power for action and since the 'idea' often resides with the facilitator, it is the facilitator who controls power in the project. In practical action research the power is shared between groups of equal participants, but the emphasis is upon individual power of action. Power in emancipatory action research resides wholly within the group, not with the facilitator and not with individuals within the group."*

Or, with a view on the interest in AR, Elliot (2005, p. 365) discussed this typology as:

> *"Technical action research serves the interests of exercising greater control over human behaviour to produce the desired outcomes; practical action research serves the interests of practical wisdom in discerning the right course of action in particular circumstances; critical action research serves the interests of emancipating people from oppression."*

It was, however, already stated by Grundy (1982) that change between the different modes might occur: "It is often the change in power relationships within a group that causes a shift from one mode to another." Such a change was described by Eilks and Markic (2012) for a group of chemistry teachers who moved from technical, via interactive, toward emancipatory AR (see also Eilks, 2014; Mamlok-Naaman & Eilks, 2012). This case will be discussed later in this paper.

Generally, we have seen that there are many different interpretations of AR used in science education (Laudonia et al., 2018). Differentiation can be made by the role of the teachers, the focus and aims of the research, or the understanding of how AR should contribute to teacher continuing professional development and empowerment. In science education, this is all subject to the general motivation and justification of why to invest in AR. The next section will provide such a justification before a concrete model for AR in science education is elaborated in its nature and how it is operated in practice for now almost 20 years (Eilks, 2014).

A justification of AR in science education

In 2000, De Jong gave an account on the lack of interaction between the fields of science education research, curriculum development, and teaching practice as one of the major systemic failures in science education. This was one of the starting points that Eilks and Ralle (2002) suggested as a re-consideration of the different fields of the practice of science education research and development. They suggested to view both of these fields as science education research if methodologies are applied to make it evidence-based, also in curriculum development. Eilks and Ralle suggested that the different areas of traditional, formal research and evidence-based curriculum development could be understood as two academic orientations within science education research, namely to understand empirical research on learning processes and

curriculum development, and as pure and applied research in science education respectively. Based on De Jong (2000) and others, Eilks and Ralle (2002) further discussed that although both fields generally should be always related to one another, they are generally often separated because of the different foci, objectives and the research methods used in each field. It might be even that in the different communities of pure and applied researchers in science education different styles of thought are used, leading to different "thought collectives" in respect of the theory of Ludwik Fleck, meaning people sharing and believing in the same theories, knowledge and views on it, having a different view than other professions (Stuckey, Heering, Mamlok-Naaman, Hofstein & Eilks, 2013).

Already Huberman, in 1993, described the hindering effect of what he called the "two-communities problem", namely the low interaction of science education researchers and practitioners. He then identified the problem as one of the most obvious issues in education. He suggested that it is caused by a difference in norms, rewards, working arrangements, or styles of thought (see above). Critics would often mention that this problem of two more-or-less independent communities exists. In domain-specific educational domains, like science education, it might however even be a three-communities problem of pure science education researchers, curriculum developers, and classroom practitioners. Literature over the years has repeatedly stated that pure empirical research in science education frequently ignored the real needs of the practitioners and did not sufficiently communicate its findings to educators "in the trenches". On the other hand, curriculum developers failed to thoroughly take into account relevant research evidence on teaching and learning when designing and changing the science curriculum and its related pedagogy. Teachers sometimes ignored both (e.g. De Jong 2000; Costa, Marquez, & Kempa, 2000; Taber 2001; Eilks & Ralle, 2002).

Aside the pure science education researchers and the applied science education curriculum developers, there are at least two more important stakeholder groups in science education: science teachers and their students. It has already been extensively discussed that there is too little interaction between teachers and the educational research community (Huberman, 1993), whether it is educational research in general, or science education in particular. One reason might be that teachers generally are not well educated in educational research methods and they were neither trained to conduct empirical research nor evidence-based curriculum development. The teachers' major concern is teaching, and to cope with everyday classroom practices in a practical, effective way. Although several approaches are suggested in the literature for combining teaching practice and teachers' continuing professional development with self-reflection and research (e.g. Feldman, 1996; Mamlok-Naaman et al., 2018; Putnam & Borko, 2000), effective interaction between research and everyday practitioners is more the exception than the rule.

The two- or more-communities problems exist in many educational domains (Wilson & Berne, 1999). The only way to bridge the gap between educational research and classroom practice was suggested by Huberman (1993) as establishing sustained interaction. He suggested installing 'multiple exchanges between researchers and potential "users" of that research at different phases of the study' (Huberman, 1993, p.4). He continues that convergences are needed between the scope of educational research and the needs and interests of practice to make the research relevant to practice. These convergences include involving teachers in the target practice to become part of the research and to help to undertake it. As already discussed above, Eilks (2014) suggested to expand Huberman's discussion of the two-communities-problem to take into account the interests and contributions of all the four potentially relevant groups when it comes to structuring and innovating science education, namely educational researchers, curriculum developers, teachers, and their students (Eilks, Markic & Witteck, 2010). An inclusive approach integrating perspectives from all the four groups is needed. It would take into consideration that both empirically validated research results and formally developed curricula on the one hand, along with teachers' knowledge and experiences or students' perspectives on the other, provide a spectrum of knowledge about teaching and learning with both ends having their own relevance and value (McIntyre, 2005).

When firstly presenting their approach of using participatory action research (PAR) in science education, Eilks and Ralle in 2002 suggested a model for research and curriculum development facilitated by external science education researchers under the active participation of teachers. This view acknowledges that teachers are the key for any sustainable implementation of innovations and reforms in class (Anderson & Helms, 2001; Hattie, 2008) and that taking their beliefs, prior knowledge and attitudes seriously into account is a necessary precondition for any success in classroom innovation (Haney, Czerniak & Lumpe, 1996; Nespor, 1987). A collaborative approach was suggested having highest potential for relevant and feasible outcomes concerning both improvements in classroom practice and generation of knowledge of practical interest. A combined research and development model was suggested based in the philosophy of AR, integrating an exchange of information from the different research- and practice-based sources between teachers and academic researchers. The exchange was suggested to also include how to make any research results or practical suggestions available for broad practical use to solve implementation and dissemination issues frequently associated with AR.

A model of AR specifically dedicated to science education

In 2002, Eilks and Ralle suggested a specific model for participatory action research (PAR), specifically dedicated to research in chemistry and science education. The model was justified by the ideas discussed in the previous sections and originally inspired by an interpretation of PAR in the field of economics (Whyte, Greenwood & Lazes, 1989). The PAR model outlined by Eilks and Ralle provides a framework for practice-oriented research in science education with the aim of leading to results that are broadly applicable. It aims at both generating empirical research findings obtained from research within authentic classroom practice as well as the development of innovative, evidence-based curricula, pedagogies, and teaching materials (Figure 1).

The PAR model defines five areas of objectives of practice-oriented research in science education: (I) new concepts and materials for teaching, (II) knowledge about teaching and learning, (III) developed practice, (IV) trained teachers, and (V) documentation of teaching practice (Figure 1).
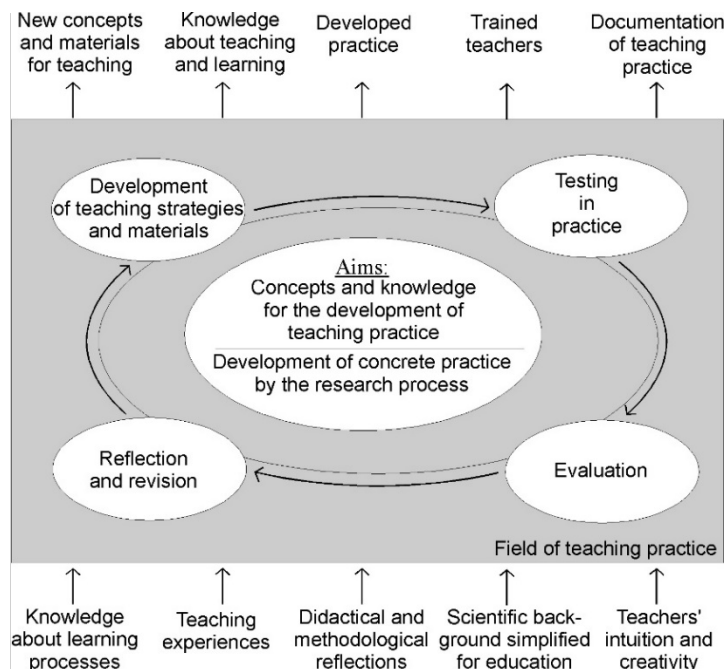
Figure 1. *The PAR model for science education by Eilks and Ralle (2002)*

Eilks and Ralle (2002) suggested that any starting point for PAR initiatives in science education should stem from both teachers' acknowledgment of any problems in teaching or from empirical research suggesting deficits in science education practice. A specific feature of the model is that it suggests to analyse the literature for the purpose of contrasting it in focus group discussions between researchers and teachers, to decide whether findings from research are considered being authentic and relevant in the foreground of the teachers' experiences. This discussion was suggested to allow both parties to decide whether, or not, any given problem is sufficiently relevant and important for both parties to invest into it. It is also suggested to allow the group of teachers and external researchers to reflect upon the role and power of evidence from the literature for offering helpful solutions taking the specific educational settings in which the teachers work into account. Additionally, background information gathered from science and explicitly discussed classroom experiences in the literature, plus the intuition and creativity of teachers alike, were outlined as important sources for the AR process (Figure 1).

Based on the analysis of any given problem, the group jointly designs new teaching approaches. The designs are tested, evaluated, and reflected/revised upon with the overarching aim of improving teaching practices in the classrooms operated by the teachers. Initial designs are suggested to be tested as early as possible in order to get an estimation whether they have potential

to solve the problem identified in the AR group. Early testing leads into a cyclical process of development which hopefully improves practice step-by-step (Figure 1).

In order to achieve quality and reliability, each of the cycles should be evaluated and jointly reflected upon. The new teaching scenarios are, however, developed within authentic practice using cycles of change, testing, and improvement. Bodner, Mac Isaac and Whyte (1999) suggest for this kind of research that traditional evaluation strategies are inappropriate, as they merely apply a positivistic and quantitative understanding of research. In authentic practice, there are too many influencing factors present and both the researchers and practitioners are personally involved. Evaluation strategies should thus be chosen which apply both a qualitative and interpretative approach based in constructivist and critical research paradigms. Criteria for corresponding kinds of interpretative research, that can be applied to AR, were identified by Altheide and Johnson (1994), namely plausibility, credibility, relevance, and importance. It is suggested that the evaluation should take the perspectives of all of the persons involved into consideration (teachers, students, and researchers). The validity of the interpretations can be tested and/or confirmed by triangulation and communicative validation of the findings within the researcher-practitioner group or with students. Figure 2 provides exemplary views that might be taken into consideration during the evaluation process.
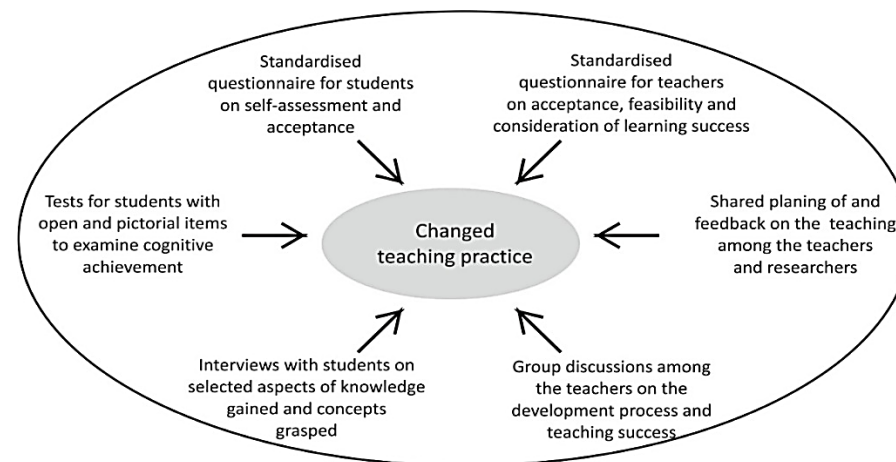

Figure 2. *Potential perspectives during evaluation (Eilks & Ralle, 2002)*

Defining and reflecting upon the roles of teachers and accompanying persons is an important issue in AR. Altrichter and Gstettner (1993) described the risk that external researchers in AR might dominate the team. This fear can be based on the widely-held beliefs that theoretical knowledge is superior to practical experience. Additionally, the implicitly hierarchical relationship between schools and universities can be a reason. Awareness of the differences in roles is needed to allow the entire group to learn and to increase awareness of the relative values of theory and

practice. It also helps to identify the different viewpoints existing between teachers and science educators, to help breaking down barriers between research and practice (Noffke 1994).

PAR as designed for science education in the model by Eilks and Ralle (2002) is a collaborative process between teachers and academic science education researchers. Teachers and researchers plan together the design, implementation, and evaluation of new teaching approaches. The group process is vital, because it ensures the emerging designs are compatible with the needs of practices, while at the same time taking all available evidence from the research side into account. As a matter of principle in critical research, the teachers are respected partners in the research and development process. They are asked to contribute equally to all of the decisions to be made. Although both groups should be considered equally important, Eilks and Ralle (2002) suggest to reflect their different roles to play (Table 2).

Table 2. Key aspects in the roles of practitioners and researchers (adopted from Eilks & Ralle, 2002)

Teacher researcher	External researcher
• Initiation of AR motivated by experience	• Initiation of AR motivated by prior research
	• Co-ordination and support of the teacher research
• Analysis of the literature in comparison to classroom experience	• Providing relevant literature and information access
• Structuring new strategies and concepts	
• Application of new strategies and concepts	• Providing access to already existing strategies and concepts
• Data collection	
	• Support in keeping ethical measures and standards of research data handling
• Evaluation of data	• Methodological training and support in evaluation of data
• Joint reflection and negotiating of further change	• Joint reflection and negotiating of further change
	• Support in dissemination and publication of the AR findings

It has also proven valuable to think of the AR process in terms of three phases of development suggested by Stang (1982). In the first phase of AR cycles, provisional concepts are developed and then pre-tested in single groups in order to decide whether the designed interventions have potential to solve the problem in focus and to improve practice. If the first teachers operating the design report sufficient indicators of success, then the development continues with phase 2. In further cycles, more practitioners start to implement the new designs for parallel testing in different learning groups operated by different teachers. This phase focuses on checking for

feasibility in different classrooms, to avoid artefacts caused by the unique conditions in one class, with one teacher, or in one school. Phase 2 finishes the moment the group decides that the changes developed are sufficiently elaborated for overcoming the jointly defined aims. Phase 3 is the phase of dissemination, in which the developed approaches, strategies and materials are presented to other teachers. Phase 3 is useful for checking whether the strategies are sufficiently documented to be used by teachers who have not been part of the AR process. Each phase can consist of several cycles of development, testing, evaluation and reflection (Eilks & Ralle, 2002; Figure 3).
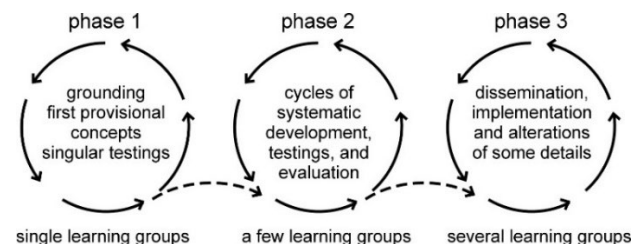

Figure 3. Three potential phases of PAR in science education (Eilks & Ralle, 2002; based upon Stang, 1982)

The PAR model for science education as described here is currently in use for almost twenty years in various research projects. Foci of research and development have included a new curriculum to teach the particulate nature of matter, implementation of cooperative learning into chemistry education, interdisciplinary and societal-oriented science education, usage of modern information and communication technologies (ICT) in science teaching, or education for sustainable development in formal and non-formal education. Detailed descriptions of and reflections on how this model is practically employed are shown by different examples in Marks and Eilks (2010) and Eilks and Feierabend (2013). Just recently, Laudonia and Eilks (2018) described a case on how this model can be used even if there is no support from academic science education available on the sight of a school and no corresponding AR network possible because of unique educational conditions. The case describes the AR of a teacher in southern Switzerland that was supported by a science educator from northern Germany and an experienced AR network in western Germany. The focus was finding the right degree of student-centeredness in teaching chemical bonding with the support of modern ICT. The authors describe that even a remote support inspired by this AR model, operated by synchronous and asynchronous communication (email, DropBox and Skype), was helpful for the process of curriculum change and the professional development of the teacher.

The model described here also became re-interpreted as a strategy for innovations in higher education, namely in establishing and developing courses in science teacher education. In 2013, Burmeister and Eilks (2013b) reported the development of a teacher education module in German pre-service chemistry teacher education on the topic of education for sustainable development in chemistry teaching. The development started with empirical studies about the

knowledge base of chemistry student teachers, teacher trainees, and in-service teachers (Burmeister & Eilks, 2013a; Burmeister, Schmidt-Jacob, & Eilks, 2013). The studies revealed very positive attitudes among the participants towards teaching and learning about sustainability issues and green chemistry in chemistry education. It also showed, however, that both the prospective teachers and experienced teachers were not able to outline any contemporary concepts and theoretical models, neither of sustainability nor of green chemistry. They also lacked knowledge about how to implement education for sustainable development in general and in chemistry classes in particular. To overcome these shortcomings, a course module was developed using a methodology inspired by the PAR model described above. Also in this case PAR model was used to cyclically develop and optimize teaching practices based on research evidence. PAR was conducted in a cooperative process just among two persons. It was done in cooperation of a practitioner accompanied by a researcher and Burmeister and Eilks (2013b) described changes in the roles and perspectives of the persons involved. Nevertheless, they suggested that this approach still offers the chance to combine internal and external viewpoints regarding practice, which is where innovation is actually thought to take place. In this specific case, four cycles of development in four consecutive academic years were described from 2009 to 2012. Each cycle was evaluated using student feedback, classroom observations, group discussions, and student feedback questionnaires. All together, fifty-eight students participated in the four cycles of development. The evaluation and feedback was used for cyclical optimization of the course, including insights into its feasibility and effects. The structure of the final course design encompasses six 90-minute sessions. It included innovative content and pedagogies, like jigsaw classroom learning, a WebQuest, and game-based education. The participants' responses were increasingly positive to the course. They considered the course as interesting, important, and valuable for later acting as chemistry teachers. They emphasized that they had learned a lot and that they felt more competent in respect to sustainability and ESD after the course. Criticism was rare in the feedback and occurred only briefly in the questionnaires and the group discussions. The criticism even diminished because of improvements in the course structure and materials from the first to fourth application. Later, many elements of the course became also used for in-service chemistry teacher professional development workshops. A similar experience was later described by Krause and Eilks (2018) for updating and innovating a pre-service teacher education course on using modern information and communication technologies in chemistry education.

An illustrative long-term PAR case from chemistry education

From 1999 to 2004, a group of ten chemistry teachers used the PAR model described above to operate the project "New ways towards the particulate nature of matter" (Eilks & Moellering, 2001; Eilks, 2014). The project focused on redesigning essential steps in teaching and learning about the sub-microscopic explanations of matter and chemical reactions, relevant for the lower secondary school chemistry curriculum. The objects of the project were derived from both teachers' prior experiences with specific student difficulties when learning about the particulate nature of matter and the many reports in the literature about students' misconceptions and learning obstacles in this field.

In focus group discussions, teachers' experiences were related to available research findings, particularly those studies dealing with student misconceptions and learning problems stemming from relating macroscopic properties and phenomena to sub-microscopic explanations (Johnstone, 1991). Teachers concerns dealt with questions of models and modelling in science education, students' learning difficulties, and dissatisfaction with the traditional curriculum approach to teach the particulate nature of matter as a sequence of models from the history of science. All this discussion is mirrored by corresponding studies in the science education literature. On this basis, both the teachers and the accompanying chemistry education researcher acknowledged the topic as a relevant field to invest time in, both concerning change in practice and evidence-based curriculum innovation. One example of students' often-reported difficulties with the explanation at the sub-microscopic level might illustrate what happened in this AR project.

One of the most basic concepts covered in introductory secondary level chemistry teaching is the introduction of a first concept of chemical reactions. Corresponding lessons focus on explanations of phenomenological observations of chemical change by sub-microscopic explanations using the concepts of particles and atoms. The teachers reported how difficult it was to them to provide a concise and clear initial definition of the chemical reaction and comprehensively connecting the phenomenological and particle levels was always a problem to most students. Science education research revealed a lot of support for the teachers' observations and enriched the discussion by further views. One teacher in the PAR group, together with the accompanying researcher, volunteered to take the lead in refining this critical stage of the curriculum.

One part on the new design of the teachers was based in a clearer differentiation between chemical reactions (like combustion) and purely physical changes (such as dissolution or changes in the states of matter) (Eilks, Leerhoff & Moellering, 2002; Eilks et al., 2007). The discussion of the teachers about the new initial design was connected to the literature review provided by the external research but also an in-depth analysis of the school textbooks available on the market. From the textbook analysis, it became apparent that teaching about the levels of discrete particles and the level of atoms was quite often mixed together, thereby leading to inconsistencies when students were developing their personal sub-microscopic mental models of chemical reactions. Formal research inspired by the focus of this AR confirmed the presence of such inconsistencies in the cognitive patterns even of many teachers (Bindernagel & Eilks, 2009; Eilks, 2013). The corresponding new approach led to a better separation of chemical reactions from physical changes, and also to better differentiating the levels of particles and atoms. This change in teaching was accompanied by more thoroughly focusing the learning on the level of discrete particles (especially molecules), instead of starting with atoms and lattice structures, which was the approach suggested by most school textbooks at the time. The teachers tried to operate a clear and explicitly differentiated approach to learning about both levels during the lessons.

This is only an example, and many ideas like this were elaborated upon with the AR group. After the content matter had been refined, the AR group also started developing teaching materials for this lesson plan. The development was carried out in monthly meetings of the practitioner-

researcher group. The sessions were prepared and led by the teacher who had volunteered to take lead in this enterprise. Support was given by the accompanying science education researcher, who worked as a facilitator for the group by providing information from research literature and helping in the selection of appropriate research tools. Between the meetings, experiments were identified and tested, worksheets were designed, and a multimedia-based learning environment was developed to provide explanations, experiment videos, and animations of the particle level. Each of these tools was discussed during the monthly meetings of the group, then initially tested and revised based on the teacher feedback.

In the meetings, the teachers expressed their view that the materials showed promise for improving their chemistry teaching and students' learning. All of the single ideas were therefore implemented in class in order to see its effects and to reflect upon the unit's feasibility, as well as student perceptions of the teaching approach. Evaluation was based on further oral and written feedback given by the teachers involved, as well as data gathered with the help of a student questionnaire. The questionnaires were applied to give learners a voice in the structuring and reform of the lesson plans. The end results showed that the final module was viewed as feasible and motivating by both the teachers and their students.

In order to evaluate the learning gains, the lead teacher in the group collected additional data. A written test and student drawings were employed to discover whether the pupils had successfully learned the new concept or not. More in-depth analysis of the development in learners' conceptual understanding was achieved by operating content-focused, semi-structured interviews with pupils, including both high- and low-achieving students. The interviews were analysed by qualitative content analysis and provided deeper insights into students' knowledge level and personal concepts after the altered lesson plan had been applied (Eilks et al., 2007).

The findings from the classroom testing suggest that the new teaching strategy made improvements with regard to the learners' understanding of sub-microscopic level explanations. The evaluation also brought some remaining learning difficulties to light, however, the study revealed that these were found primarily at the phenomenological level. This had not been expected by the teachers. One example of this concerned the decomposition of sugar. This chemical reaction had purposely been selected as the initial approach towards chemical reactions because it is only based in one initial substance. Most of the students, however, considered at the end of the unit chemical reactions to always follow the pattern of two initial substances, A and B, reacting to yield one product, C. Corresponding findings led to further improvements in the learning materials. In the end, the group developed a full curriculum approach on how to deal with the particulate nature of matter in lower secondary chemistry education. The approach got rid of all historical ballast in the lessons and provides now a coherent conceptual structure (Eilks, 2013). This approach led to several publications in science teacher journals and teaching materials collections. It was implemented by the educational researcher together with parts of the group into textbooks (Eilks et al., 2005) and became later copied in other secondary school chemistry textbooks issued by different publishers in Germany.

After their personal experience while participating in this AR project, the teachers began suggesting that conventionally-developed curricula are all too often products of the highly theoretical "green table" of academic science education or within the educational publishing offices. The teachers mentioned that such curricula unfortunately tend to focus on "the peripheral instead of the core problems of teaching practice". The teachers pointed out the necessity of a "systemic approach" in science education research, if such research really wants to improve classroom practices. In their opinion, such a process needs to integrate "cooperative work, a cyclical developmental procedure instead of conventional in-service training courses and publications". The teachers considered the AR as described in this example to represent a chance to "connect input from teachers with input from domain-specific educational research", but they also considered the process as a chance to bring "practical experience to the researcher".

A view on teachers' professional growth in long-term PAR

The AR described in the case above involved self-reflection exercises from time to time. Not just the curriculum materials and research outcomes, but also the process of AR was reflected upon and critiqued. This study was carried out by the accompanying researcher with the aim of finding out the viewpoints of the participants on the implementation and effects of the AR on the teachers' professional growth.

A corresponding long-term study took place in the PAR group which at the time had been working together for roughly seven years (to date about 20 years). At least once a year in a focus group discussion, the teachers were asked to reflect upon their personal perceptions of the project, including their opinions as to their own role within the AR process. The discussions regularly lasted 45-60 minutes and were audiotaped and analyzed by qualitative content analysis. The initial results were published in Eilks (2003); concise reports and reflections are given in Eilks and Markic (2011), Mamlok-Naaman and Eilks (2012), and Eilks (2014).

During the initial year of participatory action research, the teachers described themselves to have been very hesitant to express any opinions about the AR process. They were quite unsure about the goals of such cooperative curriculum development and research. Their original perspective when entering the project was being 'consumers of new teaching approaches', which had already been designed in advance by 'science education experts'. The teachers' personal and active engagement in the group required about a year to develop. In this time it was, however, still tied to continuing uncertainty about the sufficient trustworthiness of the newly-developed curricular and methodological approaches. The teachers were also uncertain about their own ability to confidently and practicably apply them. They viewed their own potential contribution mainly in terms of trying out new teaching strategies developed by others and contributing to checking any developments proposed by the university researchers to see if they really were applicable in practice. This path chosen by them in the beginning was perceived as 'normal and commonsensical' if one wished to actively bring oneself into the project. Preliminary signs of recognition existed among only a tiny minority of the group members. These few teachers had begun to realize that all the developments were supposed to develop through a common process of negotiation. These teachers started to understand that their contribution based on experiences

and personal intuition was valued an essential factor for bettering the quality and feasibility of the project outcomes. Nevertheless, all of the teachers expressed the view that the newly developed approaches were better than the old ones. They clearly expressed a view that cooperation between practitioners and researchers is beneficial: 'What I really liked was that we were getting input from teachers who stand in the classroom every day on the one side and from science education research, from the researchers, on the other. I have my copies of science education journals at home and leaf through them when I have time, but quite honestly I lack the time to translate them into teaching concepts. [The researchers] can really look at what is happening overall with methodology in Germany as a whole.' The indicators initially observed became increasingly visible, even without explicitly crediting them to the teachers' growing professional expertise. The teachers expressed the view that they now started to evaluate any contributions found in teachers' journals 'with a different eye.' They stated that they had begun to see newly-proposed teaching strategies in teacher journals with a more reflective view, whether they had been connected to any kind of research input or evidential reports. An emerging attitude of 'personal ownership' as directly affected shareholders also became evident. One idea, repeatedly mentioned in the thoughts of the teachers, centered around the collaboration among the group members: 'speaking with the others … and getting ideas … automatically raises the level of professionalism' and 'although the meetings were extra appointments, I always found it very helpful and interesting to exchange ideas with my colleagues'.

From the second year, the focus of the group discussions started to change. The teachers decided to focus more on the meaning of the AR for them, instead of discussing the pros and cons of the altered teaching approaches or comparing their project to traditional forms of curriculum reform and professional development. The teachers described a clear increase concerning their own activity level inside the project. This was related to the issue of having started the second trial run of the changed approaches. Notions like 'Now I know what I should have done differently last year' were typical of this change in the teachers' mindsets. The teachers also expressed acknowledgment that long-term participation in the PAR process had led to increasing openness inside the AR group. The teachers felt a tendency of self-confidently and actively bringing their personal criticisms and ideas into play. They recognized that their skills set had increased in competently reflecting upon their own teaching. They became more able to effectively exchanging ideas: 'You see everything more self-critically and examine your own teaching much more closely than you did beforehand'. The teachers explicitly mentioned themselves as becoming 'more strongly self-reflective and more self-critical when compared to our previous, personal teaching practices. You examine many things more intensively, textbooks for example.' The growth in reflective skills went hand-in-hand with developments in feeling ownership of the newly developed teaching approaches. The new strategies were viewed as personal concepts belonging to the individual teachers and the group. This development was described as moving 'from a teacher who initially wanted to be trained, into a colleague and convinced defender of the new concept' or as 'from being a consumer in a group to an activist'. The teachers, nevertheless, compared again the strategy of the project with traditional forms of curriculum reform. This aspect came into play when teachers started describing problems when attempting to pass on newly-developed knowledge to their colleagues at school. A 'fog of disinterest' was one

description of their experience concerning their colleagues' mindset. A change in the participants' ability to teach differently was also mentioned. The teachers described further changes in their own practice with a focus on 'a totally different view towards methodological variety'. The major reason was described by the interpersonal exchanges within the project, the newly-formed contact with science education research, and growing comparisons of these realizations with their own beliefs and experiences.

After the second year of PAR, individual teachers from the group began their own initiatives. The initiatives by the teachers included activities such as establishing in-service training courses together with the accompanying academic researcher, either in their own schools or in the local area. The teachers started attempts to transfer "their" teaching approaches and pedagogies to further topics and/or subject areas. Some of the group members started developing their own initiatives using the full group's potential. All teachers actively introduced ideas and materials into the group and took over part of the group leadership in certain phases. The discussions within the group started showing higher levels of self-confidence and self-efficacy in the teachers. A trend towards becoming leaders of educational change and an ability to initiate changes with increasing independence from the accompanying science educator seemed to take place. The teachers describe this as a 'change of roles'. Nevertheless, the quality of academic support and the wide-ranging possibilities offered by university collaboration were still considered as being integral and necessary.

In the fourth and fifth year, the teachers started intensively discussing the question of dissemination. Strategies were put into question of how to convince colleagues of the necessity of change and effectiveness of the newly developed strategies from the project. The teachers also expressed a wish for 'many, many more networks in this form'. A discussion from the first year about the question of whether the new ideas fit into the governmental syllabus or not now shifted. The shareholder role of the players in the educational arena was called into question. The growing distance towards teacher journal and textbook authors was now also expanded to educational authorities in general. The teachers expressed increasing disdain for the traditionalist approach of copy-and-pasting old syllabi into new ones. They started criticizing the fact that every textbook seemed to appear to be 'a compromise at the lowest common denominator.' The teachers demanded governmental regulations for teachers 'allowing for more openness and innovation'. They described a need to be more and more free to stretch regulations set up either by governmental authorities or within their schools, when actively implementing student-oriented, student-active science teaching. The teachers also described reflections of having gained a broader knowledge, e.g., knowledge about students' alternative conceptions. They felt they had become more sensitive to the reasons for students' mistakes and in analyzing textbook materials. The teachers described having learned a lot of new student-centered learning methods and having gained experience in applying them. Thus, they described having started to transfer them to applications on new topics on their own. They also described that their views on the curriculum orientation have changed towards more societal-oriented science education even beyond the topics handled in the AR group. During this change, some of the teachers enthusiastically accepted the university educator's invitation to become members of a team of school textbook

authors, which offered the chance to implement and disseminate the team's work and ideas to a broad audience.

From the fourth and fifth year onwards, a clearly recognizable saturation of the changes in the teachers' attitudes was identified in the data. From year six, the focus of the focus group discussions almost exclusively dealt with questions about potential topics for future cooperation.

The model of PAR in science education described above (Figure 1) was originally conceived as a model of practical, interactive AR (Table 1). A reflection on the teachers' professional growth in the case described here led to a reinterpretation of this assumption (Eilks & Markic, 2012). In fact, the first twelve months of the project more closely resembled technical AR, despite intensive levels of cooperation within the group. It might be that the research interest of the accompanying science educator to establish the group and to start the project on the particulate nature of matter, especially at the beginning of the project, led to this situation. Taking a slower approach at the start might, however, may have confused the clarity of the goals of the cooperation and the project, or even might have had negatively impacted the motivation of the teachers with their expressed expectations. Working in the project during the second and third years became increasingly interactive and participatory. The teachers continued working under the guidance of the accompanying university researcher, while simultaneously stepping into the expanded role envisioned for them. A sense of self-efficacy and ownership began to grow among the teachers. The systematic build-up of developed and equally important roles became increasingly noticeable during this time. This helped the group in dismantling obstacles and hierarchical attitudes, which had existed between the participants and the accompanying academic researcher. Clear signs emerged that the teacher participation during this switch to a practical and participatory mode of AR increased. Initial indicators of emancipation also became visible, at least with regard to authorities outside the group. This concerned, i.e. teacher journal and textbook authors. Anyhow, the participants still expressed wish to be able to rely on the guidance available through the external expertise of the academic science educator.

This consideration started to change from the third year onwards. The process of emancipation started to become more important and intense. It included taking a more critical stance to the opinions and practices of external authorities, like curriculum authorities. The group members started to take over the role as leaders in the means of organizing teacher trainings, joining syllabus commissions, and becoming textbook authors. This process led to a re-interpretation of Grundy's modes of AR from Table 1 and changed it into a continuing professional development model for science teachers (Figure 4; see also Eilks, 2014; Eilks & Markic, 2011; Mamlok-Naaman & Eilks, 2012).
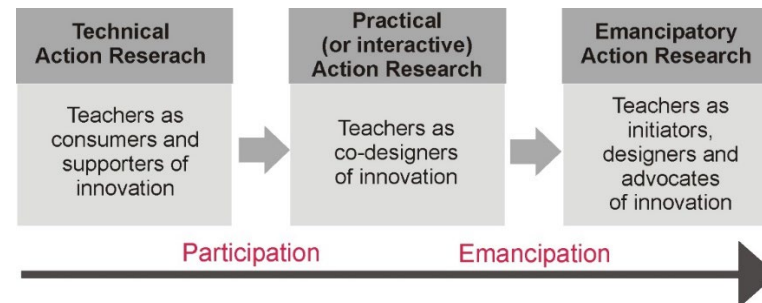

Figure 4. Potentials empowerment within PAR

Conclusion

The approach and projects discussed in this paper document the potential of AR in general and PAR as conceptualized for science education by the model of Eilks and Ralle (2002) in particular. It proved to be valuable for making substantial changes in teaching practices and in teachers' attitudes towards innovation in science education (Burmeister & Eilks, 2013b; Eilks, 2014; Eilks & Markic, 2011; Mamlok-Naaman & Eilks, 2012; Marks & Eilks, 2010).

During the described PAR experience, participants had chance to develop themselves into both the driving forces behind and the self-determined causes of change and innovation in education. The competencies for this important role in education made themselves plainly visible in the case presented above. Regardless of the fact that many of the innovations developed in corresponding PAR projects might have been initiated by the various suggestions originally stemming from any accompanying academic science educator, the switch described here from technical to emancipatory AR introduced the central elements of teacher emancipation needed to make the teachers innovators in their professional practices. The case described above can be seen as an ideal bottom-up step-model for teachers' professional development via AR, using external facilitators from educational research domains as facilitators (Mamlok-Naaman et al., 2018).

Reflecting on traditional top-down practices of curriculum reform through syllabi or textbook change, this type of innovation is normally steered by outside sources and players. In such cases, teachers frequently are very critical of the required changes and choose to distance themselves from the entire process. In many instances, these innovations never become implemented as they were intended, because the practitioners have limited access to and influence on the process and the reasons behind the proposed innovations remain unclear. Emancipation from this type of top-down regulation quite often occurs through a teacher's refusal to act or obey orders. This is different in AR.

An active understanding that in an AR project both teachers and accompanying educational researchers stand on an equal footing and merely contribute by different roles to the process of educational innovation becomes deeply ingrained in both sides of the PAR experience. The

cooperation of both partners from both domains in their chosen professions led, in the case described here, to a wish for sustained, intense contact between schools and the university that has lasted now for almost 20 years. From the teachers' point-of-view, this was rooted in the personally acknowledged understanding of the different, yet complementary, types of expertise in the researchers and practitioners (McIntyre, 2005). This understanding agrees with Huberman's (1993) call for more and sustained interaction between research and practice as a core element of effective innovation in education. It has finally became a self-chosen part of the professional life of the teachers involved in this project. The process evaluation showed that teachers had chance to change their views, to develop their pedagogical content knowledge (PCK), and improve their attitudes and self-efficacy towards innovations in science teaching and learning.

Aside from the continuing professional development of the teachers, the project proved to sustainably implement new teaching materials and pedagogies in the participating schools and beyond. The curriculum materials became part of the schools' internal curricula and profiles. The impact on non-participating schools was much harder to accomplish and to measure. There were two important indicators of change beyond the participating schools. One is a large number of invitations over the years that members from the AR network got to come to other schools to provide in-service professional development courses. The other indicator is the many requests for the newly-designed teaching materials made by other teachers during and after such in-service courses, or via email initiated by presentations of the work on teacher conferences and in teacher journals. But, in any case, this more traditional way of implementation has proven to be quite limited in intensity, and accurate measures of its effects are hard to come by.

There is, however, also the question of academic recognition since the PAR work in this case did not only involve teachers, but also academic researchers, graduate and PhD students in science education. These groups are evaluated based on academic productivity, namely publications, research grants, and awards. Over the years the work in this networks was supported with financial funding in connection with different EU-funded projects, and it also got support from both the German Federal Trust for the Environment (DBU) and the Funds of the Chemical Industry (FCI) in Germany. Part of the works were, among others, rewarded by the Award for outstanding contributions to the incorporation of sustainability into chemical education by the American Chemical Society (ACS). Finally, quite a large amount of the new curricular approaches and teaching materials were published over the years. The work led to more than 150 publications in German-language science teacher journals, dozens of published teaching materials, and many new resources in the Internet. Together with teachers from the project, the ideas became implemented via the publication of two school textbook series (Eilks et al., 2005). These textbooks are sold by the thousands all over Germany every year. And this is only one side of the medal when it comes to potential academic output. The other side concerns peer-reviewed research publications in respected international journals or books. Critics have often claimed that AR hardly leads to considerable academic output in terms of traditional measures of academic achievement. This project has proven such allegations to be false. Within the project presented above, dozens of articles have been published in peer-reviewed international science education

journals and books (e.g. Eilks, 2005; Marks & Eilks, 2010; Krause, Kienast, Witteck & Eilks, 2013; Belova & Eilks, 2015; Zowada, Gulacar & Eilks, 2018), many of them together with the participating teachers.

The project described here shows that AR has potential to positively affect both practitioners and practice. It also can contribute to the evidence-based body of knowledge in the respective academic field. This body of knowledge is documented in the academic and practice literature, in our case science education research and teacher journals, books and teaching materials collections. The conduct of AR as operated here proved itself to be able to contribute to both, the literature about curricula and teaching materials as well as to research papers. This shows that the thorough integration of the most prominent stakeholder groups in science education (researchers, curriculum developers, teachers and, indirectly, also students) can be one of the effective ways to overcome many of the deficiencies we face in science education, namely the missing connection between certain domains and stakeholder groups from within science education (De Jong, 2000; Huberman, 1993).

What remain are naturally the limitations in the reach of the model presented here (Mamlok-Naaman & Eilks, 2012). University science education groups can only utilize such intensive participation models with a limited number of teachers. The carriers of innovation in educational systems, namely school authorities and state institutes of education, must ask themselves whether such intensive supervision might be needed more since it represents one possible way to sustainably introduce changes in teaching practices or to develop leaders for educational change. This would, however, ask for corresponding recognition and support. PAR offers one option to do so, but one which shows tantalizing hints that the necessary time, money and effort invested would pay large educational dividends in the future.

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