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Designing iSTEM learning materials for secondary education

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Dissertation presented in partial fulfillment of the requirements for the degree of Doctor of Engineering Science (PhD)

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Preface

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Abstract

To deal with the complex challenges of the future, education is needed that prepares students for becoming the scientifically- and technically-literate and broadly-employable workforce the labor market is looking for. European reports emphasizes the importance of crossdisciplinary skills, such as problem solving, creativity, and critical thinking. They propagate an interdisciplinary approach towards learning that reflects reality, with inquiry- and design-based learning as a way to shape this approach. Interdisciplinarity among Science, Technology, Engineering, and Mathematics (STEM) will be established in education when the natural links between the disciplines are exposed, when the discipline-specific learning contents are addressed from a crossdisciplinary perspective, or, in other words, when the STEM disciplines are integrated. Through meaningful connections among the separate STEM curricula, integrated STEM (iSTEM) education is believed to pique students' interest for STEM subjects, and to deepen their conceptual understanding. However, this new approach towards STEM education calls for the design of new curricular materials. Research literature on instructional reform indicates that the buy-in of such materials is increased when teachers are given a voice in the decisions and the design process. The effectiveness of a reform is determined by the professional input as well as by the learning curve of the teachers themselves. This work investigates teachers' strategies and learning gains when engaging in collaborative design of iSTEM learning materials.

The aim of this work is to provide STEM teachers, teacher educators, and other stakeholders in secondary education with valuable information to give their team a kick-start into designing learning materials for high-quality iSTEM education. To this end, a 4-year case study was conducted, in which four multidisciplinary teams of STEM teachers were followed up-close in their endeavors to design such materials for subsequent implementation in their classrooms. From the observations and the outputted materials of the teams, important steps and pitfalls in their design processes were identified, as well as fruitful strategies to connect contents from different STEM disciplines. These findings were

integrated into a support model for iSTEM teacher design teams: 'CODEM for iSTEM'. After the case study, several participants were interviewed on their experiences and perception of own professional growth with respect to the co-design of iSTEM learning materials. Their reflections were compared to those of teachers who merely implemented the learning materials in the classroom.

Teachers were observed to converse on a crossdisciplinary level, formulate engaging student challenges, and manage to establish meaningful connections between the STEM disciplines in the light of these challenges. While doing so, teachers testify to have learned a lot from their colleagues in other disciplines. They value this crossfertilization as an important feature of participation in iSTEM teacher design teams. However, their attention must systematically be drawn to the desired student outcomes and strategies to attain these, as they sometimes tend to focus on creating or conducting hands-on activities with little educational value. This is due to the fact that they did not outline the desired learning outcomes in the first place. Furthermore, teachers risk resorting to a mere discipline-specific approach to the student challenge they formulated, which should be prevented from happening. CODEM for iSTEM is a support tool that comprises the important steps with guidelines and scaffolding questions, as well as quality checks to avoid the pitfalls. Accompanied by the necessary coordination, this tool is implementable in teacher education, as participation in iSTEM teacher design teams going through these steps holds promising opportunities for teacher learning. Teachers of successful iSTEM teacher design teams exhibit a high level of metacognitive thinking and an improved attitude towards problem solving. They seem to have established a strong, multidisciplinary learning community at their school, and the momentum to maintain it.

This work suggests to employ CODEM for iSTEM as leverage to lift secondary-school STEM education to high-quality integrated STEM education, as it is an inventory of knowledge and experiences gathered during 4 years of research and development. CODEM for iSTEM is an action plan that can give inspiration and direction to the design process, and can help to not overlook crucial considerations. Participation in iSTEM teacher design teams provides a powerful concept for professional development programs. CODEM for iSTEM can be used to guide such programs, if it is complemented with frequent exchange of feedback, and close follow-up by the program coordinators. It is recommended to extend its application beyond the design phase, to the implementation phase, in which the designed learning materials are reviewed based on the degree to which the student outcomes correspond with the targeted iSTEM learning goals.

Beknopte samenvatting

Om de complexe problemen van de toekomst te kunnen aanpakken, is onderwijs nodig dat leerlingen klaarstoomt om de wetenschappelijk en technisch bekwame en breed inzetbare werkkrachten te worden die de arbeidsmarkt nodig heeft. Europese rapporten benadrukken het belang van discipline-overschrijdende vaardigheden zoals probleemoplossend werken, creativiteit en kritisch denken. Ze promoten een interdisciplinaire aanpak die de werkelijkheid weerspiegelt, met onderzoeks- en ontwerpgebaseerd leren als een manier om deze aanpak vorm te geven. Interdisciplinariteit tussen wetenschappen, technologie, engineering en wiskunde (STEM) wordt verwezenlijkt in onderwijs dat de natuurlijke connecties tussen de disciplines blootlegt, dat de discipline-specifieke onderwerpen vanuit een discipline-overschrijdend perspectief benadert, kortom: dat de STEM disciplines integreert. Via betekenisvolle connecties tussen de verschillende STEM-vakken, kan geïntegreerd STEM-onderwijs (iSTEM) de interesse van leerlingen voor STEM doen oplaaien en hun inzicht in STEM-concepten versterken. Echter, zo'n nieuwe aanpak vraagt om het ontwerp van nieuwe leermiddelen. Onderzoeksliteratuur over onderwijsvernieuwing geeft aan dat het draagvlak van zulke materialen groter is wanneer leraren een stem krijgen in de beslissingen en in het ontwerpproces. De doeltreffendheid van zo'n vernieuwing wordt zowel door de expertise als door de groei in kennis en attitude van de leraren zelf bepaald. Dit werk onderzoekt de strategieën en leerwinsten van leraren wanneer ze in team deelnemen in het ontwerp van iSTEM-leermaterialen.

Het doel van dit werk is STEM-leraren, lerarenopleiders en andere belanghebbenden in secundair onderwijs te voorzien van nuttige informatie om hun team een vlotte start te geven in het ontwerpen van leermaterialen voor kwalitatief iSTEM-onderwijs. Daartoe werd gedurende 4 jaar een case studie uitgevoerd, waarin vier multidisciplinaire teams van STEM-leraren van dichtbij gevolgd werden in hun poging om zulke leermaterialen te ontwerpen, waarna ze die vervolgens ook zouden uittesten in hun klassen. Via de observaties en de door de teams ontworpen leermaterialen konden belangrijke stappen en valkuilen in hun ontwerpproces vastgesteld worden, alsook vruchtbare

strategieën om de verschillende STEM-disciplines met elkaar te verbinden. Deze bevindingen werden geïntegreerd in een ondersteuningsmodel voor iSTEM-lerarenontwerpteams: 'COOL voor iSTEM'. Na de case studie werden verschillende deelnemers geïnterviewd over hun ervaringen en perceptie van eigen professionele groei met betrekking tot het ontwerpen van iSTEM-leermaterialen. Hun reflecties werden vergeleken met leraren die de leermaterialen enkel uittestten in hun klassen.

De observaties toonden dat leraren in iSTEM-lerarenontwerpteams gesprekken voeren op een discipline-overschrijdend niveau, activerende uitdagingen formuleren voor hun leerlingen, en in het licht van deze uitdagingen betekenisvolle connecties tussen de STEM-disciplines weten te leggen. Daarbij, zo getuigen de leraren, leren ze veel van hun collega's uit andere disciplines. Ze waarderen deze kruisbestuiving als een belangrijke eigenschap van hun deelname in de iSTEM-ontwerpteams. Hun aandacht moet echter regelmatig worden gevestigd op het stellen en nastreven van gewenste leerdoelen voor de leerlingen en strategieën om deze te bereiken, gezien ze soms neigen te focussen op het creëren of uitvoeren van praktische activiteiten met een eerder beperkte kans op leren. Bovendien moet ook een mogelijke terugval op een louter discipline-specifieke aanpak van de geformuleerde uitdaging ondervangen worden. COOL voor iSTEM geeft de belangrijke stappen van het iSTEM-ontwerpproces weer met richtlijnen en -vragen, alsook kwaliteitscontroles om de valkuilen te vermijden. Vergezeld van de nodige coördinatie kan dit instrument ingezet worden in lerarenopleidingen, gezien deelname aan iSTEM-lerarenontwerpteams veelbelovende leeropportuniteiten biedt. Leraren van succesvolle iSTEM-ontwerpteams vertonen een hoog niveau in metacognitief denken en een verbeterde attitude tegenover het aanpakken van problemen. Ze slagen erin een sterke, multidisciplinaire leergemeenschap op hun school op te richten en beschikken over de dynamiek om deze te onderhouden.

Dit werk beveelt het gebruik van COOL voor iSTEM aan als hefboom om STEM-onderwijs te transformeren naar kwalitatief geïntegreerd STEM-onderwijs, aangezien het een inventaris is van de kennis en ervaringen die verzameld werden gedurende 4 jaar van onderzoek en ontwikkeling. COOL voor iSTEM is een actieplan dat inspiratie en richting kan bieden aan het onwerpproces en kan helpen om geen belangrijke overwegingen over het hoofd te zien. Deelname in iSTEM-lerarenontwerpteams is een krachtig concept voor lerarenopleidingen en nascholingen. COOL voor iSTEM kan gebruikt worden om zulke vormingen te begeleiden, als het aangevuld wordt met regelmatige uitwisseling van feedback en dichte opvolging van de programmacoördinatoren. Het is aangeraden het gebruik van dit instrument ook na de ontwerpfase verder te zetten in de uittestfase, waarbij de ontworpen leermaterialen herzien worden in het licht van de resultaten van de leerlingen ten aanzien van de beoogde iSTEM-leerdoelen.

List of Abbreviations

ASO	Algemeen Secundair Onderwijs General secondary education
Bio	Biology
Biomed	Biomedical
Chem	Chemistry
CK	content knowledge
CODEM	Collaborative Online Development of Educational Materials
Electri	Electricity
Electro	Electronics
Electromech	Electromechanics
ES	Effect size
Geo	Geography
IMPL	implementation
Infor	Informatics
iSTEM	integrated STEM
M	mean
Math	Mathematics
Mech	Mechanics
MEng	Master of Engineering
MEngTech	Master of Engineering Technology
N	number of participants
PCK	pedagogical content knowledge
PD	professional development (in-service teacher training)
PK	pedagogical knowledge
Phys	Physics
SD	standard deviation
STEM	Science, Technology, Engineering, and Mathematics
TDT	teacher design team
TSO	Technisch Secundair Onderwijs Technically-oriented secondary education
YoT	Years of teaching
5B	Higher vocational education ISCED level 5

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Chapter 1

Introduction

1.1 Problem statement

1.1.1 Need for more student literacy and interest in STEM

The problem

The world faces all kinds of challenges that become increasingly complex with time. In 2016, the World Economic Forum surveyed employees from 371 companies worldwide, involved in industrial sectors such as Infrastructure, Consumer business, Energy, Finance, Healthcare, ICT, Media, Mobility, and Personal services. The 1346 respondents ranked the following issues as the most important drivers of change: climate change, natural resources, geopolitical volatility, aging societies, rapid urbanization, cloud technology, big data, 3D printing, artificial intelligence, Internet of Things, robotics, and biotechnology. The findings from this study suggest that proactive handling is required to tackle the rising socio-economic, environmental, and geopolitical problems. Also Europe cannot avoid to act in order to ensure growth and to establish its competitive position as knowledge-driven economy (EU STEM Coalition, 2016).

The challenges of tomorrow ask for increasingly sophisticated solutions, such as the use of bacteria and microbes to develop new health treatment therapies, the design of bio-based products, the construction of systems for fast and secure data storage and mining, the search for ways to harvest renewable energy and reduce electricity consumption, the development of smart systems that accommodate human lifestyle and aging, and the optimization of sustainable

farming (European Commission, 2014a). The need to accomplish these solutions also pervades the labor market, and an upward trend in cognitively demanding STEM jobs is noticeable (see Figure 1.1). Also Europe requires more and more scientifically and technically knowledgeable workforce to foster its continuing advancement in scientific research and technological innovation (European Commission, 2010a; Caprile, Palmén, Sanz, & Dente, 2015; EU STEM Coalition, 2016). European STEM vacancies are predicted to increase by 12% by 2025, which is much higher than the expected 4% increase for non-STEM occupations (European Commission, 2015).

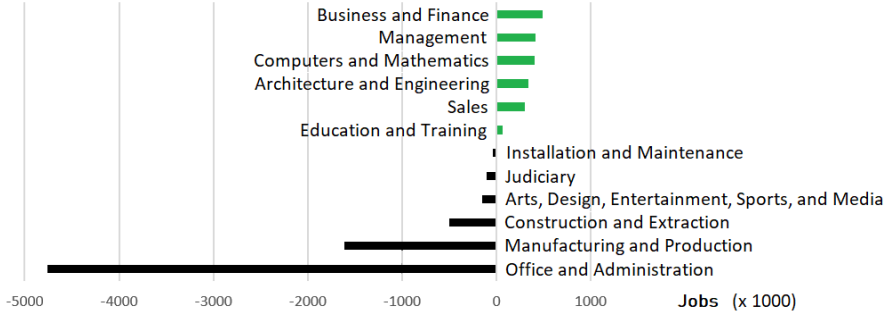


Figure 1.1: Predicted employment change in job sectors between 2015-2020 (adapted from World Economic Forum (2016))

This rising need for STEM workers in general, and highly qualified ones in particular, can be traced back to an increasing demand for STEM graduates (EU STEM Coalition, 2016). And this is where the problem lies.

News reports continuously draw the attention on the urgent need for, and the alarming shortage of qualified STEM workers, as illustrated in Figure 1.2. Next to the lack of applicants for STEM vacancies, the European labor market also reports a shortage of the required STEM skills and experience (Van den Berghe & De Martelaere, 2012; European Commission, 2014b; Caprile et al., 2015). Also in Belgium, highly qualified technical profiles cover the list of job vacancies that are the most difficult to be filled in (ManpowerGroup, 2016; Jobat, 2014; Agoria, 2015). One out of three Belgian companies struggles to find people with a technical profile (De Standaard, 2016).

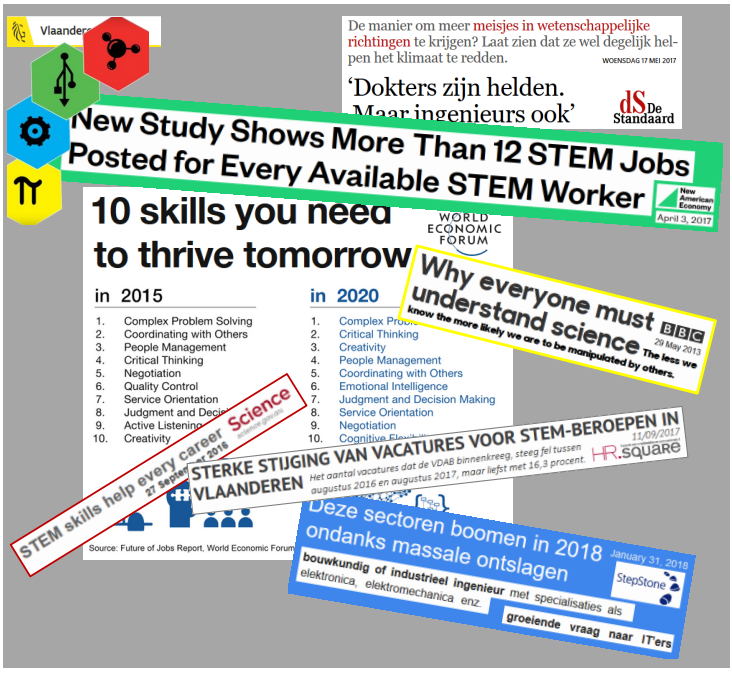


Figure 1.2: Headlines on STEM vacancies and skills

Higher education cannot keep up with this rising need. The number of higher-education degrees in science and technology has not seemed to grow much between 2010 and 2014 in Europe, or in Belgium in particular (NSB, 2018; Caprile et al., 2015). In the Flemish part of Belgium, only about 25% of the higher-education diplomas were awarded in STEM programs in 2014 (Vlaamse Overheid, 2015b). In 2016, only 22% of the awarded bachelor's degrees and around 28% of the awarded master's degrees carried a STEM label in Flanders (VDAB Studiedienst, 2016). The 'leaky pipeline' towards a STEM degree does not help: a significant number of students who first enrolled in higher-education STEM studies switch along their study track to non-STEM majors or drop out without a degree (Chen & Soldner, 2013; Pinxten, De Laet, Van Soom, & Langie, 2015).

The problem can be traced back to an even earlier stage in students' education. In 2008, the European Commission interviewed 25000 youngsters (15- to 25-year olds) across the EU member states on their attitude towards science. With regard to prospects of higher education, the interviewed youngsters preferred Social Sciences, Economics, and Business studies above Engineering, Sciences,

or Mathematics studies. Figure 1.3 shows a deviant distribution in enrollment in higher education programs in Belgium and Flanders in comparison with some neighboring and prominent countries. Even though an increase in enrollment with almost 3% was registered in Flanders between 2010 and 2016 (Vlaamse Overheid, 2018), STEM study programs are clearly even less popular in Belgium and its Flemish part as they are in other countries (Vlaamse Overheid, 2018).

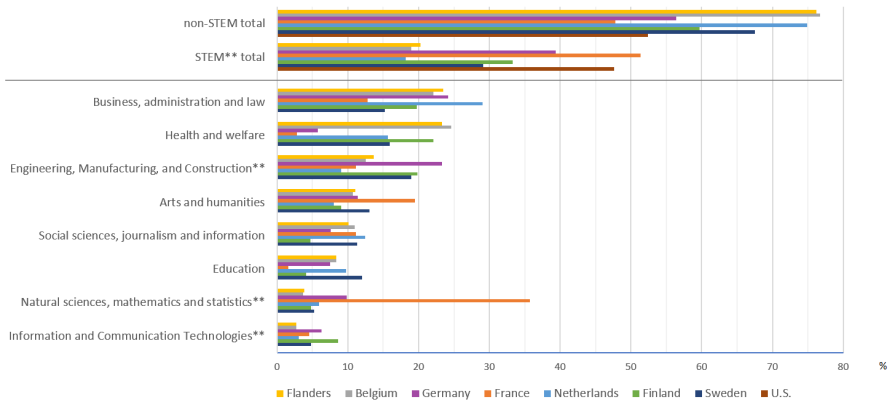


Figure 1.3: Students' first enrollment in tertiary education in 2014-2015 in Flanders with respect to some comparable and prominent countries (based on Vlaamse Overheid (2018) and Allum and Okahana (2015))

Secondary education, however, knows a higher enrollment in STEM programs than higher education. A study by the Flemish Government showed that at the upper level of Flemish secondary education, almost half of the students choose and graduate in a STEM study program, but only about 40% of this half (i.e., 20% of all secondary-education students) enrolls in higher-education STEM studies (Vlaamse Overheid, 2015b).

However, Flemish students score quite well at international tests such as PISA: in 2015, 20.7% of the Flemish 15-year olds got a top score for mathematical literacy; this is 10.0% more than the international average, and only China, Singapore, Korea and Japan have a higher ratio of top achievers (De Meyer, Warlop, & Van Camp, 2016). For problem solving, 18.0% of the Flemish 15-year olds got a top score in 2014, which was a 6.6% higher ratio than the international average and was only excelled by the previously mentioned Asian countries (De Meyer, Warlop, & Van Camp, 2014). Also in scientific literacy, Flanders can consider itself among the higher achieving regions: 12.0% of the Flemish 15-year olds were top achievers in 2015, whereas the international

average ratio lies at 8.0% and Flanders is only exceeded by previously mentioned countries, Vietnam, Canada, Estonia and Finland (De Meyer et al., 2016). The PISA2015 attitude survey revealed that, although a correlation has been found between participation in scientific activities and enjoyment on the one hand, and achievement for scientific literacy on the other hand, Flemish students appear to participate less frequently in scientific activities than the average country and experience less pleasure in science (De Meyer et al., 2016).

In short, despite decent student performance in STEM subjects, Flanders experiences a gradual but significant student dropout of STEM programs, which will eventually result in loss of STEM workforce potential.

The possible causes

On the decrease in students' choice for STEM studies in higher education, a comprehensive analysis of reports and statistics was made by Tengelin (2009). His meta-analysis revealed following causes:

a) Students lack attractive role models, do not receive enough information on prospective STEM careers and therefore perceive them as unattractive and not meaningful;
b) Students do not perceive STEM education as meaningful or sufficiently related to their own values and concerns;
c) Pedagogical innovation in STEM education is required, and teachers should be better equipped for STEM classroom practices.

These causes were corroborated by the following studies.

A public-opinion survey showed that Europeans are quite interested in new scientific discoveries and technological developments, but do not feel equally informed about them (European Commission, 2010b). They remain rather ignorant on the daily practices of a scientist or engineer, think efficient science communication is lacking, and as a result, they do not dare or care to take part in public debate on science and technology (European Commission, 2010b).

Due to this lack of information on STEM careers, a faulty image of these careers is formed. Figure 1.4 shows the discrepancies between youngsters' perception of careers in technology with respect to the perception of practicing engineers, which can be a major reason for students not to pursue STEM studies leading to technological jobs (Becker, 2010).

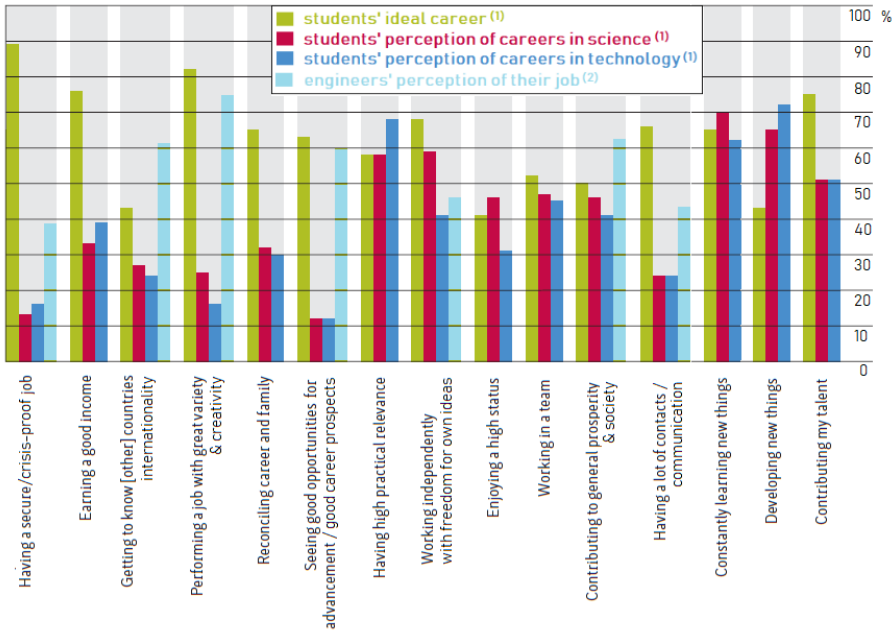


Figure 1.4: Students' image of their ideal career, students' image of careers in science and technology (1), and engineers' perception of their job (2) (adapted from (1) Bennecke and Lohel (2009) (with $N = 3500$) and (2) Becker (2010) (with $N = 350$), respectively)

Bennecke and Lohel (2009) conducted in-depth surveys among 3500 German secondary-school students and found that their perception of technical professions is not all that negative, and that students do understand the contribution of technical research to societal developments. However, in spite of some students' positive image of science and technology careers, and in spite of some students' interest and performance, they do not wish to pursue careers in science or technology for reasons like complexity and risks (Bennecke & Lohel, 2009). In other words, some of the students who have the desired competences and attitude, mistakenly think that STEM jobs are too difficult for them, and therefore divert from enrolling in STEM studies. On the other hand, some students who do enroll in STEM studies underestimate the required skills and insights (Bennecke & Lohel, 2009). These findings bear witness to a mismatch between student and study profile. A comprehensive understanding of the cognitive and attitudinal demands of STEM practices is thus necessary to guide students towards a deliberate and positive choice for STEM studies and careers.

Since young people's lack of interest for STEM appeared to be an international phenomenon, the University of Oslo set up a large-scale investigation: the ROSE study (Relevance of Science Education) (Sjøberg & Schreiner, 2010). In this study, 15-year olds from all over the world were queried on their areas of interest as well as their opinion about statements regarding their school science courses. This survey showed poor interest in science among European youngsters, and the huge contrast with the enthusiastic youngsters in less industrialized countries. Possibly, students are not very excited about science and technology because the impact of these disciplines on their current living standards has become obscure to them, as in industrialized countries, technology is omnipresent and taken for granted (Becker, 2010). Because most of the interaction with technology happens through interfaces, such as computer or smartphone screens, youngsters do not get in touch with e.g., the sophisticated, but invisible microchips and computer systems that make it all work (Becker, 2010; Vandewalle, 2010; Gramm, Hornung, & Witten, 2012). Neither do they have to understand the material characteristics and strength calculations behind equipment, such as e.g., a snowboard, to be able to use it (Becker, 2010).

A major problem seems to be the way school science is perceived by youngsters. A European survey conducted in 2008 already revealed that almost 70% of the European (and of the Belgian) students think the Science classes at their school are not sufficiently appealing (European Commission, 2008). The adolescents surveyed in the ROSE study, indicated that the courses given at school, do not give them any insight in the importance of STEM for society and do not provide prospects of exciting STEM careers (Sjøberg & Schreiner, 2010). At school as well as in the media, the contributions of science and technology to economic, medical, cultural, and political issues are not properly communicated (Bennecke & Lohel, 2009). As a result, even though youngsters are quite convinced of their potential personal influence on nature and society, they do not realize that science and technology provide means to exert this influence (Sjøberg & Schreiner, 2010). These student opinions raise questions on the effect of current science and technology education and instigate a deliberate reform of STEM education.

1.1.2 Need for a reform of STEM education

Rationale

Students' declining interest in STEM is attributed to the the rather isolated way in which STEM courses, such as Math, Science, and Engineering, are taught (Wandersee & Clary, 2006; Sanders, 2000). This compartmentalized approach to STEM education strongly conflicts with the aim to prepare students

for solving real-world problems, as these problems almost always call for a combined understanding and connection of concepts and skills from different STEM disciplines (Wang, Moore, Roehrig, & Park, 2011; Czerniak, Weber Jr, Sandmann, & Ahern, 1999; Breiner, Harkness, Johnson, & Koehler, 2012):

> Unlike most problems that come up in STEM curricula, which fit neatly within single disciplines and can be solved with well-established methods, real science and engineering problems are multidisciplinary, often poorly defined, and require ... creativitiy, attention to detail, experimentation, mathematical analysis and computation, and design and troubleshooting, flashes of insight, and a tendency to check calculations and replicate data. (Felder & Brent, 2016, p. 189)

Because profound connections between learning contents from the separate STEM disciplines are seldom made, and because the applicability of these connections for solving real-world problems is rarely illustrated, students do not perceive STEM subject matter as relevant or contributive to the world or to themselves (Holmegaard, Madsen, & Ulriksen, 2014). These personal perceptions and values are, however, important determinants of students' interest in and pursuit of future STEM careers (Nicholls, Wolfe, Besterfield-Sacre, Shuman, & Larpkiattaworn, 2007; LaForce, Noble, & Blackwell, 2017). In order for students to appreciate the complex and dynamic character of scientific knowledge and its contribution to solving environmental issues (Fortuin, van Koppen, & Kroeze, 2013), STEM education should show how real-life practices and careers are impregnated by an integrated application of STEM subjects (Archer et al., 2013; Sanders, 2000; Samaey & Vandewalle, 2016).

Classroom practices focusing on such integrated application of STEM subjects have proven to be fruitful in terms of student knowledge and attitude towards STEM. Integration of STEM learning contents was found to positively affect student performance on standards-based science, math, and integrated science/math problems (Becker & Park, 2011; Kiray & Kaptan, 2012; Thibaut, Knipprath, Dehaene, & Depaepe, 2018a). Also students' problem-solving, analysis and modeling skills were found to improve as a result of this approach (Ross & Hogaboam-Gray, 1998; Satchwell & Loepp, 2002). In terms of attitude, students involved in integrated STEM education have demonstrated a higher perceived relevance and importance of STEM courses for daily life and for future careers (Kutch, 2011; Tseng, Chang, Lou, & Chen, 2013). They exhibited a higher self-efficacy in science, motivation for learning, and interest in engineering careers (Kutch, 2011; Tseng et al., 2013; Ross & Hogaboam-Gray, 1998). Additional classroom activities inherent to authentic STEM practices, such as problem solving, inquiry or design, and cooperation, even elevate these positive effects (e.g., Sungur, Tekkaya, & Geban, 2010; Wenglinsky, 2002; Mehalik, Doppelt, & Schuun, 2008; Hänze & Berger, 2007).

The research presented in this work is thus based on the rationale that connecting STEM learning contents in the context of current real-world problems motivates students for STEM and leads to enhanced discipline-specific and crossdisciplinary knowledge and skills (Stubbs & Myers, 2016; Ackerman, 1989), as illustrated by following videos: `https://youtu.be/AlPJ48simtE` (The National Academies of Sciences, Engineering, and Medicine, 2014), and `https://youtu.be/wRV28EOCGGo` (Digital First, 2017).

The remedy

Several educational initiatives around Europe were set up to "boost economic competitiveness through technological innovation" (EU STEM Coalition, 2016, p. 7), such as networks of STEM professionals, museums and science centers, and programs to inspire youngsters' choice of study towards STEM subjects.

In 2012, the Flemish departments of Education and Formation, Work and Social Economy, and Economy, Science and Innovation drew up the 'STEM Action Plan', in which they established eight objectives towards an increase of graduates in scientific and technical study domains: (1) provide attractive STEM education, (2) empower teachers, educators and supervisors, (3) enhance the process of choosing a study or career, (4) attract more girls to STEM studies, (5) go for excellence, (6) adapt the curriculum, (7) encourage companies and knowledge centers, and (8) increase the societal appreciation of technical professions (Vlaamse Overheid, 2012).

The research presented in this work was carried out in the scope of STEM@school (see further), a research program that directed its efforts towards realization of many of the Action Plan's objectives. In support of the STEM Action Plan, the Flemish Department of Education and Formation created a 'STEM Framework' as a reference against which school initiatives can be evaluated (Vlaamse Overheid, 2015a). The student learning objectives listed by this Framework were inspired by STEM@school and are largely those formulated in Section 2.2 of Chapter 2.

The approach towards a solution

A renewed pedagogical approach towards STEM education is needed, in which stronger links are forged between the different STEM disciplines in order to show students the relevance of what they are learning. Possibilities to connect STEM domains through real-world situations are plenty, and many of them are still to be explored (World Economic Forum, 2016). Students should be confronted

with real-world problems for which they need to understand and purposefully connect key STEM concepts to reach a solution (Kelley & Knowles, 2016). STEM education should provide them with effective strategies to acquire and apply knowledge (European Commission, 2014a). But it should also transcend the pursuit of deeper student understanding of STEM subject matter.

STEM education should focus more on student acquisition of 21st Century skills. European companies increasingly demand a not only highly specialized, but also very broad skill set, including critical thinking (European Commission, 2014a), problem-solving and communication skills, and social awareness (European Commission, 2015). A lifelong-learning habit of mind will help students adapt to the changing labor markets in their future careers (European Commission, 2014a).

The approach to STEM education should be differentiated to accommodate different student motivations. Students pursue studies and careers based on very diverse motivations: intrinsic, such as interest and relevance, as well as extrinsic, such as high income and career opportunities. STEM education should attract as many student profiles with a predisposition for STEM as possible (Bennecke & Lohel, 2009).

The report of Bennecke and Lohel (2009) demonstrated that technology education favors students' aspiration to pursue technical careers. The report states that "[t]echnology education is a part of general education. It is a central component of the ability to fully participate in social and political life" (Bennecke & Lohel, 2009, p. 26). STEM education should thus put more emphasis on technology education that goes beyond merely using technology or explaining its function, but that involves creating it, through hands-on experiences in order to solve an authentic need (Bennecke & Lohel, 2009; Becker, 2010; Bergner, Holz, & Schroeder, 2012). Moreover, STEM education should highlight the cooperative, problem-solving character of engineering (Becker, 2010).

STEM education should also invest in disseminating a comprehensive image of the daily-life consequences, opportunities, and risks engendered by scientific and technological practices (Bennecke & Lohel, 2009).

All of these objectives are crystallized into '**integrated STEM**' or '**iSTEM**' **education** (The National Academies of Sciences, Engineering, and Medicine, 2014; Digital First, 2017). iSTEM education aims to equip students with STEM literacy, i.e., the ability to identify, appreciate, use, and combine concepts and skills from science, technology, engineering, and mathematics to understand and solve complex problems, and situate them in today's economic, societal, and environmental needs (Zollman, 2012):

> [Integrated] STEM education is the use of science, technology, engineering, mathematics, and their associated practices, to create student-centered learning environments in which students investigate and engineer solutions to problems, and construct evidence-based explanations of real-world phenomena. Evidence-based STEM education promotes creativity and innovation while developing critical thinking, collaboration, and communication skills while students seek explanations about the natural world to improve the built world. (Shernoff, Sinha, Bressler, & Ginsburg, 2017, p. 3)

As such, iSTEM education prepares students for the ever-innovating, high-tech world they live in and encourages them to be the answer for the many unoccupied vacancies waiting for dynamic, competent STEM professionals (Perkins & Unger, 1999; Sawyer, 2006).

1.2 Context of this work: STEM@school

Many initiatives have been launched to boost STEM education in Flanders. However, few actually focus on integration of the STEM disciplines. Appendix A sheds light on some of the programs that do emphasize iSTEM, and to which this work has contributed. These programs offer readily-available learning materials for various teacher needs, going from a science-technology project day to short hands-on, inquiry-based modules for a few hours during a few weeks. The research presented in this work was carried out in the scope of STEM@school.

Foundation

STEM@school (`http://www.stematschool.be/en/`) was initiated as a collaboration between the KU Leuven, the University of Antwerp, and the educational umbrella organizations of the catholic education (KathOndVla) and the education organized by the Flemish Community (GO!). The design-based research set up by STEM@school was funded by the Agency for Innovation by Science and Technology (IWT), which was later incorporated by the Research Foundation - Flanders (FWO). STEM@school started in June 2014 and ended in June 2018.

Rationale

STEM@school wanted to give students a clear and complete image of what STEM entails, so they are better prepared to make an deliberate study choice when they enroll in higher education (Knipprath et al., 2018). The rationale of STEM@school was that students will get a better idea of what STEM entails and how STEM learning content is relevant when they get acquainted with the many applications of the STEM disciplines, and of the crossdisciplinary dimension of real-world problem solving. Therefore, STEM@school wanted to give shape to iSTEM education by connecting concepts and skills from the different STEM disciplines and embedding them in real-world or authentic problems.

Target group and context

STEM@school targeted students of grades 9 to 12 of secondary education. Even though enhanced STEM literacy is important for every student (Meeder, 2014), STEM@school was directed towards students who have a predisposition for engineering and/or math and science (De Meester, De Cock, Knipprath, & Dehaene, 2015). Two study tracks of the Flemish educational system focus on this type of students: 'Sciences' in General Secondary Education (ASO), and 'Industrial Sciences' in Technically-oriented Secondary Education (TSO). These study tracks prepare students for a continuation of their studies towards a bachelor's or master's degree in higher STEM education and provide a high amount of engineering and/or math and science classes.

Research and design setup

STEM@school set out to design, implement, and evaluate iSTEM learning materials together with multidisciplinary teams of STEM teachers from 10 schools. The learning materials were designed in cycles, and each time implemented the year following the design in 30 schools who had been selected as test schools. Figure 1.5 shows the cycles of research and design during STEM@school.

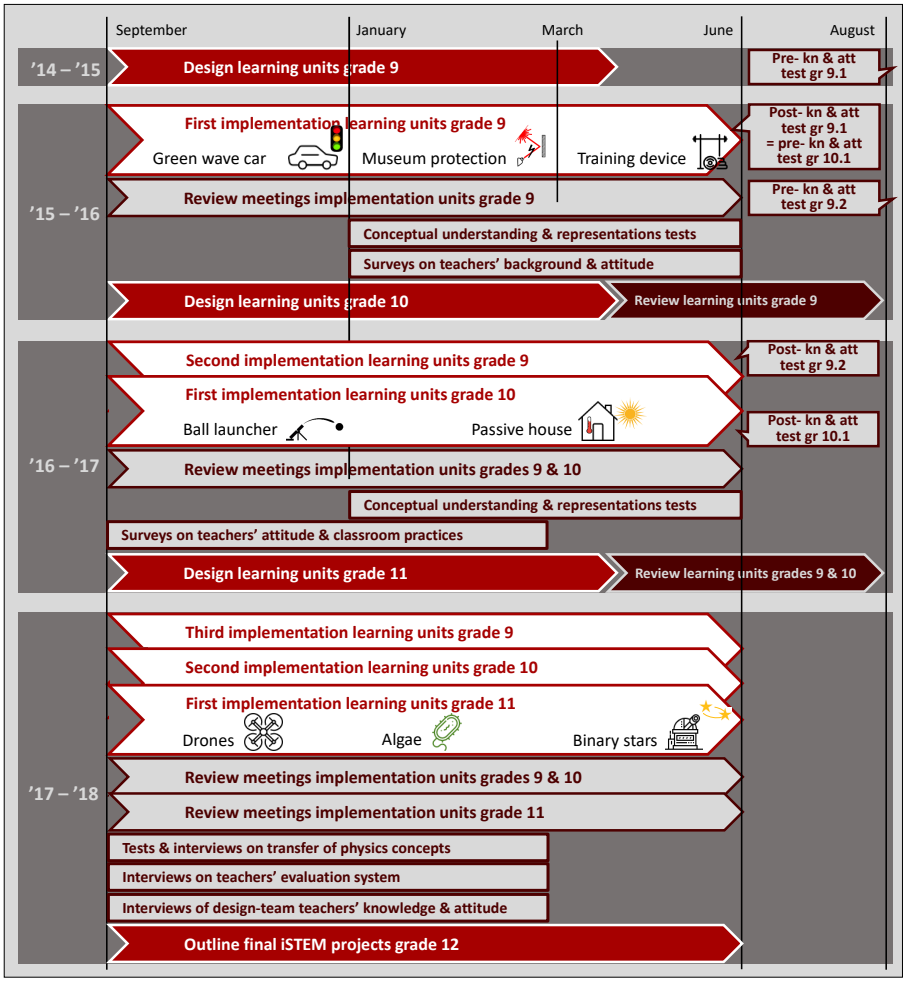


Figure 1.5: STEM@school scheduling of research and development

Several inquiries were set up to evaluate the design and implementation of the STEM@school learning materials. The process of designing these materials was studied in depth in the scope of the work presented here (see Chapter 3) (De Meester, Knipprath, et al., 2017). During the implementation of the learning materials, one or two meetings per quarter were organized in which the teachers of the test schools exchanged their experiences with the learning materials: the effect on their students, the organization of their classes, and practical impediments and concerns. Their remarks gave an idea of the degree to which

the learning materials were being implemented in the test schools, and were taken into account in the review of the designed materials afterwards.

Tests and surveys were developed to gauge students' status or improvement in conceptual understanding and their attitude towards STEM subjects, whether or not as a result of implementing the STEM@school materials. Different tests on students' performance on mathematical, scientific, and integrated problems were developed and validated (De Loof, Ceuppens, et al., 2018), as well as a survey on attitude towards STEM subjects (Struyf, Boeve-de Pauw, & Van Petegem, 2017). These tests and the survey were administered to students of the 30 test schools and of 10 control schools before (pre) and after (post) the implementation in grades 9 and 10, respectively. After taking into account the implementation fidelity, and after controlling for the pre-implementation scores, the comparison of the post-test and -survey scores could give an image of the influence of the iSTEM learning materials. During the successive years of STEM@school, additional research was carried out on students' misconceptions and their ability to reason with different representations in analogous math and physics problems (Ceuppens, Deprez, Dehaene, & De Cock, 2018b, 2018a; Ceuppens, Bollen, Deprez, Dehaene, & De Cock, 2019). To a sample of students of grade 11, tests and interviews were administered to gauge the degree to which they transfer concepts like 'slope', 'area under a curve', 'programming loop', 'resistor' and 'parallel and series configuration' from one context to another context (e.g., math to kinematics, or electricity to thermodynamics) (De Meester et al., 2018; Goovaerts, De Meester, et al., 2018).

Other research within the scope of STEM@school examined teachers' attitude towards designing, implementing and evaluating iSTEM classroom practices. A multi-faceted study focused on teachers' attitude towards the different key principles of iSTEM education, the degree to which their classroom practices are congruent with these key principles, the teachers' background characteristics, their students' scores on the math, physics, and integrated tests, and the correlation between all of these factors (Thibaut, Knipprath, et al., 2018a; Thibaut, Knipprath, Dehaene, & Depaepe, 2018c, 2018b). To this end, several surveys were developed, validated and administered, and the scores of the aforementioned pre- and post-implementation tests were taken into account. As iSTEM education asks for a varied approach to evaluating student work and performance, teacher interviews were carried out to identify assessment methods and instruments used by teachers, and the degree to which these are coherent with the learning goals and classroom practices (Goovaerts, Buyse, De Cock, Struyven, & Dehaene, 2018). Other teacher interviews were conducted in the scope of the work presented here (see Chapter 4) to gauge teachers' knowledge and attitude towards (teaching) iSTEM after participation in the teacher teams who designed the STEM@school learning materials.

Designed learning materials

The learning units developed in STEM@school cover approximately a quarter or a semester at 4 or 5 class periods a week (see Figure 1.5). In the learning units, students study and connect key concepts from physics, mathematics, biology, chemistry, computer science, astronomy and/or earth science. Each learning unit is centered around an engaging challenge.

In grade 9, students successively build and program a car to drive through a green wave, design a museum protection by means of lasers and mirrors, and design a rehabilitation device for a wheelchair patient with the constraint of a maximum applied force. In grade 10, students build and control a ball launcher, and control the indoor temperature of a passive house heated by a sun boiler (Goovaerts, De Cock, Struyven, & Dehaene, 2018). In grade 11, teachers can choose between a learning unit on algae cultivation and harvesting, a learning unit on analysis of data on binary stars generated by a telescope, and a learning unit on investigation and control of drones. A student experiment of the first unit (Green wave car) is pictured in Figure 1.6.

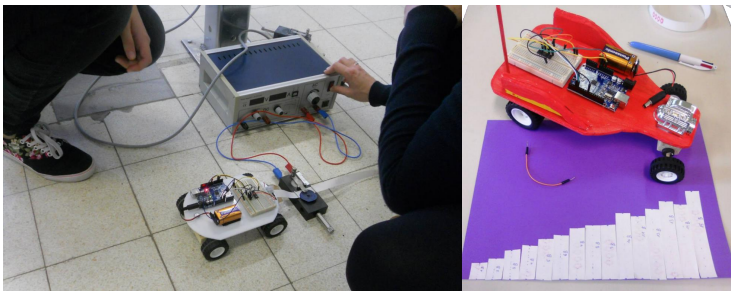


Figure 1.6: Experiment with the car built by students in STEM@school

The learning units on the Green wave car, the Ball launcher, and the Algae were the focus of design processes that were examined in depth in this work's research (see Chapter 3).

The STEM@school learning materials are developed in the first place for teachers. The materials contain a student challenge, possible learning activities accompanied by suitable instructional strategies, extra information and tips, references to curriculum standards and textbooks, material lists, example solutions, programming codes, and drawings. Teachers can adapt these materials to syllabi that are tailored to their class context and students.

1.3 Focus and outline of this work

1.3.1 Design of iSTEM education as research focus

The research presented in this work is based on the rationale that introducing an integrated approach to STEM education with cooperative, inquiry- and design-based learning experiences, holds the promise of equipping students with a solid and multi-employable set of competences, and with a more positive attitude towards science, technology, engineering, and mathematics. Integrated STEM (iSTEM) learning materials (i.e., standards, curricula, instruction, and assessment instruments) are impregnated with (a) scientific and engineering practices, (b) crosscutting concepts, and (c) discipline-specific core ideas (Hernandez et al., 2014).

Research is taking an increasing interest in the efforts and implications of the *implementation* of iSTEM learning materials (O'Neill, Yamagata, Yamagata, & Togioka, 2012; Shernoff et al., 2017; Dare, Ellis, & Roehrig, 2018). However, only a handful of studies have explored key aspects of iSTEM learning materials (Guzey, Moore, & Harwell, 2016; Kelley & Knowles, 2016; Thibaut, Ceuppens, et al., 2018). Even less studies have looked into the *design* of such learning materials by teachers (Guzey, Moore, & Harwell, 2016; James, Lamb, Householder, & Bailey, 2000; Satchwell & Loepp, 2002). Some studies have focused on teachers' collaboration, their experiences, and the support they need when designing context-based science curricula (Stolk, Bulte, De Jong, & Pilot, 2016; Binkhorst, 2017; Coenders, Terlouw, Dijkstra, & Pieters, 2010). Some research has investigated the knowledge, skills, and attitude teachers gain from collaboratively designing curricular materials (Voogt et al., 2011; Coenders & Terlouw, 2015; Fulton & Britton, 2011; Binkhorst, 2017; Meirink, Imants, Meijer, & Verloop, 2010). From their research, Coenders et al. (2010) concluded: "The question that surfaces is whether it is possible to design a development process of learning material[s] that maximizes teacher learning and if so, what distinctive qualities would such a process have?" (p. 554). Specifically for teacher learning in iSTEM education, this question has remained unanswered. The research presented in this work aims at providing an answer to this multifaceted need. In short, this work attempts to investigate the following, overall research question:

What process do teachers go through, how do they tackle the integration of STEM disciplines, which tool can support their process, and what do they learn in terms of knowledge and attitude when co-designing learning materials for integrated STEM education?

This question is investigated by means of two types of qualitative research: a combination of the methods 'case study' and 'grounded theory' was used to obtain a model of the iSTEM design process of teacher teams, and 'grounded theory' was adopted to identify their learning gains. The characteristics that led to the choice of these two research methods can be consulted in Table B.1 of Appendix B. Although qualitative research investigates some very specific settings and thus produces findings that can not always be generalized to broader contexts, it nevertheless creates valuable, in-depth insights into the experiences and dynamics of teacher practice (Wenglinsky, 2002).

1.3.2 The content of this work

Figure 1.7 gives an overview of the chapters in this work, and demonstrates how they gradually seek for and provide an answer to the overall research question.

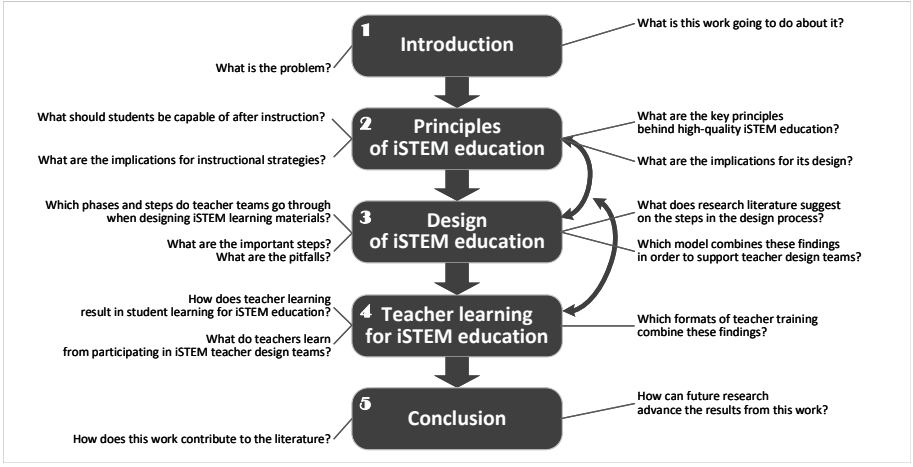


Figure 1.7: Overview of the chapters of this work

Chapter 2 addresses the key principles behind iSTEM education. In this chapter, first, the learning goals targeted by iSTEM education are listed. With regard to these learning goals, a comprehensive review of the literature on instructional design was conducted. The findings from this review are reported, classified into five key principles: (1) integration of STEM learning contents, (2) problem-centered learning, (3) inquiry- and design-based learning, (4) cooperative learning, and (5) conceptual learning. The chapter discusses possible classroom activities and strategies, suggested by the literature, on how

to implement each principle. These instructional practices were translated into design principles, i.e., guidelines that should be followed when designing iSTEM learning materials. The chapter finally translates all these principles into a list of requirements for high-quality iSTEM education with which the learning materials should comply.

Chapter 3 discusses the process of designing iSTEM learning materials, with the purpose of (1) identifying its steps by observing and abstracting teachers' actual design processes, and (2) assembling a model that can support teacher teams who embark upon designing such materials. Via a case study, four teacher teams of STEM@school were followed up close in their endeavor to design iSTEM learning materials. The aim of this case study was to unravel the phases and steps that constitute their design process. Five phases returned in the design process of the four cases, each consisting of several steps. The chapter describes these steps by means of the observations and meeting reports of each case. The steps are then assessed in terms of their importance, by means of the evaluation of the learning materials designed in each case against the requirements for high-quality iSTEM education. Based on the steps that appeared to be important and/or missing, and on instructional strategies suggested by the literature, a model was constructed with the purpose of supporting the design process of future teacher teams towards high-quality iSTEM learning materials: CODEM for iSTEM. The chapter presents this model. It shows the actions that should be carried out per step, and provides examples and scaffolding questions to guide teachers to the desired outputs. A digital version of CODEM for iSTEM was tested in two workshops to verify its comprehensibility and suitability, the findings of which are shown in the chapter.

Chapter 4 examines the learning gains experienced by and gauged among the teachers who participated in the design teams of STEM@school. The chapter first explains how teacher learning for iSTEM education might eventually lead to improved student knowledge and skills in (i)STEM. Teachers from teams of STEM@school were interviewed on their experiences with designing and/or implementing iSTEM learning materials, and on whether and how they felt an improvement of their own knowledge and attitude towards (teaching) iSTEM. This chapter analyzes the reflections of the teachers who had designed the learning materials before implementing them, against the reflections of teachers who had merely implemented the learning materials. The chapter also addresses the prerequisites for iSTEM education, expressed by the interviewed teachers. Finally, based upon these findings, two formats of pre- and in-service teacher training are presented and elaborated.

Chapter 2

Principles of iSTEM education

2.1 Introduction

iSTEM (integrated STEM) education must trigger students' motivation for STEM subjects and provide them with a clearer image of the practices performed by STEM professionals, in order to foster a deliberate and positive choice for science and engineering studies in higher education (Veretennicoff et al., 2015). This chapter sets the framework for iSTEM education. Based on a literature review, a set of principles was identified that are key to effective iSTEM education, i.e., positively affecting students' knowledge and attitude towards STEM subjects. Apart from fostering STEM-integrated learning, these key principles all support the idea of social constructivism in that they encourage students to construct their own knowledge, based upon their prior knowledge, and in close collaboration with their peers, instead of passively receiving information from an omniscient teacher (Thibaut, Ceuppens, et al., 2018; Schunk & Zimmerman, 2003). In iSTEM education, these key principles are intertwined. This chapter distangles them to demonstrate each principle's contribution to meaningful iSTEM education.

Section 2.2 lists the learning goals that are targeted by the approach to iSTEM education adopted in this work. Based on these goals, Section 2.3 describes the key principles that underpin iSTEM education. These key principles are corroborated by means of instructional models developed in cognitive psychology. The principles call for a teaching approach that moves away from direct lecturing

towards coaching, for which Section 2.4 provides some strategies. Section 2.5 finally translates the key principles into design principles. The design principles are the characteristics of iSTEM learning materials, and thus provide guidelines for the design of such materials.

2.2 Learning goals for students in iSTEM education

The first step in curriculum design, is to establish the **learning goals**: the set of competences (knowledge, attitude, and skills (OECD, 2018)) students should master after having been involved with the designed learning materials (Wiggins & McTighe, 2005; Hattie, 2012). Before embarking upon the curricular design as a whole, overarching learning goals must be formulated, which students are expected to achieve in the long run (Krajcik, McNeill, & Reiser, 2008). These goals are determined by the mission and objectives of the design, which try to improve certain aspects of student performance (Wiggins & McTighe, 2005).

The learning goals aimed at in iSTEM education are a combination of the goals formulated by the U.S. National Research Council (2012b), and important 21st Century skills (Ananiadou & Claro, 2009). They are:

Students can:
- ☐ understand, integrate, and apply STEM learning contents;
- ☐ ask relevant questions and/or analyze an authentic, multidisciplinary problem;
- ☐ plan and carry out scientific investigations;
- ☐ model, analyze, interpret, and manipulate scientific and technological phenomena, systems, and processes with mathematical and computational tools;
- ☐ construct an evidence-based explanation and/or solution;
- ☐ apply and develop technology in a creative, responsible, and justified way;
- ☐ communicate and reflect critically about STEM subjects or processes;
- ☐ cooperate in STEM practices;
- ☐ illustrate the relevance of, and demonstrate motivation towards STEM subjects.

Based on these learning goals for the students, the key principles behind iSTEM education were identified that should guide the curricular design. They are presented in the following section.

2.3 Key principles behind iSTEM education

This section presents the **key principles behind iSTEM education**. They form the basis and determine the features that must be present in the learning materials (Thibaut, Ceuppens, et al., 2018; Guzey, Moore, & Harwell, 2016). An extensive literature review, supplementary to the one conducted by Thibaut, Ceuppens, et al. (2018), shed light on several fundamental instructional models developed in cognitive psychology. From these models, five key principles were extracted that are most inherent to (learning) STEM contents and practices and that form a manageable overview. As shown by Thibaut, Ceuppens, et al. (2018), these principles are the ones that most frequently underpin studies in iSTEM education, although not always all of them are used, and not always in this combination. While Chapter 4 (Section 4.2.1) demonstrates their effect on students' knowledge and attitude towards STEM subjects, following subsections illustrate the epistemological and pedagogical implications of each of these key principles by means of the literature on instructional models.

2.3.1 Integration of STEM learning contents

A key principle in the preparation of students for real-world problem solving is the integration of learning contents of the different STEM disciplines. As shown in Box 2.1, science, technology, engineering, and mathematics have their own particular learning contents and habits of mind (NAE & NRC, 2014), but they also have overlapping features and practices. In secondary education, discipline-specific learning contents have long been taught in a rather disconnected way in isolated STEM courses (Sanders, 2000). In contrast, real-world problems rarely present such compartmentalization (Wang et al., 2011; Czerniak et al., 1999; Breiner et al., 2012). Integration of STEM learning contents therefore aims to tackle the disconnectedness among the STEM courses. But what does 'integration of STEM learning contents' entail? From the many definitions of (STEM) learning-content integration available in the literature (Kelley & Knowles, 2016), this subsection distills the ones that are most applicable and relevant to this work.

Integration of STEM contents is the action of alternating (a) a crossdisciplinary approach, in which knowledge of a STEM discipline is inspected from the perspective of another STEM discipline, with (b) an interdisciplinary approach, in which knowledge and methods from different STEM disciplines are applied interchangeably and the disciplinary borders fade away (Stember, 1991).

Box 2.1 The four STEM disciplines (NAE & NRC, 2014)

Science is the discipline that is concerned with the study (description, prediction, and understanding) of the natural world through scientific inquiry, which encompasses the collection of empirical evidence and the application of concepts and principles. The natural sciences, referred to by the S in STEM education, comprise the laws of nature, associated with physics, chemistry, biology, astronomy, and earth science. Scientific knowledge informs the engineering design process.

Technology is the discipline that describes the entire system of organizations, principles, processes, and devices underlying the creation and operation of technological artifacts. The technology referred to by the T in STEM education entails the understanding and use of materials, tools, algorithms, and processes related to the manufacturing, construction, transportation, management and communication of artifacts and data, such as softwares, mechanical or electronic devices and systems. Technological design is often need-driven and relies on scientific principles, mathematical calculations or logic reasoning, and engineering practices.

Engineering is the overarching discipline that encompasses the practices behind problem solving. A problem can be the need for a justified answer to a scientific question, or the need for a sound device or functioning system. The problem-solving process indicated by the E of STEM education, often happens under constraints. Such constraints can be the laws of nature, or time, money, available resources, environmental regulations, or manufacturability. In engineering, concepts from all other disciplines are used in order to solve the problem.

Mathematics is the discipline that studies patterns and relationships among variables, numbers, and space. The mathematical knowledge referred to by the M of STEM education, is constructed by logical arguments based on foundational assumptions. Unlike scientific knowledge which is built on empirical evidence, mathematical arguments cannot be overturned, unless the foundational assumptions are nullified. Mathematics is used to justify decisions made in the practices of the other STEM disciplines.

Bryan, Moore, Johnson, and Roehrig (2015) state that STEM integration comprises the coverage of several disciple-specific learning objectives, sometimes in support of a main activity performed in the scope of one discipline. Satchwell and Loepp (2002) and (Sanders, 2000) define STEM integration as the explicit assimilation of concepts of more than one STEM discipline, in which equal attention is paid to two or more disciplines. A similar definition of integration,

labeled as 'interdisciplinarity', was given by Vasquez, Sneider, and Comer (2013). An interdisciplinary approach is defined by Jacobs (1989) as: "[a] knowledge view and curriculum approach that consciously applies methodology and language from more than one discipline to examine a central theme, issue, problem, topic, or experience" (p. 8). Addressing learning content in an interdisciplinary way should be mutually beneficial for all the disciplines involved: what is learned should be more than the sum of what would be learned if the content was addressed in isolation by the separate courses (Ackerman, 1989). As such, integration transcends 'multidisciplinarity', which merely gathers separately learned concepts under a common theme (Vasquez et al., 2013).

Roehrig, Kruse, and Kern (2007) and Moore and Smith (2014) state that STEM integration should make an effort to combine *all* four disciplines: "STEM integration refers to students participating in engineering design as a means to develop relevant technologies that require meaningful learning through integration and application of mathematics and/or science" (Moore & Smith, 2014, p. 5). However, because not all real-world STEM practices include 'design of technology', the approach adopted in this work does not consider it to be an essential ingredient of all iSTEM learning units. Nevertheless, like scientific inquiry, design of technology should be part of several units throughout the iSTEM curriculum, so students get the chance to experience this kind of practice (National Research Council, 2012b; WFCO, 2017). In this work, engineering is conceived as the greatest common divisor, in agreement with Bryan et al. (2015), who call 'engineering practices' the integrator that brings the different components together into a coherent whole. As indicated by (Sheppard, Colby, Macatangay, & Sullivan, 2007), engineering is the integration of (a) the process of defining and solving problems, and (b) the knowledge on mathematical, scientific, and technological contents that "fuels" this problem-solving process.

STEM learning contents should be integrated in an *explicit* manner. Implicitly embedding crossdisciplinary connections is not sufficient for iSTEM education, as students do not spontaneously recognize these connections, and, consequently, the intended integration does not occur (NAE & NRC, 2014). Therefore, the NAE and NRC (2014) report recommends accentuating the built-in links between the STEM disciplines. Students should furthermore be scaffolded to effectively apply and combine the knowledge they acquire:

> [S]tudents do not always or naturally use their disciplinary knowledge in integrated contexts. Students will thus need support to elicit the relevant scientific or mathematical ideas in an engineering or technological design context, to connect those ideas productively, and to reorganize their own ideas in ways that come to reflect normative, scientific ideas and practices. (NAE & NRC, 2014, p. 5)

A focus on concepts, rather than on procedures (Chappell & Killpatrick, 2003), can facilitate integration of STEM learning contents. Opportunities for students to connect concepts should not be left unexploited (Goldstone & Day, 2012), because connected concepts are easier for the human mind to retrieve than unconnected concepts (NAE & NRC, 2014). Concepts that must be connected by the students should be presented near to one another in space and time (Hattie, 2012). The framework constructed by the U.S. National Research Council (2012b) presents several overarching topics, such as patterns, cause and effect, proportion, systems, states, and change, that facilitate creating bridges across discipline-specific STEM phenomena and concepts (Fortuin et al., 2013). Aligning the curricula of the separate STEM courses can furthermore reveal some crosscutting concepts, i.e., concepts that have applications in different STEM disciplines (National Research Council, 2012b), such as e.g., 'resistance', 'slope', and 'energy'. As the school year is often already too short to cover the breadth of learning contents prescribed by the separate STEM curricula (Apedoe, Reynolds, Ellefson, & Schunn, 2008), integration of these concepts can contribute to a deeper understanding while freeing up time for addressing discipline-specific concepts that are harder to integrate.

Furthermore, the integration of contents from different STEM disciplines can be established by embedding them in overarching STEM practices. These practices should be incorporated in iSTEM education because they involve valuable STEM skills, such as sense-making, critical thinking, planning, and iteration or revision (Bryan et al., 2015):

- **Mathematical reasoning and computational thinking** - Mathematical reasoning and computational thinking involve the construction of new knowledge and structures based on logical arguments that are consistent with the existing body of knowledge. These types of reasoning involve strategic use of appropriate tools, pattern recognition, algorithmic problem solving, and abstraction (Bryan et al., 2015; Kelley & Knowles, 2016; Voogt, Fisser, Good, Mishra, & Yadav, 2015). They ask for flexible application of variables, functions, logical sequences, and assembly of structures (Gal-Ezer, Beeri, Harel, & Yehudai, 1995).
- **Modeling** - Modeling is externalizing mental ideas, translating mathematical relations, physical phenomena, or technological constructions into a representation, such as a formula, diagram, graph, sketch, algorithm flowchart, simulation, or scale model, that can be discussed, applied, and manipulated (Carberry & McKenna, 2014; Vosniadou & Kampylis, 2013; National Research Council, 2012a). As such, modeling is part of the creative engineering process (Vandewalle, 2010). It involves causal reasoning (Perkins & Salomon, 1988), abstraction and interpretative decision making (omission of irrelevant details, approximation, and idealization based on subjective judgement and assumptions) (Goldstone & Day, 2012;

Gainsburg, 2013). Scientific models form a basis upon which hypotheses for inquiry can be derived, new knowledge can be constructed, or behavior can be explained, which causes them to be in constant development (Van Driel & Verloop, 1999; Vosniadou & Kampylis, 2013; Erduran & Duschl, 2004). Modeling can resolve inconsistencies between one's reasoning and what actually happens (Minstrell, 1989).

- **Scientific inquiry** - Scientific inquiry is characterized by questioning, collection of evidence, construction of explanations, argumentation, and communication of results (Bryan et al., 2015).
- **Technological design** - Technological design is the design, manufacturing and operation of prototypes, systems, processes, or machines for a specific purpose. Design habits of mind are creative thinking, perseverance, risk taking, consideration of environmental issues, and communication (Bryan et al., 2015). 0mm

Since a thorough disciplinary knowledge base is fundamental for effective integration of learning contents (NAE & NRC, 2014; Jacobs, 1989), STEM integration should not overrule the instruction of contents in the separate STEM courses (Hinde, 2005). Although links to other disciplines should be made within any of the STEM courses involved, a separate iSTEM course might provide more time for integrative activities (Kutch, 2011). In this course, discipline-specific content, learned in the separate STEM courses, can be applied. However, this iSTEM course can also create the need for learning some concepts more deeply in the separate STEM courses (Gilbert, Bulte, & Pilot, 2011).

As the integration of STEM learning contents requires students to thoroughly understand and flexibly use concepts from and across different disciplines, iSTEM education is assumed to provide suitable training for transfer. Training for transfer asks for an approach which "inspire[s] students to be 'intellectual entrepreneurs' who proactively create their own opportunities for leveraging their prior knowledge" (Goldstone & Day, 2012, p. 151). Furthermore, transfer of concepts requires two reasoning strategies that are common to scientific as well as technological practices: (a) logical deduction, in case the existing knowledge framework contains the answers, and (b) analogical reasoning, in case the existing knowledge base does not suffice for solving the problem at hand (Feldon, Hurst, Rates, & Elliott, 2013). iSTEM education happens to train for both types of practices (Stohlmann, Moore, & Roehrig, 2012).

In short, the integration of STEM learning contents is defined in this work as: the meaningful and explicit connection of discipline-specific concepts across as many STEM disciplines as relevant to solve a central, multidisciplinary problem, through mathematical and computational reasoning, modeling, scientific inquiry and/or technological design, and with respect for the integrity of each of the separate disciplines.

2.3.2 Problem-centered learning

Problem-centered learning is an approach in which learning is initiated by an authentic, ill-structured, real-world problem, that is interesting and meaningful to students and representative of what they will encounter in the future practices they are being prepared for (Merrill, 2002; Van Merriënboer & Kirschner, 2017; Asghar, Ellington, Rice, Johnson, & Prime, 2012; Savery & Duffy, 1995; Minstrell, 1989; Jonassen, Strobel, & Lee, 2006). However, such problem should be packaged in a version of which the cognitive demands are tailored to the student level (Perkins, 2010). Problem-centered learning was initially developed and studied by Barrows and Tamblyn (1980) as 'problem-based learning' in medical education. Although problem-centered learning has some characteristics in common with problem-based learning and with project-based learning, such as e.g., student activation and engagement in authentic practices, yet some nuances differentiate these learning strategies (Thibaut, Ceuppens, et al., 2018). Project-based learning focuses on the production of a certain end product for which the desired specifications are provided at the start (Asghar et al., 2012). Connecting the project to course contents is possible but not necessary, and students mainly apply concepts they know or have previously learned (Edström & Kolmos, 2014). In problem-centered and problem-based learning, students are presented with an ill-structured problem they have to analyze, and for which they must organize their prior knowledge and strategies to acquire extra information to solve it (Duch, 2001; Jonassen, 1999). Problem-based learning focuses on the acquisition of problem-solving skills, while problem-centered learning focuses on acquiring knowledge of new concepts, for which the problem is the driving force, and problem-solving skills are an appreciated but additional learning outcome (Thibaut, Ceuppens, et al., 2018).

Learning occurs when the contents to be learned are meaningful for the learner, which is the case when the problem connecting these contents relates to previous experiences or personal values of the learner (Savery & Duffy, 1995; Jonassen, 1999). Contents that are meaningful to the learner are more likely to remain in the learner's long-term memory (Felder & Brent, 2016). The central problem must be presented to the students at the start of a learning unit to spark students' interest (Merrill, 2002; Perkins, 2010; Jonassen, 1999). It should elicit an eagerness among students to know the outcome and, as such, keep them motivated throughout the learning unit (O'Neill et al., 2012). To evoke students' willingness to take ownership over it (create 'learner buy-in') (Jonassen, 1999), the problem should result in intermediate outcomes that are realistic, immediate, and visible (Jonassen, 1999).

Apart from adding meaningfulness, a central problem should coherently harbor important learning contents from different STEM disciplines. Solving the problem can contribute to achieving discipline-specific learning goals when it raises the need for students to learn the intended STEM concepts and principles (Guzey, Moore, & Harwell, 2016; Duch, 2001; Singer, Marx, Krajcik, & Chambers, 2000). As such, the problem is functional to the disciplines involved (Perkins & Unger, 1999; Ackerman, 1989). Today's ethic, societal, or ecological issues are thus particularly suitable as central problems, as they require knowledge and skills from different STEM disciplines (Perkins, 2010; Fortuin et al., 2013). Centering learning around an overarching problem or challenge prevents the instruction from 'elementitis', the educational phenomenon in which students have to digest fragmented pieces of knowledge without ever having to bring them together to a larger whole (Perkins, 2010). Under the guise of a larger enterprise, that is: solving the central problem, students get an image of what their learned concepts and practices contribute to, and how these are interconnected (Perkins, 2010; Van Merriënboer & Kirschner, 2017). The central problem should thus "make learning whole" (Perkins, 2010). In contrast with a deductive teaching approach (concepts and principles first, applications later), which is often detrimental to students' sense-making and motivation (Felder & Brent, 2016), problem-centered learning calls for an inductive approach (Prince & Felder, 2006; Rocard et al., 2007), in which a challenge asks for a solution (in the form of an analysis or a design), through which the desired knowledge and skills are acquired (Felder & Brent, 2016; Vandewalle, 2010).

In order to simulate a real-world problem, the central problem should furthermore be ill-structured and open-ended (Felder & Brent, 2016; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Hollingworth & McLoughlin, 2005). This means that the problem encompasses unarticulated goals and constraints, multiple possible solutions and/or solving strategies, which are often not determined or defined in advance (Jonassen, 1999). Conflicting goals or constraints will urge students to determine those with the highest priority (Jonassen et al., 2006), which promotes their decision-making and argumentation skills. When the problem is presented to the students, either should the full context and background be provided, or should only the basic question be posed (Savery & Duffy, 1995). However, the problem could comprise several subproblems that become increasingly complex in terms of cognitive demands and skills as the students progress in their problem-solving process (Jonassen, 1999; Merrill, 2002; Van Merriënboer & Kirschner, 2017). According to Turner and Paris (1995), open-ended tasks contribute to six important C's: they allow students to make personal Choices, provide a Challenge to students, allow students to take Control over their own learning, encourage Collaboration, foster Comprehension, and their visible Consequences give students a feeling of self-confidence.

Problem-centered learning should foster the development of students' problem-solving skills (Thibaut, Ceuppens, et al., 2018), creative and critical thinking (Savery & Duffy, 1995), self-regulated learning (Asghar et al., 2012), flexible thinking and perspective-taking, and their appreciation of the complexity of real-world issues (Ackerman, 1989). Through problem-centered learning, students should familiarize themselves with the way experts solve problems. What distinguishes expert problem solvers from novice problem solvers, is their ability to classify problems based on their underlying principles, through metacognitive thinking (self-monitoring), and self-efficacy (Felder & Brent, 2016; Feldon et al., 2013; National Research Council, 2012a). As students often mistakenly think the road towards a solution is straight-forward, effective instruction of problem solving requires teachers to model (demonstrate) the problem-solving process (Hollingworth & McLoughlin, 2005; Barron & Darling-Hammond, 2008). Teachers should explicitly instruct students on how to monitor and question their own thinking, how to articulate and justify decisions, and how to make corrections in unsuccessful methods (Felder & Brent, 2016; Hollingworth & McLoughlin, 2005; Dignath-van Ewijk, Dickhäuser, & Büttner, 2013).

In this work, problem-centered learning is conceived as the learning of key STEM concepts, principles, and skills, that is initiated, maintained, and advanced by the search for a solution to a relevant and authentic problem, through gradually but increasingly complex subproblems that build on understanding and integration of these key concepts and skills.

2.3.3 Inquiry- and design-based learning

Inquiry- and design-based learning are hands-on, inquisitive approaches to acquiring new knowledge and insights (Gerber, Cavallo, & Marek, 2001). Both forms of learning overall encompass similar stages, as shown in Figure 2.1, which are rarely executed in a linear sequence (Meinel & Leifer, 2012; Pedaste et al., 2015): these stages are embarked upon in a rather iterative, sometimes even random manner, depending on what seems appropriate, given the planning and the circumstances at that point in the process (Meinel & Leifer, 2012). Despite these similar stages, inquiry and design have their own specificities as well.

In inquiry-based learning, students are directly confronted with phenomena that induce questioning and ask for a restructuring of their conceptual schemas towards more scientifically correct ones in order for them to understand the phenomena (Gerber et al., 2001). First, students must analyze what exactly needs to be inquired, which problem needs answers (Pedaste et al., 2015). Students actively take part in questioning (Pedaste et al., 2015), formulating and testing a hypothesis (Kelley & Knowles, 2016; Pedaste et al., 2015), and

exploring this hypothesis, in which they identify and efficiently apply the knowledge they already acquired (Satchwell & Loepp, 2002). Then, they set up their own investigations and engage in experimentation (Kelley & Knowles, 2016). During experimentation, students perform practical work, and constantly discuss with peers, and reflect on intermediate results (Gerber et al., 2001; Pedaste et al., 2015). Finally, they try to make sense of the data they gathered, and formulate a conclusion (Pedaste et al., 2015). Inquiry-based activities are thus more than a series of (scripted) lab sessions (Kelley & Knowles, 2016). They should be designed in such a way that they illuminate key concepts, balance instruction with opportunities for hands-on inquiry, and facilitate team work (Barron & Darling-Hammond, 2008).

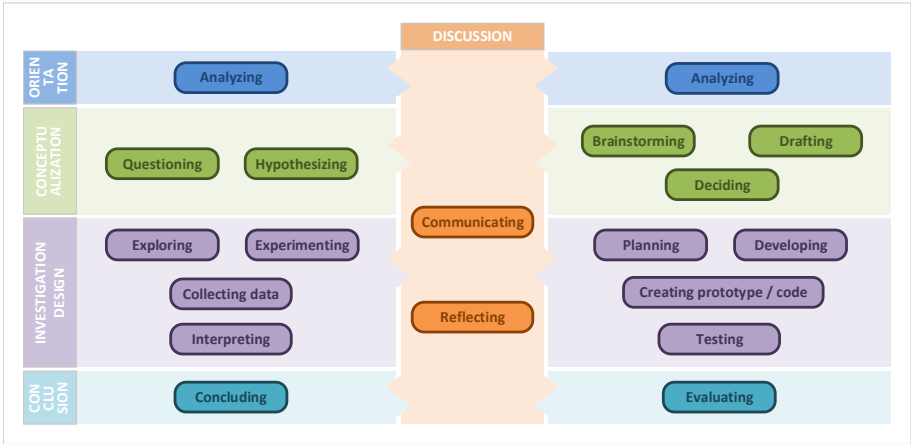


Figure 2.1: Parallel stages of inquiry and design
(based on Pedaste et al. (2015))

In design-based learning, students also have to analyze the problem, which entails defining the problem, or decomposing it into its several parts (Voogt et al., 2015). In this stage, students furthermore have to examine the constraints, requirements and risks: an activity inherent to design (Guzey, Moore, & Harwell, 2016). Students then draft possible models that might provide a solution to the problem (Voogt et al., 2015). These models can be drawings, diagrams, pieces of code, equations. Possible materials, shapes, functionalities, or structures have to be examined (Edelman & Currano, 2011). Students must consider the different alternatives to the problem solution (Guzey, Moore, & Harwell, 2016). Relying on the knowledge they already acquired, they must then decide upon a good solution candidate, and justify this choice by means of insightful arguments (concerning the list of requirements, constraints, and scientific foundation)

(Bryan et al., 2015; Wells, 2016). The students develop a prototype or code, meanwhile making responsible and safe use of technology (Voogt et al., 2015). The prototype or code must be tested against the list of requirements that was established in the orientation stage, and the test results are used to optimize the design (Fortus et al., 2004; Bryan et al., 2015; Wells, 2016; Voogt et al., 2015). Since designing is not a straight-forward process, also failure handling is part of design-based learning (Bryan et al., 2015).

Powerful iSTEM learning environments are created when students have to combine inquiry and design in their attempt to solve a given problem. In design-based science instruction, the design of artifacts is the vehicle through which students construct new scientific knowledge that in turn serves as resource for the design (Fortus et al., 2004). But also an inquiry-based technology approach provides promising learning opportunities, when students create and conduct experiments that will inform them about the functioning and performance of technologies (Kelley & Knowles, 2016). Students could also be asked to use technological tools to model scientific phenomena and refine these models through real and virtual experiments (Ross & Hogaboam-Gray, 1998). To ensure that learning through inquiry and design is not only hands-on, but also minds-on (Kelley & Knowles, 2016), students should be asked to justify their actions by means of scientific principles and mathematical calculations (Kelley & Knowles, 2016).

In this work, inquiry- and design-based learning is considered a vehicle through which students actively explore and study key STEM concepts and acquire important STEM skills such as critical and creative thinking, argumentation, and failure management, while they engage in real-world STEM practices such as analysis, modeling, and testing, with the purpose of solving a concrete problem.

2.3.4 Cooperative learning

Cooperative learning is an approach in which students work together in small teams, through which they develop their communication and team-work skills (Guzey, Moore, & Harwell, 2016). Meirink et al. (2010) make a distinction between cooperation and collaboration: collaboration involves shared responsibility and authority for making decisions about common practices, whereas cooperation is working together towards a common goal to make private practices more successful. Cooperative learning relies on the fact that student learning is demonstrated when students are able to explain what they have studied to their peers (Perkins, 2010).

Cooperative learning in small teams (of four to five students) can lead to higher student performance, higher perseverance, improved higher-order reasoning, improved attitude towards learning, better relationships with peers, improved self-efficacy (Johnson, Johnson, & Stanne, 2000; Prince, 2004), but only if following conditions are met (Kagan & Kagan, 2009; Felder & Brent, 2016):

- positive interdependence: individual success contributes to and depends on the success of the other team members;
- individual accountability: each team member can account for his/her own learning and contribution to the team;
- equal participation: each team member participates during an equal amount of time;
- simultaneous interaction: team members exchange knowledge, solution strategies, and encouraging feedback;
- team-skill development: team members communicate and manage their tasks and team dynamics effectively, set common team goals, and evaluate their progress with respect to those goals.

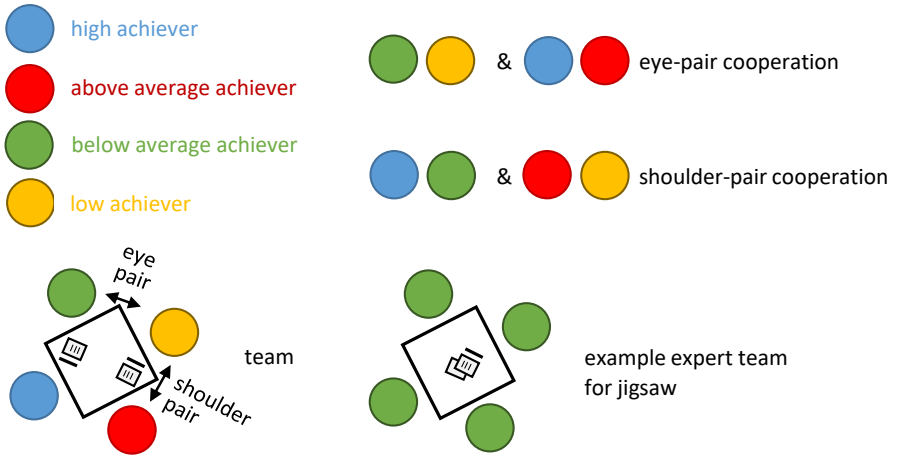


Figure 2.2: Different forms of student cooperation

Heterogeneous teams should be composed in such a way that skills are equally divided among the teams (Felder & Brent, 2016). Kagan (1989), Slavin (1991), and Hertz-Lazarowitz, Kagan, Sharan, Slavin, and Webb (2013) propose several forms of cooperative student learning with accompanying team compositions. As shown in Figure 2.2, the team composition depends on the desired form of cooperation. By adjusting team scores according to the team members'

individual improvement (i.e., relative, not absolute performance), these strategies allow differentiation within the classroom and meanwhile hold every single student accountable for progressing in learning (Kagan, 1989). Also the SCRUM method (Sutherland & Schwaber, 2013) can be applied, in which the teams of students participate in short improvement sprints, i.e., short cycles after which the students report on their actions and check their team's progression against the goals they formulated and the requirements of the team task (Mahnic, 2010).

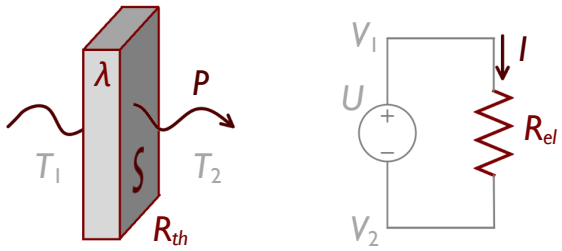
In this work, cooperative learning is considered an effective and differentiating form of learning with and from peers in which students develop social competences that are important in STEM practices, such as collaboration, listening, and negotiation, whilst being involved in problem solving, inquiry, or design.

2.3.5 Conceptual learning

Concepts are the building blocks of knowledge, and they are thus the foundations upon which STEM knowledge is built and integrated. Conceptual learning is acquiring "[an] implicit or explicit understanding of the principles that govern a domain and of the interrelations between units of knowledge in a domain" Rittle-Johnson, Siegler, and Alibali (2001, p. 346-347). This definition was shared by Streveler, Litzinger, Miller, and Steif (2008). Procedural learning, on the other hand, can be considered the memorization of steps or routine operations and their sequence necessary to attain a desired outcome of a problem without necessarily understanding the underlying principles and interrelations (Arslan, 2010). Procedural learning and conceptual learning interact when the existing conceptual knowledge forms the basis upon which new procedures can be acquired (Byrnes & Wasik, 1991; Star, 2002). Therefore, the link between these two types of knowledge must be explored with students as well (Arslan, 2010). According to Rittle-Johnson et al. (2001), conceptual knowledge is discipline-specific, but not tied to a certain type of problem, as opposed to certain types of procedural knowledge (such as, e.g., heuristics and algorithms). A deep understanding of basic discipline-specific concepts and crossdisciplinary links between them is however a necessary precondition for being able to identify principles and mechanisms underlying a problem, and to select adequate procedures to solve it (Streveler et al., 2008; Rittle-Johnson et al., 2001). Furthermore, as explained in Section 2.3.1, conceptual learning is an approach that facilitates the integration of multidisciplinary learning contents, and was therefore incorporated as a key principle.

Students' ability to relate concepts and extend their mental maps can be harmed by their difficulties in truly understanding certain concepts and their inability to construct a coherent conceptual knowledge base (Hattie, 2012; Gilbert et al.,

2011). Verbal and visual connections (e.g., presentation of multiple examples, hierarchical charts, system diagrams, analogies) can help students to understand and connect new concepts, possibly by means of educational technology (Hattie, 2012; Van Heuvelen, 1991). Conceptual difficulties among students are however inevitable. Perkins (2010) insists on tackling those difficulties, rather than avoiding them. Whenever a conceptual difficulty is encountered, it is better to bring the concept to a higher, more comprehensible abstraction level, than to obscure the complexity of the problem by means of superficial descriptions (Perkins, 2010). If the subject matter is too complex to be comprehensible to students, a 'blackbox' approach can be applied (Bunge, 1963), in which the subject matter is abstracted into a model or system of which only the inputs, outputs, and behavior is explained to the students, without elaborating on its internal structure. Analogies, such as the one presented in Figure 2.3, are a tool to expose students' conceptual difficulties (De Meester et al., 2018). Having students generate their own analogies is also a powerful strategy, as it urges students to articulate their interpretation and connection of concepts (Lancor, 2014; Blanchette & Dunbar, 2000; Haglund & Jeppsson, 2012; Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001). However, students should be supported in evaluating the applicability, the effectiveness, and the constraints of the analogies and models they constructed (Feldon et al., 2013; Vandewalle, 2010). In this way, students learn to transfer their conceptual knowledge within and across STEM disciplines (see also Appendix C).



Thermodynamics	Electricity
$\Delta T = T_1 - T_2$	$U = V_1 - V_2$
$P = \frac{\Delta Q}{\Delta t}$	$I = \frac{\Delta q}{\Delta t}$
R_{th}	R_{el}
$P = \frac{\Delta T}{R_{th}}$	$I = \frac{U}{R_{el}}$

Figure 2.3: Analogy between thermodynamics concepts and electricity concepts

Students can also hold a downright incorrect understanding of certain concepts: misconceptions, which need to be intercepted. Chi (2005) argues that students are prone to persistent misconceptions on quantities (e.g., heat) and relations, when these are part of scientific phenomena caused by unobservable (often microscopic) processes (e.g., molecule collisions). A greater focus on the causal relations that underlie scientific processes is thus advisable (Chi, 2005). When dealing with new information, a learner always starts by inspecting his/her mental maps and trying to fit the new information with his/her own existing conceptions, a process called assimilation (Posner, Strike, Hewson, & Gertzog, 1982). When, during assimilation, the learner encounters a cognitive conflict, i.e., a clash between the learner's existing conceptions and the new information, most likely, the existing conceptions are misconceptions, and conceptual change is required (Vosniadou et al., 2001). According to Posner et al. (1982), conceptual change occurs through accommodation, i.e., the process in which the learner reorganizes or replaces his/her own existing conceptions. In order for accommodation to take place, the new information must induce a dissatisfaction with the students' existing conceptions, it must be comprehensible and appear plausible to the students, and it must provide opportunities for further inquiry (Posner et al., 1982). Vosniadou and Kampylis (2013) propose several strategies that help students recognize situations that call for conceptual change: making students' intuitive beliefs explicit (for example through predictions), and designing experiments that refute students' incorrect predictions by means of empirical evidence. Other ways to foster conceptual change are the use of analogies or multiple representations, and initiation of classroom discussions (National Research Council, 2012a). Through such practices, students learn to think in a scientific way: they learn to understand that scientific ideas are complex and constantly evolving through inquiry (Vosniadou & Kampylis, 2013).

Many of students' conceptions are documented in discipline-specific educational research literature, together with instructional strategies to identify and accommodate them (such as the use of concept inventories), as well as evidence-based recommendations (such as the sequence in which certain concepts should be addressed) (e.g., Prince, Vigeant, & Nottis, 2012; Allen, 2006; Hestenes, Wells, & Swackhamer, 1992). These suggestions should be taken into account in the design of learning activities (Vosniadou et al., 2001) – as corroborated by following testimony:

> "As a teacher, I would encourage other teachers to become involved in research related to the cognitive processes of their learners. I predict it will enliven their time in the classroom, as it has mine. I also predict it will enhance students', and perhaps their own, understanding of the natural world." (Minstrell, 1989, p. 147)

Sustainable and crossdisciplinary conceptual learning can be directed by a purposeful design of entangled learning trajectories. Learning trajectories are the paths by which students' development of conceptual structures might progress from novice to more sophisticated levels of understanding (Confrey & Maloney, 2010), often empirically established by discipline-specific research on student learning. In an iSTEM curriculum, those learning trajectories should be interconnected. This description meets the definition of a spiral curriculum. According to Harden (1999), the features of a spiral curriculum are: (1) the revisitation of topics, (2) increasing levels of difficulty, (3) linkage of new ideas to previous ideas, and (4) increasing complexity and competence. However, contrarily to Harden and Stamper, who claim there should be continuity from one learning stage to the next one, and vertical integration between the different stages, the curriculum design in the scope of this work proposes quite the opposite, as explicit integration of STEM learning contents calls for (horizontal) integration of concepts that are typically instructed in separate STEM courses. Continuity and advancement in discipline-specific learning is, however, guaranteed by (vertically) revisiting these concepts in one of the following stages (subsequent learning units or school years). This approach is illustrated in Figure 2.4.

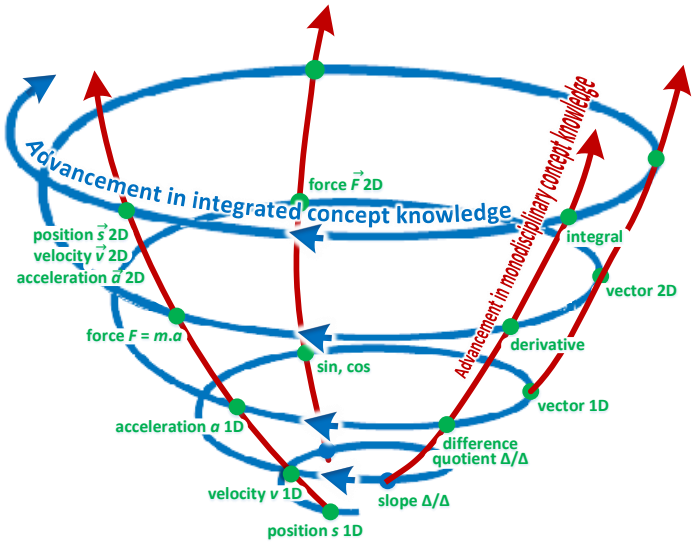


Figure 2.4: Spiral addressing of STEM concepts

In this work, conceptual learning is given explicit attention through consideration of research findings on students' conceptual difficulties and on recommended instructional strategies, and through purposeful design of learning trajectories that connect concepts across STEM disciplines and gradually raise the complexity of the discipline-specific concepts.

2.4 Implementation of iSTEM education

The key principles behind iSTEM education, and especially problem-centered, inquiry- and design-based, and cooperative learning, call for a teaching approach that instigates students' self-regulated learning (Prince, 2004; O'Neill et al., 2012). A learning process that is too scripted ('cookbook'-like), or fully directed by the teacher will not invite students to improvise or to construct their own knowledge (Sawyer, 2006). To engage students in self-regulated learning for deep understanding, "the [classroom] activities must be designed around important learning outcomes and promote thoughtful engagement on the part of the student" (Prince, 2004, p. 226). Such activities are supported by structure and scaffolding but have a substantial built-in flexibility (Sawyer, 2006). Furthermore, such learning activities focus on developing students' higher-order reasoning skills (Hernandez et al., 2014). Students involved in self-regulated learning are not only actively engaged in the learning activities taking place in the classroom (Prince, 2004), they also are in control of, and held accountable for their own learning (Nelson, 1999; Blumenfeld, Marx, Soloway, & Krajcik, 1996; Schunk & Zimmerman, 2003), which becomes evident when they independently maintain on-task discussions, explain subject matter to peers, or make thoughtful decisions (Perkins & Unger, 1999).

In fostering students' self-regulated learning in iSTEM, the teacher acts as a facilitator or coach who supports his/her students through targeted support (Felder & Brent, 2016; Asghar et al., 2012; O'Neill et al., 2012). Scaffolding is a key element in coaching: it is the support, in terms of hints and reminders, that the learner requires in his/her attempt to solve a problem in a way that approximates a more expert-like approach (Collins, Brown, & Newman, 1989). According to Puntambekar and Kolodner (2005), scaffolding of inquiry- and design-based activities manifests itself through (1) verification of a shared understanding of the goals, (2) ongoing evaluation of student understanding, (3) flexible support (adapted to situation and student), (4) dialogue with students, (5) several mediums (teacher, peers, materials), (6) multiple learning opportunities, and (7) fading support and growing student responsibility. Scaffolding helps students to progress along their individual zone of proximal development, i.e., the zone between the students' current problem-solving skills

and the level of problem solving they can attain with help of a coach (i.e., a teacher or a more capable peer student), as illustrated in Figure 2.5 (Vygotsky, 1978). At the start of their learning process, students need considerable support from their coach and the provided learning materials, but this support gradually fades as they become more skilled and self-regulated learners (Collins et al., 1989; Van Merriënboer & Kirschner, 2017). The key is thus to put the stakes a bit higher than at the student's level, then provide scaffolding, and let the scaffolding diminish the closer the student gets to independent mastering of the cognitive demands of that level (Perkins, 2010).

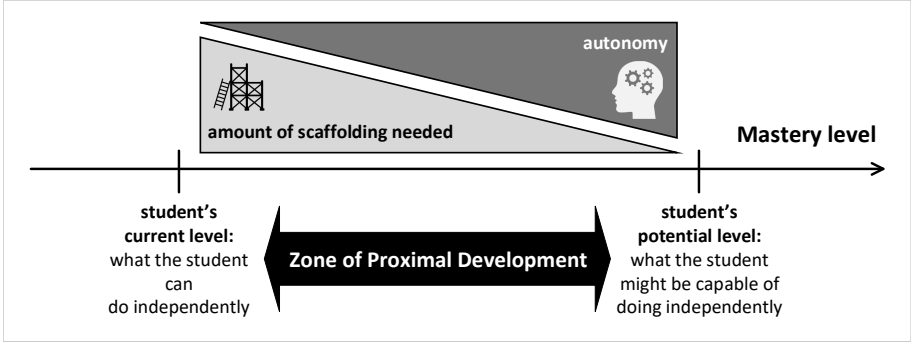


Figure 2.5: A student's Zone of Proximal Development

While teachers scaffold their students' progression through their zone of proximal development, they should emphasize that *learning*, rather than intelligence, is valued (Dweck, Walton, & Cohen, 2014). Teachers should point their students to the fact that mistakes are just opportunities for learning (Dweck et al., 2014). When their efforts, focus, and persistence are praised, rather than their performance, students gradually adopt a growth mindset, which will incite them to try out even more challenging tasks (see `https://youtu.be/Yl9TVbAal5s`). A growth mindset even manifests itself through brain activity that corresponds to conscious allocation of attention to mistakes, and improved subsequent performance (Moser, Schroder, Heeter, Moran, & Lee, 2011). To foster students' growth mindset, Boaler (2015) suggests designing learning activities that involve risk-taking, curiosity, failure, and problem-solving strategies. Indeed, activities involving problem-centered, and inquiry- or design-based learning lend themselves very well to this end. Instructional strategies tackling students' misconceptions and stimulating conceptual change might deliberately build in opportunities for students to make mistakes. In such activities, student reflection, instruction of metacognitive strategies, formative evaluation, and diagnostic feedback emphasizing learning play a crucial role (Boaler, 2015).

Fostering student reflection is an important facet of scaffolding, and therefore, of coaching (Stover, Kissel, Haag, & Shoniker, 2011; Murphy, Mahoney, Chen, Mendoza-Diaz, & Yang, 2005; Coulson & Harvey, 2013). A good coach urges the learner to synthesize what s/he learned, to demonstrate his/her newly acquired abilities, to reflect on his/her own progress, and to diagnose and remediate his/her learning impediments (Merrill, 2002; Collins et al., 1989). Frequent feedback and prompts provided by the teacher(s) should automatize student reflection and foster their critical thinking and self-regulation (Barron & Darling-Hammond, 2008; Paris & Paris, 2001; De Corte, Verschaffel, & Masui, 2004). In turn, metacognitive reasoning or reflection on one's own thinking leads to "more rapid acquisition of expertise" (Felder & Brent, 2016, p. 201). Instruction on metacognitive reasoning includes explicit demonstration of the kind of questioning and techniques required in problem solving (e.g., experimenting, searching for underlying principles, arguing, activating prior knowledge, and constructing diagrams), instead of mere directives to use them (Kistner et al., 2010; Paris & Paris, 2001; Dignath-van Ewijk et al., 2013; Van Heuvelen, 1991).

A catalyst for students' self-regulated learning towards personal improvement is formative evaluation (Quinton & Smallbone, 2010). In contrast to summative evaluation, which results in final grades that locate a student's performance with respect to those of their peers in the classroom, formative evaluation shows the student's individual progression with respect to his/her previously diagnosed level of performance (Felder & Brent, 2016). Formative evaluation should be aligned with the learning goals (Guzey, Moore, Harwell, & Moreno, 2016) and should aim to enhance students' self-efficacy and independent learning (Quinn, 2005). Rubrics are transparent assessment instruments that focus on progression, and in which the proximal levels of mastering of certain knowledge or skills are made explicit (Barron & Darling-Hammond, 2008). They provide a powerful tool for self-, peer- and teacher-evaluation (Goovaerts, De Cock, & Dehaene, 2015) and can guide student learning (provided that the evaluation is accompanied with constructive feedback) and teacher interventions (Perkins & Unger, 1999; Boaler, 2015).

Students are not always keen on engaging in learning activities promoting self-regulation and prefer to adopt a rather passive attitude (Weimer, 2002). Nevertheless, teachers should fight the temptation to resort to traditional (teacher-centered) strategies. It is, however, important to always announce the reasons for using these student-activating strategies to students at the beginning of each classroom activity, that is: how these strategies are connected with the learning objectives, and how research has shown evidence of improved student performance (Felder & Brent, 2016).

Furthermore, not only teachers' classroom practices, but also other factors, such as teachers' knowledge and attitude, and teaching context, play a major role in the implementation of iSTEM education (Thibaut, Knipprath, et al., 2018b) (see Chapter 4). Stolk et al. (2016) and Satchwell and Loepp (2002) identified some important prerequisites of these factors for the successful implementation of iSTEM education:

- collaboration among teachers, administrators, and other stakeholders, and sufficient time;
- reflective actions: planning, evaluation, debate, and problem solving with the aim to improve designed materials and classroom practices;
- support by external experts, extensive training and follow-up;
- supportive resources from which suitable contexts and student challenges can be elicited;
- holistic focus on curriculum, classroom practices, assessment, sustainability;
- continuation by the school for a long period of time; and
- a change in teachers' beliefs, knowledge, and skills towards an approach that is congruent with the key principles and the promotion of students' self-regulation.

2.5 Design principles for iSTEM education

From the combination of the key principles, described in a previous section, **design principles** were derived, which should guide the curricular design of iSTEM education (Singer et al., 2000). They are in line with those established by Berland (2013), who promotes content contextualization, learning-goal specification, inclusion of engineering practices, building in the need for students to learn STEM concepts for successful project completion, and alignment with the national standards. This section briefly discusses the design principles, and finally translates them into a list of requirements on learning materials for high-quality iSTEM education, as can be seen in Figure 2.6.

2.5.1 Formulation of a challenge

Relevance

The challenge or driving question must be relevant, either to real-world issues, or to the students' personal daily life, and preferably to both. If the challenge is authentic and approximates a real-world problem, it illuminates the necessity of integrating scientific, technological, engineering, and mathematical knowledge

and practices. In terms of cognitive and practical demands, the challenge should be adapted to the student level and to the access to equipment. The final solution to the challenge might be a design that answers a certain need, or the conclusions of an inquiry.

Multiple subproblems and multiple solutions

The challenge consists of several consecutive or free-standing subproblems which demand increasingly complex knowledge and skills. Each subproblem builds on prior knowledge or knowledge constructed by students while they were solving a previous subproblem. The challenge is furthermore formulated in such a way that it is open-ended. This means that there are multiple possible solution strategies and/or multiple possible solutions.

Need for STEM learning content

The challenge is designed in such a way, that it naturally evokes the need for understanding and connecting STEM concepts and skills. This constantly emerging need is meant to keep students motivated for solving the challenge, and thus for learning, throughout the learning units. Frequent recaps will remind the students of why they are studying certain concepts and of how crossdisciplinary connection is useful to finally solve the challenge. The challenge ensures the coherence and integration of what students are learning.

2.5.2 Addressing of STEM learning contents

Curriculum standards

The choice of integrated learning contents is rooted in the standards of the national STEM curricula. The separate STEM curricula contain an exhaustive amount of contents teachers must address in their STEM courses. Integration of these STEM contents can reconcile curriculum coverage with meaningful learning and application of these contents. However, the standards of the course curricula are formulated in a very restrictive and introspective way: conceptual knowledge is constructed according to a monodisciplinary learning trajectory and the standards leave little room for crossdisciplinary connections. An open-minded interpretation and creativity should be brought to bear in order to distill from the separate curricula valuable learning contents, and standards that favor connections across the different STEM disciplines.

Explicit integration

The iSTEM learning materials contain explicit links across the STEM disciplines. Crosscutting concepts are explored and connected through an alternation of modeling and abstraction with hands-on experiences. Integration is established in such a way that it expands students' mental maps but also strengthens their understanding of the concepts and interconnections among them. Whenever crosscutting concepts are addressed in the learning units, they are explicitly linked to related concepts in other STEM disciplines.

2.5.3 Design of learning activities

Constructive alignment

The learning activities are developed with the primary purpose of establishing the desired learning goals. These goals are made explicit at the beginning of each learning activity. Formative evaluation and exchange of feedback is interwoven with the activities, aiming to inform students and teachers about the student progress, to detect learner needs, and to verify student outcomes with respect to the formulated goals. Through frequent assessment and scaffolding, students are challenged to think creatively and question their own working methods and conclusions.

Student activation through inquiry, design, and cooperation

The learning activities are developed in such a way that they urge students to take control over their own learning process. Active engagement in a combination of mathematical and computational reasoning, modeling, scientific inquiry, and/or technological design positions students at the intersection of the different STEM disciplines. Students cooperate in small teams in such a way that their individual learning and progression depends on the success of their team members.

Compliance with research findings

The learning activities are based on findings from research on (conceptual) learning. The literature produced by discipline-specific and/or pedagogical research does not only point out regular and persistent student conceptions, but also provides effective strategies to accommodate them.

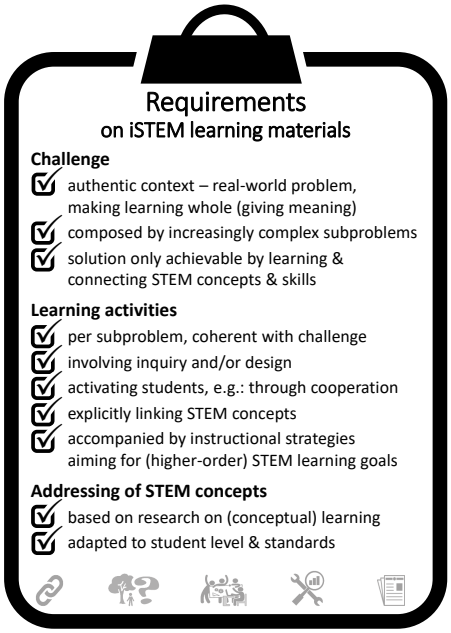


Figure 2.6: List of requirements for high-quality iSTEM education

2.6 Conclusion

An integrated approach towards STEM education encourages students to actively connect the different STEM disciplines in order to solve a real-world, complex inquiry or design problem. This chapter formulated the learning goals for the students who enroll in iSTEM education. iSTEM students should be able to apply and integrate concepts and practices across STEM disciplines in order to solve problems, conduct meaningful investigations, engage in creative design, work in close cooperation with their peers, and reflect critically on their own learning process. Based on an extensive literature review, these learning goals were translated into five key principles that underpin high-quality iSTEM education: (1) integration of STEM learning contents, (2) learning centered around an authentic, real-world problem, (3) inquiry- and design-based learning, (4) cooperation with peers, and (5) conceptual learning, rooted in educational research. These key principles resulted in design principles (criteria for the curricular design), which were briefly summarized and crystallized into a checklist of requirements on high-quality iSTEM learning materials.

Chapter 3

Design of iSTEM education

3.1 Introduction

A new approach to STEM education calls for the design of new curricular materials. Curricular materials are a combination of learning objectives, topics, course books, equipment, learning activities, and instructional strategies (Shawer, 2017). iSTEM learning materials are curricular materials that integrate STEM contents throughout students' secondary school years according to the key principles discussed in Chapter 2. However, for learning materials to be adopted and sustained by teachers, the primary users of such materials, they should be standards-based (Deboer, 2002). As standards are tied to educational context, customized iSTEM learning materials, that are aligned with localized needs and national standards need to be designed (McFadden & Roehrig, 2017). To empower teachers and to make them feel comfortable to apply such materials in the classroom, they should better be involved in this design (Stolk et al., 2016; Coenders & Terlouw, 2015) (see also Chapter 4).

Although the implementation of teacher design teams (TDTs) in curricular innovation has gained much interest in educational research, often in the scope of professional development (Binkhorst, 2017; Huizinga, Handelzalts, Nieveen, & Voogt, 2015; Voogt et al., 2011), there is little in-depth research on teacher endeavors to design iSTEM learning materials. Guzey, Moore, and Harwell (2016) examined such effort by analyzing 20 iSTEM learning units designed by teams of Science teachers. The units were produced during a three-week summer course, and iteratively improved via classroom testing. The design teams seemed to struggle with integration of the STEM disciplines: in some learning units,

the integration was inferior to the formulation of an engaging design challenge (Guzey, Moore, & Harwell, 2016).The integration of math content was the least present STEM component, probably because of the teachers' smaller subject-matter knowledge in math (Guzey, Moore, & Harwell, 2016). Effective formative and summative assessment was lacking in almost all learning units, while such assessment could provide evidence of student understanding and emergent needs for unit improvement (Guzey, Moore, & Harwell, 2016). Also James et al. (2000), who examined teachers' experiences after designing learning units that integrated math, science, and technology (software use), found that the teacher design teams struggled to integrate math. This might be due to Math teachers' perception of lack of time, or inability to reconcile math curriculum standards with the goals of the iSTEM units (James et al., 2000). Guzey, Moore, and Harwell (2016) concluded from their study:

> [I]ntegrated or interdisciplinary science curriculum is not a new concept; however, designing instructional materials for integrated STEM education is new for many teachers. Put simply, there are few resources available for teachers to help them develop integrated STEM curriculum materials and designing curriculum materials is a complex process. (Guzey, Moore, & Harwell, 2016, p. 14)

Stolk et al. (2016) implemented a framework for designing new curricular materials for context-based chemistry instruction among six teachers during five 3-hour meetings. He found that implementation of pre-designed learning units, and collaborative design of a new learning unit empowered teachers for teaching and designing such instruction. However, even though they got the opportunity to try out example materials in their classroom, the teachers struggled to creatively design a new contextualized student challenge. Satchwell and Loepp (2002) studied the 3-year lasting design process of a team of nine competent middle-school STEM teachers (three math, three science, and three technology teachers) in their effort to assimilate concepts from as many STEM disciplines as possible into integrated learning units. For each of the 20 designed units, the teacher team (1) identified a shared theme based on the national Math and Science standards, (2) created an introductory challenge to raise students' interest, (3) designed learning materials in which students had to explore, study, and apply new concepts, and (4) developed authentic student assessment instruments. The learning units were reviewed on content by STEM experts, and also feedback from field-tests and classroom visits was incorporated. Satchwell and Loepp (2002) state that "[t]he development of a standards-based, integrated mathematics, science, and technology curriculum is a challenging task" (p. 16) and indicate that the development of a framework, field testing, collection of feedback, reflection, and revision are important parts of the design process.

None of these studies, however, elaborates on the actions and/or difficulties constituting teachers' design processes, even though this is invaluable information to future efforts in constructing and improving iSTEM education (Guzey, Moore, & Harwell, 2016). The research presented in this chapter aims to fill this gap by means of an in-depth study of the steps, challenges, pitfalls, and opportunities encompassed by the process teachers go through when designing iSTEM learning materials. As this work aims to examine the process and the support needed by the teacher design teams, the research question addressed in this chapter is:

RQ1: How can the process teacher teams go through when designing iSTEM learning materials be modeled? Which steps can be identified in the design process?

i) What are important steps?
ii) What are unimportant steps?
iii) What are missing steps?

RQ2: Which model do these findings and the research literature suggest with the aim to support teacher teams in designing iSTEM learning materials for high-quality iSTEM education?

By recording, analyzing, and evaluating the actions of the **design process** teachers go through, this research can provide insight into the guidelines teachers need for designing learning materials that meet the requirements for high-quality iSTEM education. Section 3.2 discusses the research methodology and the analysis of the steps and actions comprised in the observed process. Section 3.3 shows the steps that were observed in the studied design processes, and illustrates these steps by means of the observations. Afterwards, the important and missing steps in the observed processes are identified by verifying whether and how the requirements are met by the designed learning materials, and tracing this back to what has happened during the design process (RQ1). In Section 3.4, these important and missing steps, strategies to anticipate the pitfalls, and additional tips from the research literature are combined into a support model to guide teacher teams in their efforts to design high-quality iSTEM learning materials (RQ2): CODEM for iSTEM (Collaboratively Organized Design of Educational Materials for integrated STEM).

3.2 Research method

3.2.1 Setup: case study

The design of learning materials that comply with the key principles behind iSTEM education is basically the design of a product that meets certain requirements. This task can therefore be regarded as a real-world, complex problem that encompasses a complex solving process towards a product that can immediately be implemented in practice. Furthermore, it involves interactions among people with differing expertise (practitioners and researchers), which in turn introduces multiple, mutually-dependent variables (participants' background, dynamics, means, approaches, outcomes). These features, and several others (see Appendix B), are the characteristics of the kind of process that is commonly studied through **design-based research** (Barab & Squire, 2004; Reeves, Herrington, & Oliver, 2005; Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003; Kelly, 2004). Design-based research aims to construct a theory while solving a real-world problem (Reeves et al., 2005). As these arguments comply with the aim of the study presented here, design-based research seemed the appropriate methodology for this study.

In design-based research, the process under study is considered a 'design experiment' (Cobb et al., 2003). The scientific-engineering approach is to construct a model from this design experiment, and to investigate this model to verify whether its outcome agrees with the design practice in reality (Van Driel & Verloop, 1999). The model needs to represent the process under study. According to Hommes and Van Reijswoud (2000), a process can be defined as a chain of organizational activities, with a beginning, an end, and in- and outputs, that are carried out in order to accomplish a certain product. A process can thus be modeled by determining its constituting *activities* or *steps* and the order in which they were carried out (Hommes & Van Reijswoud, 2000).

Such a model can be deduced from different cases (i.e., different design experiments) (Eisenhardt & Graebner, 2007). Therefore, **case study** was chosen as method to conduct the design-based research. According to Deaton and Malloy (2017), "[t]he blend of case study and design-based research provides a systematic approach to examining instructional innovations that are bounded by perspective, context, and time" (p. 72) (see also Case & Light, 2011). An important constraint of case-study research is that the context-dependent features cannot always be clearly distinguished from the process under study. Furthermore, the process does not happen under controlled experimental conditions. Hence, the results are context-dependent and should be interpreted as such (Kitchenham, Pickard, & Pfleeger, 1995; Balbach, 1999). However,

case-study research provides a way to observe and interpret what actually happens, in order to get insight in possible links between the process and the outcome (Balbach, 1999).

To construct a model of the process under study, case-study research makes use of direct interpretation and categorical aggregation within the separate cases (Stake, 1995) and synthesis across the cases (Yin, 2013) (see Section 3.2.4). As such, the activities or steps that will constitute the model, emerge bottom-up from the data gathered during the process (Eisenhardt & Graebner, 2007). By means of the empirical data gathered in the successive cases, the identified steps are iteratively confirmed or rejected and, as such, the model is refined (Van Driel & Verloop, 1999; Deaton & Malloy, 2017; Yin, 2013).

Because in this type of qualitative research, the events and the emerging steps in the process under study are socially constructed, validity can be established from three perspectives (Creswell & Miller, 2000). In the first place, validity is determined by well-founded judgment and reflection of *the researcher*: s/he determines the duration of the experiment, the amount of data necessary to identify recurring steps, and a procedure of analysis to extract a persuasive model from the data. While doing so, s/he iteratively returns to the data, trying to make sense of what s/he has observed. Secondly, validity can be established from the perspective of *the participants*, who can check how accurately the events are represented in the model and how complete the model is (Hommes & Van Reijswoud, 2000). Finally, *outsiders* or reviewers who are not affiliated with the project can verify the suitability, coherence, and comprehensibility of the model from their perspective (Hommes & Van Reijswoud, 2000). The data and resulting models of this study have been subjected to scrutiny with the lens of each of these three groups, by means of different validation procedures, as described by Creswell and Miller (2000). Throughout these procedures, triangulation was applied: multiple sources and types of evidence were gathered and checked by multiple actors (Golafshani, 2003), so the constructed models are looked at from different perspectives (Baxter & Jack, 2008). It is a way to strengthen a qualitative study and to deal with the fact that the researcher and the process under study are by nature inseparable (Creswell & Miller, 2000).

For constructing a model of the observed design processes, and evaluating the importance of the identified steps (RQ1), the following validation procedures were used:

1. First, the steps in the design processes of the different cases were identified and a representative model was constructed based on the data gathered through design-based case-study research. Multiple sources of evidence constituted this data (Yin, 2013): observations, meeting reports, field notes, informal conversations, and audiorecordings. The studied cases were

four design experiments conducted by different teams of teachers involved in the program STEM@school (see Section 1.2 of Chapter 1). As observer and team coordinator in three of the cases, and as mere observer in the last one, the researcher built a better understanding of why some decisions were made.

2. A participant of three of the cases was asked to draft his own model of the design process as he had experienced it. Comparing the model constructed through the case study with his impression of the design process would enable to verify the veracity, or representativity, of the constructed model (Van Driel & Verloop, 1999).
3. The important, unimportant, and missing steps of the model were determined by means of the product of the design experiments. The learning materials designed in each case, were collected and analyzed by three researchers affiliated to STEM@school (among whom also the main researcher of this study). The learning materials were evaluated on the requirements of high-quality iSTEM education (see Figure 2.6 in Chapter 2). Apart from this, the steps observed in the cases were linked to each of the requirements based on the relatedness of the actions within each step to each requirement. This was done by an external researcher (not affiliated to STEM@school). By comparing the occurrence or absence of the steps with the fulfillment or failing of the requirements for each case, the value of each step could be assessed.

For constructing a model to support teachers' design process (RQ2), the following validation procedures were used:

1. The important steps and pitfalls determined in the previous part were gathered, and enriched by instructional tips from the research literature to assemble the support model.
2. This support model was subjected to critical review by the team coordinator of one of the cases, and by a teacher who had been involved in the design teams of STEM@school but had not participated in the observed cases. These two internal reviewers were asked to comment in writing upon the completeness, coherence, and suitability of the model (Hommes & Van Reijswoud, 2000).
3. To check the comprehensibility and suitability of the support model (Hommes & Van Reijswoud, 2000), it was tried out by outsiders in two workshops: one at an international conference, and one at a professional-development training in a school that was not affiliated to STEM@school. Through unstructured interviews, the experiences of the participants with the model were gauged.

3.2.2 Selected cases

For the design-based case-study research in this work, cases were sampled from the teacher design teams (TDTs) participating in the project STEM@school. By comparing the events happening in the several cases, a trend in their processes of designing iSTEM learning materials could be detected. For this purpose, one case in its particular context and with its particular team composition would not supply sufficient data, and a multiple-case study therefore appeared appropriate (Balbach, 1999).

In case-study research, the sampling of the cases should be purposive and should yield a lot of information (Mortelmans, 2007; Baxter & Jack, 2008). The number of studied cases depends on the amount of properties of the emerging activities (or steps) needed to clearly define and interrelate them. To enable identifying but also exploring the emerging steps in the process under study, the sampling criteria should control for variables that are known or expected to affect the process, but they should also allow variation in these influential variables (Mortelmans, 2007; Kitchenham et al., 1995). For this study, four cases were selected based on the criteria 'informational contribution', 'homogeneity', 'heterogeneity', and 'stage in the process' (Mortelmans, 2007). The application of these criteria will be illustrated when the context of the cases is explained.

From the three to four teacher teams who would design learning materials for the project STEM@school each school year, one case was selected per year to allow the researcher to fully capture the events occurring in the design process of a case. The team members of the cases were teachers from two types of secondary education: one providing a general formation (indicated by 'ASO'), and one with a more technical focus (indicated by 'TSO'). An overview of the four selected cases is presented in Table 3.1, and the background information on their team members can be found in Table 3.2. In each case, the design process lasted around 8 months (from September until April).

Being the team coordinator in three of the four cases, the main researcher of this study would have to take a bird's-eye perspective, while at the same time being immersed in the process. This would require her to stick to observations and evidence, and shove away personal emotions or opinions. Conversely, Mortelmans (2007) argues that the fact that the researcher is part of the process under study, is actually a good thing, because s/he gets to know the setting from inside out. Nevertheless, special attention was paid to reducing bias to a minimum: by the time the data were more or less crystallized into separate steps (see Section 3.2.4), the researcher chose to study the design process of a (fourth) case that would not be coordinated by herself. This would prevent her from steering the team of that case towards any identified step.

Table 3.1: Overview of the selected cases C1, C2, C3, and C4

Case	**Learning materials**		**Teacher team members**
Name	grade	Theme	Teacher names*
C1	gr 7	Motion 1D	C1_Math, C123_Physics, C123_Coordinator
C2	gr 9	Automatic car through green wave	C123_Physics, C23_TA, C23_Electronics1, C23_Math, C23_Electronics2, C23_Physics, C2_Math, C23_Principle, C123_Coordinator
C3	gr 10	Ball launcher	C123_Physics, C23_TA, C23_Electronics1, C23_Math, C23_Electronics2, C3_Electromechanics, C23_Physics, C23_principle, C3_Mechanics1, C3_Mechanics2, C3_Electronics, C3_Mechanics3, C123_Coordinator
C4	gr 11	Algae	C4_Math1, C4_Physics, C4_Bio/Chemistry1, C4_Math2, C4_Bio/Chemistry2, C4_Phys/Chemistry, C4_Biology, C4_Electronics, C4_Chemistry, C4_Coordinator

**For background information: see Table 3.2*

Case 1 (C1)

Case C1 took place 2 years before the start of STEM@school and can therefore be considered an exploratory case. A school, further referred to as 'ASO-A', picked-up on the international call for more stimulating STEM education. To get started within her school, the science coordinator contacted Prof. Wim Dehaene for advice. A team meeting was organized in which Prof. Dehaene was invited to demonstrate

his preliminary idea of what iSTEM education could look like. The teachers had the opportunity to present their proposals for student projects, which were critically revised by Prof. Dehaene. From this meeting with approximately 20 teachers, two of them decided to go along with his demonstrated approach and take their project a step further towards iSTEM. One teacher was a Math teacher in grade 7, the other teacher was a Physics teacher in grades 11 and 12 with a Master's degree in chemistry. Their design process was coordinated by the main researcher of this study.

The target group of the learning materials to be designed were students of grade 7 in general secondary education. In these classes, 5 periods a week would be gathered from complementary class periods and dedicated to a new course called 'STEM'. The teachers wanted to develop a learning unit to teach students about velocity. The theme these teachers chose for their project was 'Biking', which would soon be renamed 'Motion'.

Cases 2 to 4

Cases C2 to C4 were cases observed during the design phases of STEM@school (see Section 1.2 of Chapter 1). In total, 10 schools were elected to participate in the development of STEM@school learning units. The educational umbrella organizations had designated the participating schools based on their motivation and organization. Each of these schools delegated one team of teachers for the design of STEM@school learning materials. The participating schools were asked to schedule common meeting time on a fixed, weekly afternoon for these teachers. On these afternoons, monthly STEM-team meetings, and 2-monthly plenary group meetings were organized. In the first plenary meeting of each design year, the rationale of STEM@school was presented (or recited) to the participating teachers, and the approach to iSTEM education was proposed, in the form of the five key principles (see Section 2.3 of Chapter 2). During the design processes, team coordinators, who were researchers affiliated to STEM@school, supported the teams with information, scheduled team meetings, and set the deadlines for the final learning materials. They, however, never steered the actions undertaken by the team members. The coordinators asked questions for clarification on the actions or reasons behind them, but never pushed the team into following a certain direction for the design.

The target group and context of the learning materials to be designed were announced to be as follows. The learning materials would aim at the study options 'Sciences' of the general study track and 'Industrial sciences' of the technical study track in secondary education. The schools who would implement the designed learning materials would be asked to schedule around 3 class periods a week, gathered from complementary class periods, for a course 'iSTEM' (especially dedicated to inquiry- and design-based and cooperative learning activities), plus 1 period of each of the courses Math, Physics, Informatics, and other relevant courses (depending on the learning unit).

Case 2 (C2)

Case C2 took place during the first year of STEM@school. The design team of case C2 was composed of teachers from three schools, further referred to 'ASO-A', 'TSO-B', and 'ASO-C'. The Physics teacher from case C1 also took part in the design team of case C2. School TSO-B, a school providing technical secondary education, delegated two Electronics teachers, one Math teacher and one technical advisor (TA). The principle of school ASO-C, a school providing general secondary education, sent one Physics and one Math teacher, and participated in the design meetings himself as well. It is worth noticing that, although they were eager to participate in the design, schools TSO-B and ASO-C did not plan to implement the designed materials in the intended form in their classrooms, as they refused to create an iSTEM course. The technical advisor of school TSO-B gave as reason that they already were involved in many iSTEM initiatives, and rather wanted to set an example for other (technical and non-technical) schools who would contemplate setting up iSTEM education. The composition of these three school teams, who were all stationed in the same region, was imposed by the STEM@school research team with the main reason that meetings could easily be organized closeby to every participant. Case C2 was coordinated by the main researcher of this study.

Case 3 (C3)

Case C3 took place during the second year of STEM@school. Due to a reorganization of manpower, the four design teams that had started STEM@school were recombined into two teams. The team of case C2 was extended by four teachers of two schools: 'TSO-D' and 'TSO-E'. These two schools were located at a considerable distance from the schools of case C2 and from each other. Their distinct locations made synchronization, again coordinated by the main researcher of this study, challenging.

Case 4 (C4)

Case C4 took place in the third year of STEM@school. A whole new teacher team was chosen as focus of case C4. The teachers of this case had already been participating in learning-unit design for STEM@school for the past 2 years. Since these teachers (as well as STEM@school) wanted to broaden the integration of STEM disciplines by including biology and chemistry, the team composition of case C4 was rather dominated by teachers with a background in these disciplines. These teachers however came from different schools: 'ASO-F', and 'TSO-G'. The science coordinator of school ASO-A of case C1, who is also a Chemistry teacher, participated in this case as well. The coordinator of this team was a researcher of STEM@school (other than the main researcher of this study).

With these descriptions, the criteria based on which the cases were selected will become better understandable. From the ones outlined by Mortelmans (2007), following criteria for case selection played a role in this work:

- *informational contribution* – From all teacher design teams participating in STEM@school, the most unsuccessful teams were left out in the study. These were two teams who did not manage to get started with the design of iSTEM learning materials. Even though these would make interesting cases to examine in terms of motivation for curricular design, nothing about the actual topic of this study, i.e., the design process, could be learned if no process was taking place whatsoever. Furthermore, the teams of cases C1, C2, and C3 were selected because they would be coordinated by the main researcher of this study. The great deal of time allocated for this coordinator role would thus provide plenty opportunities to gather observations and data from these teams.
- *homogeneity* – Case C3 was selected as a case much corresponding to case C2 in terms of influential variables such as team composition, facilities (time and materials provided by the schools), learning content to cover, and team coordinator. Studying these similar cases would allow to explore the commonalities in their design process, and the reasons behind the refinement or omission of certain activities. Furthermore, it could inform the study about the evolution of a design process through the years.
- *heterogeneity* – Case C2 had a different team size and a different target group for the design than case C1. Case C4 consisted of completely different team members than case C3 (including the coordinator). By varying on the influential variables among the cases, other accents could be registered. The effect of the variation in these variables was, however, not the focus of this study. Instead, the question was: what is, despite the heterogeneity, common to the processes observed in these cases?
- *stage in the project* – Case C1 took place before the start of STEM@school, while case C4 ran at the end of STEM@school. Since transforming separated STEM education into integrated STEM education is a change process, the project stage in which the cases took place, mattered. Teachers at the start of the program were pioneers in iSTEM design and implementation. From what could be learned from this exploratory case, the outline and goals for the further rollout of STEM@school would be given shape. Conversely, being in the final design stage of STEM@school, the teachers of case C4, who had been involved in STEM@school from the beginning, could exhibit a more matured vision and approach to iSTEM education. This could shed light on what a process driven by more experienced teachers would look like.

Table 3.2: Background of the teachers of cases C1, C2, C3, and C4

Teacher name*	Sex	Age	Education	YoT	School
C1_Math	♀	>30	BEd Math	?	ASO-A
C123_Physics	♂	40	MSc Chem	10	ASO-A
C23_TA	♂	50	MEngTech Electro	?	TSO-B
C23_Electronics1	♀	>45	?	?	TSO-B
C23_Math	♀	>45	?	?	TSO-B
C23_Electronics2	♀	>40	?	?	TSO-B
C23_Physics	♂	46	MEngTech Electromech	10	ASO-C
C2_Math	♀	>40	?	?	ASO-C
C23_Principle	♂	55	MSc Math	33	ASO-C
C3_Electromechanics	♀	>40	?	?	TSO-B
C3_Mechanics1	♂	46	BEd Mech	22	TSO-D
C3_Mechanics2	♂	51	5B Mech	17	TSO-D
C3_Electronics	♂	38	BSc Electro	14	TSO-E
C3_Mechanics3	♂	57	?	?	TSO-E
C123_Coordinator	♀	29	MEngTech Electromech	3	KUL
C4_Math1	♀	57	MSc Math	36	ASO-F
C4_Physics	♂	54	MEngTech Electromech	12	ASO-F
C4_Bio/Chemistry1	♂	28	MSc Veterinary	4	ASO-F
C4_Math2	♂	?	MSc Math	?	ASO-F
C4_Bio/Chemistry2	♀	?	MEng Bio	7	ASO-F
C4_Phys/Chemistry	♀	46	MEng Bio	16	TSO-G
C4_Biology	♀	27	MSc Bio	4	TSO-G
C4_Electronics	♂	46	MEngTech Electro	16	TSO-G
C4_Chemistry	♀	46	MSc Veterinary	15	ASO-A
C4_Coordinator	♀	29	MEngTech Chem	5	KUL

**For case information: see Table 3.1*

? = participant chose not to provide this information

3.2.3 Data collection

For this study, various sources of data were gathered and consulted. The main data sources were the *observations* from STEM-team meetings and plenary meetings, and the *meeting reports* and *field notes* written down by the team members, researcher, and other team coordinator. During these meetings, the teachers' occupations and progress in the design process were registered, but also

informal conversations provided useful information. The topics that dominated certain meetings were considered an indicator of the teachers' concerns and design approach.

Next to these observations, the *e-mails* sent among team members and coordinators served as a secondary data source. Also more formal documents, such as *reports* and *powerpoint presentations* for internal use and for external communication, e.g., with the pedagogical support of the umbrella organizations, supplemented the data set. Furthermore, information was retrieved from *annual course schedules* made by the teacher teams.

Case C4 was followed up more intensively by the researcher: for this case, she audio-recorded team meetings, transcribed relevant discussions, labeled excerpts and inserted them into a matrix with different dimensions, as suggested by Mortelmans (2007). An example is shown in Table 3.3. Through this labeling, the researcher could unravel general topics, actions, key issues, tactics, decisions and the reason for these discussions.

Although the participants' personal attitudes and beliefs, interpersonal relations, and the team coordinator's style could have affected the design processes (Binkhorst, 2017), these factors were not examined in depth as they were not the focus of this case study. Nevertheless, they were not simply ignored. Teacher and coordinator aspirations, emotions, and reflections were registered in the form of *memos* which were taken into account during the analysis of the observations.

For verifying the representativeness of the model of the observed design processes, teacher C123_Physics was asked to make a *draft of the design process* as he had experienced it.

For determining the important, unimportant, and missing steps of the observed design processes (RQ1), the *learning materials* designed by the teams of each case were gathered. Because these materials were the outcome of the design process, their compliance with the requirements for high-quality iSTEM education could be traced back to what did or did not happen in the design process. In a *debriefing meeting* after each case, the researcher consulted the project leader of STEM@school, Prof. Wim Dehaene, and a colleague-researcher to evaluate the designed learning materials against the requirements for high-quality iSTEM education.

For evaluating the support model (RQ2), the following data were gathered: the *written comments* on the support model by C4_Coordinator and another teacher who had designed STEM@school learning materials (however not in one of the studied cases), and the *oral testimonies* of the external researchers and teachers who participated in the workshop trial of the support model.

Table 3.3: Observation-scheme example from C4

Time	Sept 6th, 2016 (three weeks since previous meeting) - 1,5 h
Place	Meeting room school ASO-F & (via Skype) classroom school TSO-G
Goal	Quest for suitable theme
Activity	Meeting about theme
Actors	C4_Coordinator, C4_Math1, C4_Physics, C4_Bio/Chemistry1, C4_Math2, C4_Bio/Chemistry2 & (via Skype) C4_Phys/Chemistry, C4_Biology, C4_Electronics
Objects	-
Actions	Brainstorm
Events	– Proposal of new idea for theme, because of "many information available and more easily manageable" – Discussion about including "design of experiments" (C4_Physics) – Debriefing of conversation with expert – Propositions of learning contents – Agreement to search for alternatives – *Skype connection with TSO-G* – Acquaintance with new team members – Reporting of company visit – Discussion of new idea, conclusion that it takes too much time – Listing of theme options (by C4_Coordinator) – Proposal to combine themes – Proposition to study contents inherent to themes (by C4_Coordinator) – Proposition to have students build something and let learning goals emerge from that (by C4_Physics & C4_Phys/Chemistry) – Conclusion about further approach (by C4_Phys/Chemistry) – Reminder to keep integration between math, chemistry, bio, electronics, and electricity in mind (by C4_Coordinator) – Agreement to meet in two weeks and decide about theme then – Discussion about student team-work approach – *Skype disconnection with TSO-G* – Discussion about possible extra learning content math
Atmos-phere	– Chaos; enthusiasm about certain design approach (C4_Physics), no objections / openness to shuffle learning contents over school year or grades (C4_Math1, C4_Bio/Chemistry2 and C4_Biology), hesitation about pre-allocation (C4_Bio/Chemistry1), disappointment about sequence appointed by curricula (C4_Physics) – Interest (C4_Phys/Chemistry & C4_Biology), enthusiasm over amount of possibilities (C4_Bio/Chemistry2) – Enthusiasm for design (C4_Physics & C4_Phys/Chemistry) Resistance against mutual dependency of student teams (C4_Math1) – Fearlessness of extra work / study (C4_Physics & C4_Bio/Chemistry2) – *Teachers display large content knowledge.*

3.2.4 Cross-case analysis

The data gathered during the observed design processes were subjected to direct interpretation and categorical aggregation within the separate cases (Stake, 1995) and synthesis across the cases (Yin, 2013). Within a case, the researcher first made direct interpretations of individual events and actions undertaken by the participants: in her field notes, she attached meaning to a collection of impressions during design meetings (Stake, 1995). Actions interpreted as similar or related, were then aggregated to form a class (Stake, 1995). Such a class will from hereon be referred to as an *activity* or *step*. The steps were consolidated by means of secondary data (presentations, e-mails, reports, informal discussions) (McFadden & Roehrig, 2017).

With each case, the steps identified in the previous case(s) were further refined by evidence from the new case. The new and older data were subjected to selective coding (McFadden & Roehrig, 2017; Mortelmans, 2007), in which the researcher looked for case-specific actions on the one hand, and reappearing actions on the other hand (Mortelmans, 2007). While doing so, she challenged her data interpretation and aggregation to assert the adequacy of the steps that were yet identified (Stake, 1995). The overall sequence in which the steps occurred was determined as well. The steps together with their sequence, emerging, as such, bottom-up from the data, would constitute the model to be constructed (Eisenhardt & Graebner, 2007).

The memos on the team members' motivations, intentions, purposes and feelings as well as on the team dynamics were considered in the data interpretation, with the purpose of situating the emerging actions in their case-specific context.

3.3 Observed design processes

In order to answer research question RQ1, this section first reports the findings from the case study in a concise manner (Baxter & Jack, 2008). In a chronological order, the steps that could be identified, as well as the cases in which they were observed, are presented (Yin, 2013; Baxter & Jack, 2008). They are illustrated by the evidence that was gathered from observations, e-mails, and conversations of each case. The important, unimportant, and necessary steps of the observed processes are then determined by means of the evaluation of the learning materials designed in each case.

3.3.1 Phases and steps identified in the design processes

An overview of the observed design processes is shown in Figure 3.1. Overall, five phases could be distinguished in the design processes:

- context analysis,
- theme selection,
- content/challenge brainstorm,
- reporting, and
- development.

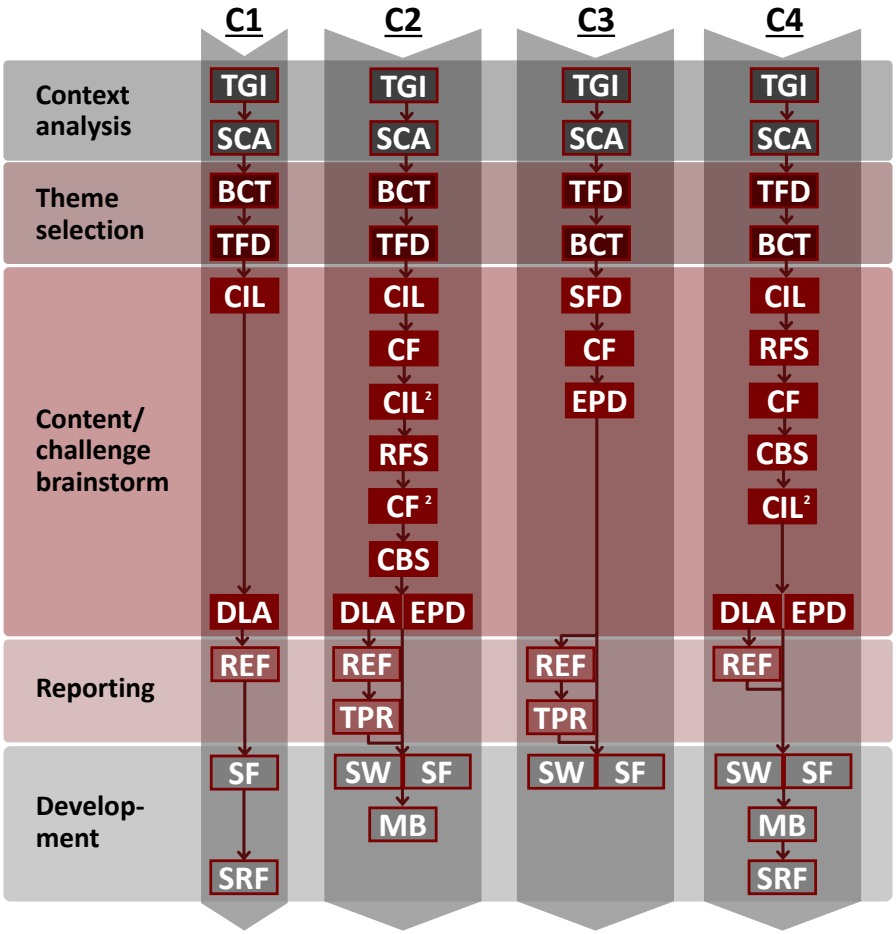


Figure 3.1: Model of the phases and steps identified in the design processes studied in cases C1, C2, C3, and C4

The first two phases of the design process were in each case found to occur in a big multidisciplinary group of STEM teachers. At the end of the 'Theme selection phase', this big group was split up into smaller STEM teams, of which one per case was followed up further.

Context analysis phase

In the Context analysis phase, two steps could be distinguished that were carried out in a big group of teachers in all of the cases:

- target-group identification, and
- specific context analysis.

Target-group identification (TGI)

As a first step, the (big) group of teachers identified the target group, i.e., they decided for which group of students they would design the iSTEM learning materials. This step merely encompassed the making of a justified decision.

The teacher group in C1 was determined to design for students of grade 7 in general education, who would specifically choose for an 'iSTEM' study track. By choosing to start an iSTEM implementation in grade 7, the teachers could set the tone for the following six years of these students' trajectory in secondary education.

This step also took place in case C2, but was carried out by the research team of STEM@school before the teacher teams started the design proces. The research team wanted to start with students who would already have a notion of some basic mathematical, scientific, and technological concepts, since this prior knowledge would give the teacher design teams a basis for integration. The choice of target group is explained by the STEM@school project proposal:

> We start in the 3rd year of secondary school. ... [B]y starting in [grade 9], we can involve teachers at professional bachelor level and at master level from the beginning of the project. The study programs we will address are situated in the general and the technical education track. We will focus on those study programs that already provide a substantial amount of science and mathematics curriculum contents, as the primary goal of our project is to turn STEM oriented study programs into true [i]STEM study programs. (Dehaene, Knipprath, et al., 2013, p. 20-21)

STEM@school aimed to continue the iSTEM education of this target group. Therefore, as cases C3 and C4 succeeded case C2 within STEM@school, the learning materials designed in these cases naturally targeted the same group of students, but in grades 10 and 11, respectively.

Specific-context analysis (SCA)

In a next step, that was observed across all studied cases, the group of teachers performed an analysis of the specific context in which the designed learning materials would be implemented. This step entailed figuring out the constraints of the curricular design: (1) the prior knowledge of the target group, and (2) the objectives these students would need to achieve in terms of STEM knowledge and skills. To this end, the teachers gathered the national curricula of the separate STEM courses (Science or Physics, Mathematics, Technology, and Engineering) of grades 7 and 8, grades 9 and 10, and grades 11 and 12 (some standards are formulated per two grades). Through analysis of these curricula and classification of the curriculum standards, the teachers extracted learning contents that already had been addressed in the previous grades, or that had to be addressed in the STEM courses of the targeted grade. These learning contents were discussed within the group.

Theme selection phase

In the Theme selection phase, two steps could be distinguished:

- brainstorm on learning contents and themes, and
- team formation and theme/content division.

Brainstorm on learning contents & themes (BCT)

In all cases, a brainstorm took place in which the previously-established learning contents were grouped and regrouped to identify overarching themes that could unite these contents. Such a theme was found to function as a common ground based upon which crossdisciplinary conversations were held. After the specific-context analysis, in which the teachers had been registered arguing in terms of their own discipline, this step was found to facilitate getting the teachers of all different STEM disciplines on the same page. Several themes were detected that had a minimal overlap in terms of learning contents to be covered.

The group of teachers involved in case C1 decided to develop multiple smaller learning units. The themes they identified in this step, were gathered in a spreadsheet together with the related learning contents per STEM discipline. The themes selected in case C1 were: ‘electric circuits’, ‘computer communication’, ‘health’, ‘microscopy’, ‘biking’, ‘biotopes’, ‘robots’, and ‘(bio)plastics’.

In case C2, the brainstorm on learning content and themes was done by a select, but multidisciplinary group of teachers. Figure 3.2 is taken from one of the first plenary design meetings and shows the result of this brainstorm. As can be seen in the figure, the themes were indicated by physics disciplines, and no technological contents were included.

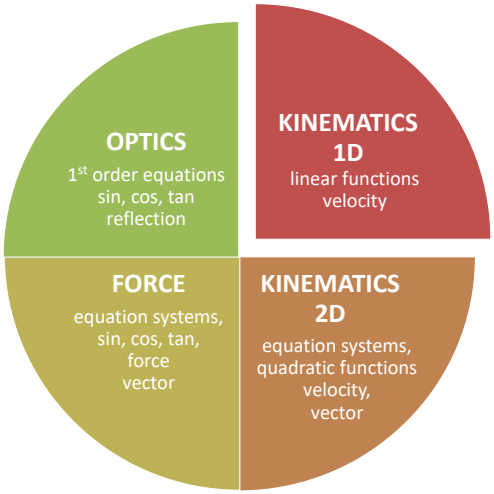


Figure 3.2: Themes selected in C2

In cases C3 and C4, also a brainstorm on themes was conducted, but only *after* the formation of the STEM team (see step 'TFD'). The team studied in case C3 was asked to develop learning materials which would address the learning contents on quadratic functions and vectors, taught in Math, and 2D kinematics and conservation of energy, taught in Physics. The team coordinator proposed to work with the theme 'hovercraft', since another team had already done a lot of exploratory work on that theme in the previous design year of STEM@school, and had managed to embed the learning contents and theme into a socially relevant problem. Two team members countered this proposal with the theme 'ball launcher', because they had some experience with student projects on trebuchets. The team members decided to continue with this theme because they found the design of a ball launcher a nice way to integrate and to visibly demonstrate the targeted learning contents.

In case C4, the team was found to spend several meetings on this brainstorm step. Whereas up until this moment, only contents from the courses Physics, Technology, Engineering and Math had been integrated, the team studied in case C4 wanted to expand the integration of the STEM disciplines and include learning contents from the courses Chemistry and Biology. During several design meetings, the team members were recorded to share multiple ideas, such as: 'water treatment' (initially proposed by the team coordinator), 'hydroculture/indoor farming', 'batteries', 'composting', 'geothermal energy', 'bioplastics', and 'algae'. The team went back and forth between these ideas and discussed the learning contents that could be connected to the different themes. Although they decided to gather more information on the different themes, the greatest common divisor of the targeted learning contents, seemed to be the theme 'water treatment'.

Team formation & theme/content division (TFD)

In this step, the big group of teachers was split up into several smaller design teams. Apart from case C1, this step was carried out by the research team of STEM@school to increase the individual engagement of the participating teachers and to increase the efficiency of the design work (Morgan, 2015). In each case, the teams were formed in such a way that their members were teachers of different STEM disciplines. The learning contents and/or themes identified in the previous step were now divided among the teams.

In case C1, the bigger group split up into three smaller design teams of two or three teachers who would also implement the designed learning materials in the classroom afterwards. The two teachers of the team followed in this case study decided to work with the theme 'biking', which they changed into 'motion 1D'.

In cases C2 to C4, the teams were formed in such a way that each team was composed of three to five teachers of at least one school in general education ('ASO') and three to five teachers of at least one school in technically-oriented education ('TSO'). As such, the characteristics of the two targeted student profiles (Sciences and Industrial sciences) were taken into account in each team, and each team had easy access to expertise and equipment in science, as well as in technology. In case C2, the geographical location of the schools of the team members was included as extra criterion for the team formation, as to facilitate the team gatherings. STEM@school delegated four (in C2) and later two (in C3 and C4) members of its research team to take up the role of team coordinators. The team coordinators were assigned to a team randomly, or according to the design experiences they already had with the team. As the teams were already multidisciplinary, the learning contents and/or themes were divided among the STEM teams according to the expertise of the team coordinators.

Content/challenge brainstorm phase

In the Content/challenge brainstorm phase, multiple steps could be distinguished:

- learning-content identification and linking,
- subteam formation and content division,
- challenge formulation,
- challenge breakdown into subproblems,
- requirements and feasibility study,
- experiment tryout, prototype production, and documentation, and
- design of S, T, and M linking learning activities.

From this phase on, the steps were carried out in the smaller teams composed in the step 'team formation and content/theme division' of the previous phase.

Learning-content identification + linking (CIL)

In this step, the design teams gathered the (mostly standards-based) scientific, technological, and mathematical concepts that were relevant to the selected theme, and discussed the possible ways in which these concepts could be connected. This step was observed in all cases, except C3. It was even observed again in the design process of cases C2 and C4 later in the design process, when these teams revised the list of learning contents to add extra concepts and skills necessary to solve the challenge formulated in a later step (see step 'CF'). These extra concepts and skills were not necessarily mentioned in the curriculum standards. The repetition of this step demonstrates iteration in the design process.

The most explicit occurrence of this step was observed in case C2. As in other cases, the learning contents were initially extracted from the curriculum standards, gathered in the previous step. For case C2, whereas the curriculum standards for Engineering were very generic objectives on inquiry or design, the standards of Computer Science mentioned programming structures, the standards of Physics and Applied Sciences revolved around the basics of linear motion and electric circuits, and the standards of Math addressed the use of variables, and linear functions. The team started quoting the learning contents per discipline. The digitized version of this team discussion is shown on the left of Figure 3.3. In the crossdisciplinary conversation registered next, the teachers quickly connected the mathematical 'linear function' to the scientific description of the position of a 'uniform linear motion' as a function of time. The teachers also discovered that a 'variable' is a concept common to analysis (math) and programming (technology). During iteration of this step, based on the preliminary challenge that was formulated (see further), even extra learning contents, and crossdisciplinary connections among the contents were established. The final result of this step was digitized into the overview on the right of Figure 3.3.

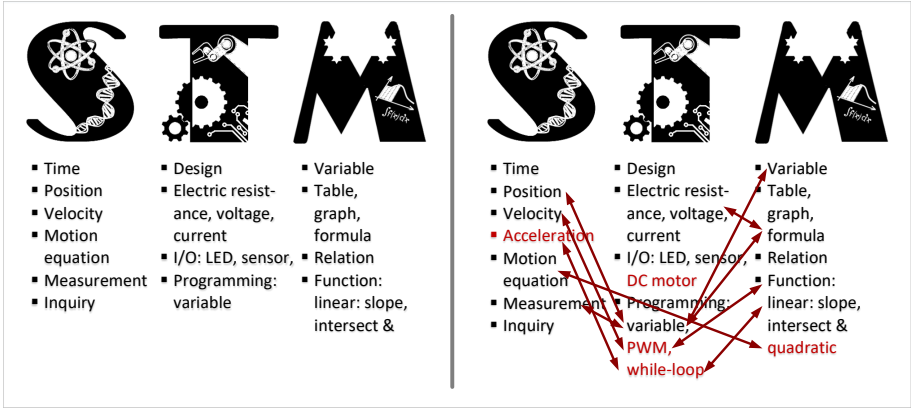


Figure 3.3: List of STEM concepts
after the first (*left*) and the second (*right*) encounter of step 'CIL' in C2

In case C4, the team members exchanged learning contents they associated with the theme 'water treatment' and which, according to them, appeared in the curriculum standards of the STEM courses. At one team meeting, two teachers summarized these learning contents and the crossdisciplinary connections between them:

> We made the exercise: what can be addressed from the learning contents in ... the curriculum of [grades 11 and 12]? In biology, it's indeed more about microscopy, mitosis: what is that? Eh, the connection with the growth charts, but that is the math. Photosynthesis, we thought. ... And then, more the biochemistry of what plants and algae consist of. The link with lipids, proteins, and which nutrients do we need to [grow] them. And then we get to the link with growth medium. ... Then, within chemistry, we [distinguished] determination of concentration and dilution, possibly, in preparing the media. ... And also, if we are working with acidity, if we are following that up in our medium, eh... we could develop some learning material on that as well. And eh... then, of course, also the separation and extraction techniques, if we want to go into... the isolation of the lipids. (C4_Bio/Chemistry2)
>
> What we would like to develop is, of course, eh... about [spectrophotometry]: precisely what it is, what the relation is between the concentration and the [light spectrum]. Eh, we also want to develop learning material on LDRs and phototransistors: what the relation is between the light intensity and the electric current. (C4_Physics)

Subteam formation & content division (SFD)

This step was only observed in case C3. In a design meeting after the one in which the contents and theme had been identified, teachers of the different schools of which the team was composed, did not agree upon the focus of the design. They all expressed their desire for a different focuses:

- a car controlled by two stepper motors (engineering teachers of school TSO-E),
- a ball launcher (engineering teachers of school TSO-B),
- the quadratic function described by a launched ball (math teachers of schools TSO-B and ASO-C),
- experiments on launching a ball (physics teachers of schools ASO-A and ASO-C), and
- a ballistic pendulum (engineering teachers of school TSO-D).

Accordingly, the team of case C3 split up into these small, monodisciplinary subteams who separated and went their own way.

Challenge formulation (CF)

In a meeting following the learning-content identification and linking, the teachers of case C2 came up with the idea to formulate an engaging challenge to which the

identified learning contents could be connected. Because this idea appeared to appeal to all design teams of STEM@school and was corroborated by the literature, this step was carried out in the following cases as well. The teachers' conversations in this step clearly showed that they wanted to incorporate either prototype design or scientific inquiry into the challenge. Also this step of the design process was found to be iterated, more particularly in case C2. This step was not observed in case C1.

In case C2, the teachers established the challenge depicted in Figure 3.4, for which students would have to build and program a car that would drive through a green wave of traffic lights in one motion. In other words, without stopping, the students' cars would have to pass the traffic lights of three intersections at moments on which they are green. First, the students would have to scale the given model. Although this challenge is not personally relevant to students, autonomous cars and more ecologic traffic control are contemporary issues of students' surrounding environment.

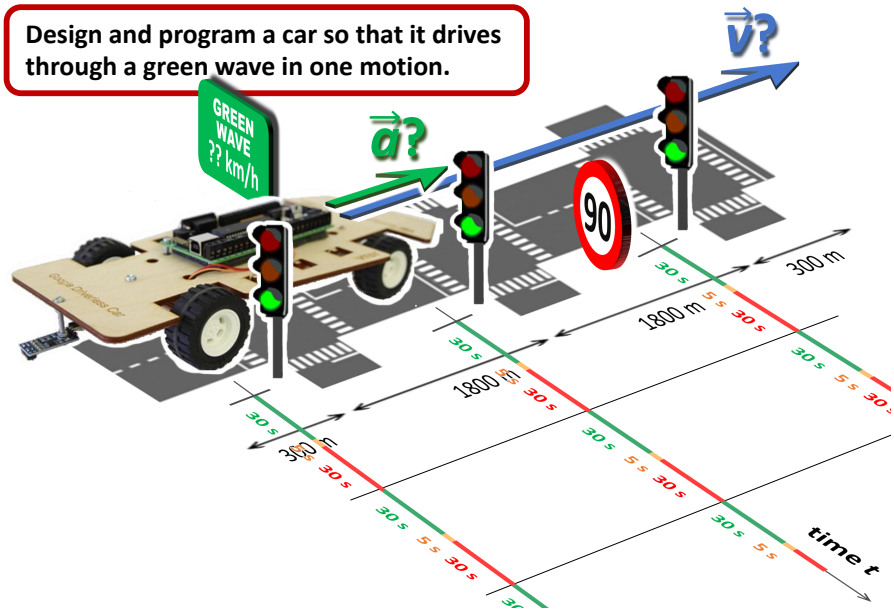


Figure 3.4: Challenge formulated in C2

After studying the requirements and conditions of this challenge in the step 'requirements and feasibility study' (see step 'RFS'), the teachers in case C2 decided to add an artificial feature to the challenge in order to make it open-ended (i.e., to increase the number of possible solutions). Whereas in real life, a recommended speed is indicated at the side of the road and the traffic lights are adapted to this speed, in the new challenge, all traffic lights would be showing the same cycle of green-orange-red

simultaneously, and the car's velocity and/or acceleration would be the unknown parameter(s) (see Figure 3.4). Using the formula of average velocity, different constant velocities would be possible to get the car subsequently through the green lights, as illustrated in Figure 3.5. A given maximum speed limit was added by the team coordinator as an extra constraint to the challenge.

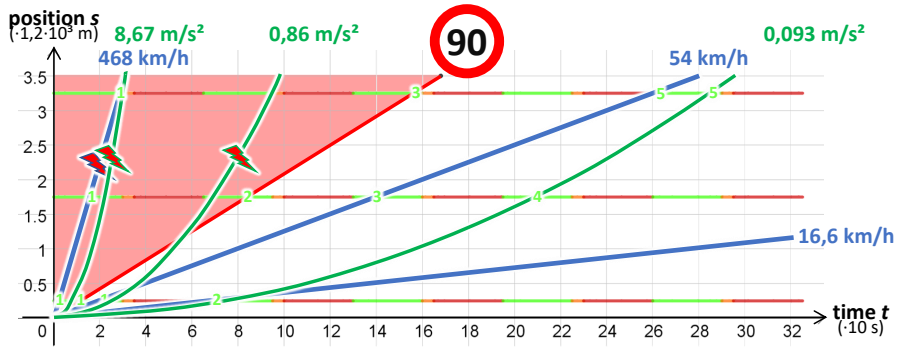


Figure 3.5: Multiple possible velocities and accelerations for the car in the open-ended challenge formulated in C2

At the beginning of this step, the teachers of case C3 were looking for a challenge that would be relevant to the students. However, because they were much intrigued by the idea of designing a car and a ball launcher, they quickly diverted from that effort. The team coordinator proposed a challenge that could unite the ideas of the different subteams, which was rejected because the team members considered it technically and cognitively infeasible. Therefore, the team reformulated the challenge. Students would be provided with a large grid of square boxes on the ground. Their task would be to (a) design and control a ball launcher so that it could fire a ball into a particular grid box, and (b) design and program a car that could drive in straight lines to that same box, to catch the ball.

The teachers of case C4 chose to perform a feasibility study first (see step 'RFS'), to have enough information on what would be possible. As a result, the focus was shifted from 'water treatment' to 'algae'. One design meeting was then dedicated to formulating a challenge. The team members were recorded expressing their concerns on whether the applications of algae they came up with would be "fun enough" for students. They finally found a consensus in granting students the freedom to look for an application of their own choice, and in supporting them with just-in-time information. Therefore, the team landed on the challenge: "Grow algae, monitor their growth, and use them for an application of your choice."

Requirements & feasibility study (RFS)

In this step, the team members checked the conditions, constraints, and expected end products of the student challenge they had in mind, to verify if it would be feasible for classroom implementation. This step was observed in two cases: C2 and C4. Although two different approaches were adopted by these cases, they could both be classified under this step.

In case C2, the teachers discussed the implications of solving the challenge they had formulated in a previous step (i.e., their first encounter of step 'CIL'). They realized that this challenge would not make much of an open-ended challenge, as all students would easily program one and the same velocity. At that point they decided to reformulate the challenge.

The teachers of case C4 performed a requirements and feasibility study after they had identified the learning contents they wanted to integrate (in step 'CIL'). To this end, they visited four research centers and consulted experts and literature on water treatment and algae cultivation. The initial idea of the wastewater treatment plant troubled teacher C4_Math1 because of the space it would occupy, and the bad smell it would leave behind in the classrooms. The latter argument was confirmed by one of the consulted experts, which made the team shift its focus towards algae cultivation. Teachers C4_Bio/Chemistry2 and C4_Phys/Chemistry were often recorded referring to articles they had read about the measures and growth conditions for algae cultivation. In one research center, an expert explained that algae are difficult to harvest and give a small yield. From the several visits, the teachers concluded in a design meeting that, if they would work with algae, it would be hard to have students extract biofuel because of the small efficiency, and it would be too dangerous to have students produce nutritional supplements because of the heavy metals in the algae. On the other hand, the visits made the team realize that algae cultivation provides many opportunities for inquiry and for reflection in terms of possible applications and efficiency.

Challenge breakdown in subproblems (CBS)

This step, in which the teacher team broke down the formulated challenge into different components or subproblems, emerged in two cases: C2 and C4. In this step, the team identified the subproblems their students would subsequently encounter when progressing through the challenge.

In case C4, the initiative to break down the challenge into its subproblems was proposed by the team coordinator. The other team members agreed that this would help dividing the work afterwards. During a design meeting, they established following subproblems in the algae challenge: (1) algae growth and the influence of parameters such as nutrients, medium, CO_2, and pH, (2) algae harvest by means of flocculation and drying, and (3) algae application.

The successive subproblems determined during two design meetings by the teachers in case C2 are demonstrated in Figure 3.6.

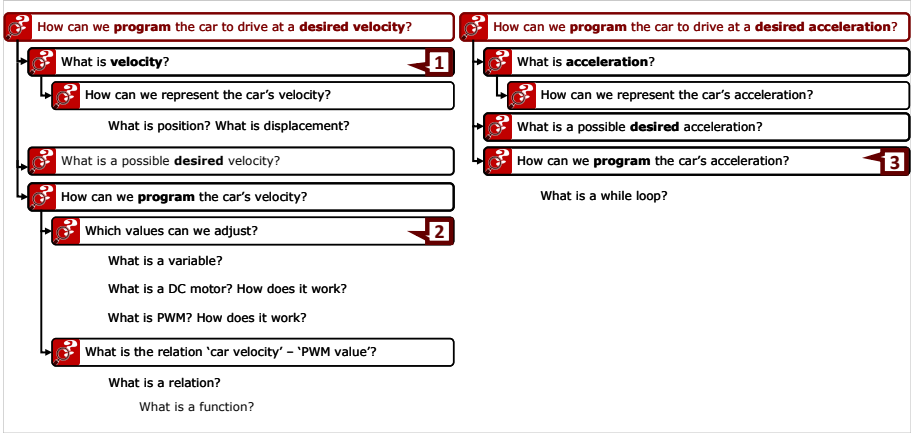


Figure 3.6: Subproblems of the challenge sequentially listed in C2

Design of S, T, & M linking learning activities (DLA)

In this step, the teacher teams outlined the classroom learning activities in function of the challenge. Intermediary reports of the team meetings showed how teachers had gathered existing learning activities or created new ones. For these activities, the teachers drafted experiments and exercises in which the students would need a combination of concepts and skills from different STEM disciplines. During the design meetings within this step, the teachers showed evidence of crossdisciplinary collaboration. This finding gives this step an iSTEM-specific focus and discerns it from other design processes. This step was not found in case C3.

In the design process of case C1, the learning activities drafted by the team mainly included exercises on the calculation, interpretation, and analysis of graphs on velocity and acceleration. Some ideas for experiments were included in the draft as well: walking at different velocities towards or away from a motion sensor or firing a plastic-bottle rocket in front of a camera, and analyzing these motions. The teachers also included an experiment designed by the RVO society (see Figure A.2 in Appendix A).

Based on the determined subproblems (see step 'CBS' and Figure 3.6), the team of case C2 gathered and created learning activities that were a mixture of inquiry and design and that made explicit links between the different STEM disciplines. Via teacher C123_Physics, the team of case C2 got easy access to and imported some of the activities gathered in case C1. Furthermore, through a constructive discussion in a particular meeting, the teachers came up with four experiments. These experiments

are shown in Figure 3.7. Through the experimentation, representation, analysis, and abstraction involved in the experiments, the teachers gradually connected the concepts identified in a previous step (see step 'CIL'): 'velocity', 'acceleration', 'motor pulse width modulation', 'programming variable', 'function', and 'programming loop'.

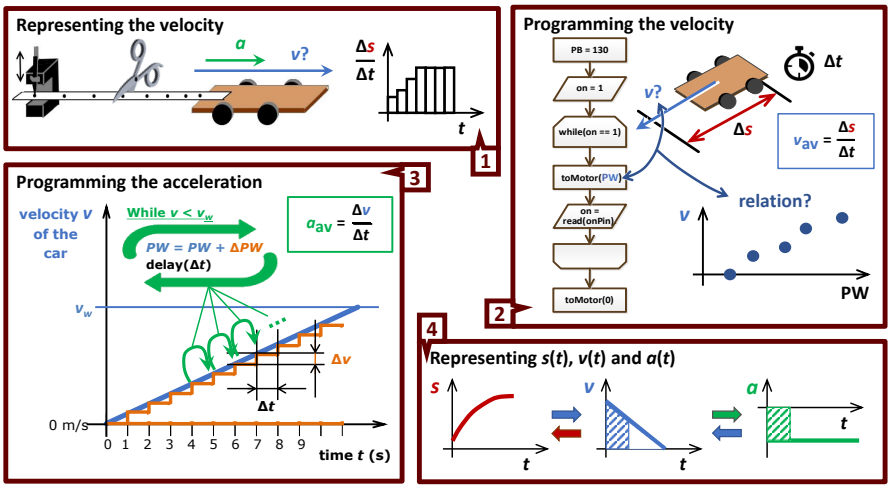


Figure 3.7: Learning activities of C2: [1] visualizing the car's average velocity by means of the RVO-society experiment (see Figure A.2) with a car and a ticker timer, [2] measuring the car's real velocity based on the formula for average velocity v_{AV} and determining the car's velocity as function of the motor pulse width: $v = f(\mathrm{PW})$, [3] programming a constant acceleration with a programming loop, $\mathrm{PW} = f(v)$, and the formula of average acceleration a_{AV}, [4] measuring and analyzing a car's recorded motion as function of time

The team of case C4 decided to include a combination of design and inquiry. They talked about experiments to measure the effect of several parameters on the growth of the algae, and about the design and calibration of a spectrophotometer that should be used in the measurements.

Experiment tryout, Prototype production + documentation (EPD)

In this step, the teams of cases C2, C3, and C4 started designing and testing a prototype and setting up the experiments they associated with the formulated challenge. During this step, the team members also ordered and tested the electronic components or lab equipment. This step was not observed in case C1.

In cases C2 and C3, a long period of design time was devoted to developing the prototypes. The intermediary reports and documentation of the subteams of C3, mentioned the teachers' efforts to finetune the design, test the accuracy of the ball launcher, and make a stepwise building plan for the students to follow. The prototypes produced by two subteams during this step are shown in Figure 3.8. A subteam assigned the design of a ballistic pendulum to their students, who had to create a prototype and register its motion with video-analysis software. This step resulted in C3 in a list of electronic components, some program code, a manual to use a certain type of video-analysis software, and the 2D and 3D drawings of the prototypes.

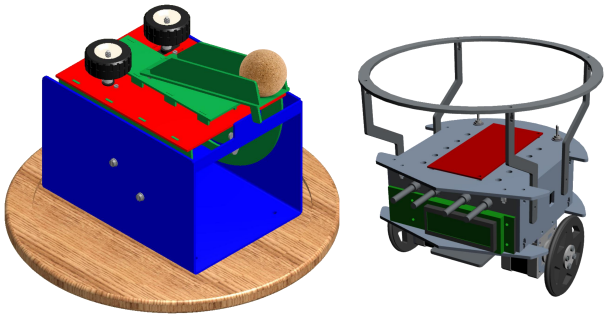


Figure 3.8: Ball launcher and car prototype designed in C3

In case C4, the teachers started setting up an algae culture in two schools. The team members of one school tried out the whole process of growing, harvesting, and producing oil, while the team members in the second school tried out growing algae and testing the influence of factors such as CO2 and light on the concentration of the algae. Meanwhile, they kept notes on their observations. During this step, the recorded meeting conversations were dominated by the teachers' practical concerns about growing and harvesting the algae, and about the control and measurement of their growth. The documents that resulted from this step mostly consisted of a lot of information (plain text) and instructions on how to perform the experiments.



Figure 3.9: Algae experiment setup of C4

Reporting phase

In the Reporting phase, two steps could be distinguished:

- reporting and exchange of feedback, and
- theme-planning revision.

All of the steps in this phase took place in one plenary meeting within the initial, big group of teachers.

Reporting & exchange of feedback (REF)

In this step, the design teams were asked to report their intermediary results to other teams. This step was inserted by the team coordinators to provide the teams with an incentive to produce some results, and to exchange feedback on these results.

In case C1, the draft of the learning activities was sent to Prof. Mieke De Cock, an expert in the field of pedagogical research in physics. She suggested to include small assignments and questions related to daily-life motions, so students would discover and distinguish some concepts by themselves, such as reference position, displacement, and traveled distance.

In cases C2, C3, and C4, this step took place in the big group of teachers in which the design process had started off. A plenary meeting was scheduled in which the design teams were asked to present their draft of the challenge and their ideas for learning activities to the other STEM@school teams. A rotational setup was used, so delegates of each team could receive feedback from each of the other teams.

A teacher of case C4, C4_Bio/Chemistry2, obviously seized the opportunity of the coffee breaks at the plenary meeting to go around and ask people for feedback or ideas on what her team had presented. In case C4, also math and physics advisors of a national pedagogical support committee were invited at the plenary meeting. The observed team of case C4 did however not receive any feedback from this committee.

Theme-planning revision (TPR)

From the teams' presentations on the drafts of their learning units, the need arose in cases C2 and C3 to revise the initial planning of the themes (and learning units) in the students' school year. This step emerged when one or more learning units assumed a profound understanding of a certain concept that appeared to be addressed in a more elaborate way in a subsequent unit. Therefore, the teams considered the advantages and consequences of switching these learning units.

From the plenary STEM@school meeting in case C2, it became clear that four learning units would be too much to squeeze into one school year. The group of design teams came to the consensus that the learning unit on the theme 'Kinematics 2D' would be too difficult for grade 9. Furthermore, many arguments pleaded to start the school

year with the learning unit 'Kinematics 1D' in the first trimester and proceeding with the unit 'Optics' in the second trimester, instead of the other way around as was the initial plan.

In case C3, a vivid plenary discussion took place on whether (a) to schedule the ball-launcher unit in the second semester, *after* students had learned about quadratic functions and would thus be able to apply it in this unit, or (b) to schedule this unit in the first semester, as an incentive for students to learn about quadratic functions. The pros and the contras of both schedules were balanced, and the group finally decided to go for the latter option.

Development phase

In the Development phase, four steps could be distinguished:

- script writing,
- syllabus finalization,
- material bundling, and
- syllabus review and finetuning.

Script writing (SW)

In this step of the design process, the outline of the learning units was elaborated by the team coordinators. This outline started from the challenge and included the connections between this challenge and the learning activities. This step was inserted in cases C2, C3, and C4 to get an overview of the scenario and to detect the gaps for which extra learning activities had to be developed. In cases C2 and C4, the script was based on the subproblems that were identified in an earlier step (see step 'CBS'). The script contained the challenge and references to the syllabi in which students would find more information about a certain subproblem.

As no challenge breakdown into subproblems had been performed in case C3, the team coordinator had to construct a scenario based on the different design activities of the subteams. This resulted in the script shown in Box 3.1. This script included scaffolding questions leading students to realize they were encountering a new subproblem to the challenge, or checking their understanding of the STEM concepts they had just learned while solving a subproblem. In between these two types of questions, students were referred to the learning materials on that particular subproblem. During this step, it became clear that there were no learning activities available to refer to, only information and technical drawings. All learning activities (thinking exercises and assignments) still had to be developed.

Box 3.1 Script of the learning materials of C3

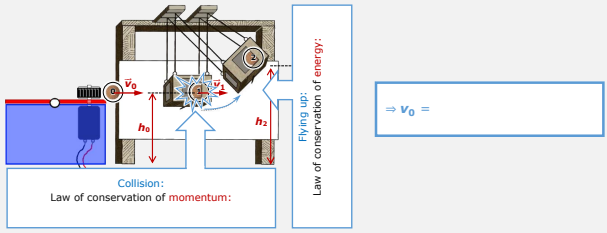
1) The design
→ syllabus 'Design ball launcher'
→ syllabus 'Design car'
Recap:
- List the requirements of the prototype and the proposed solutions.

2) The shape of the projectile motion
Teaser: To be able to predict and control where the ball is going to land, we need a model for the ball's motion. But which parameters play a role?
→ syllabus 'Experiments projectile motion' (Quadratic functions)
Recap:
- Draw the projectile motion. By which formula is it represented?
- Which parameters play a role?
- What aspect of the motion would we want to control (indicate on the graph)?

3) The parameters of the projectile motion
Teaser: Which configurations of the ball launcher can we control? How? What is their relation to the parameters influencing the motion?

Configuration(s)	How	Related parameters

Teaser: What is initial velocity and how is it related to the motor PWM value?
→ syllabus 'Experiments projectile motion' (Ballistic pendulum)
Recap:
- Explain in own words what initial velocity is and how it is initiated.
- Explain why we addressed conservation of energy, and write down the formulas we found.



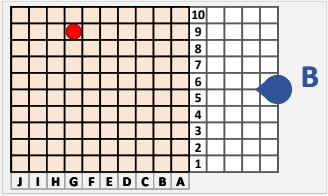
- Draw the relation you found between the motor PWM value and the initial velocity.

4) The configurations of the car

Teaser: How can we program the car to automatically drive to the grid cell of our choosing?
→ syllabus 'Design car' (programming of potentiometers and stepper motors)
Recap: Write down the program code to make the car drive towards grid cell G9.

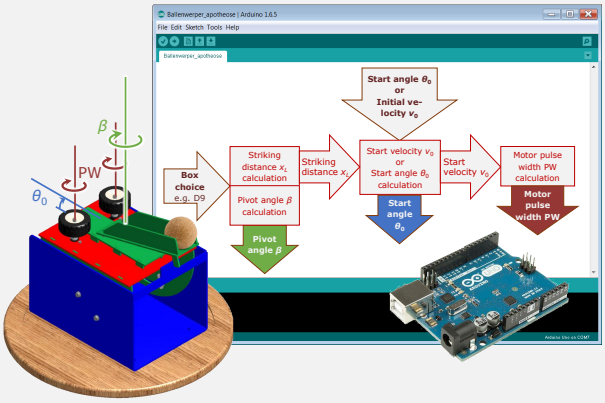
5) The configurations of the ball launcher

Teaser: Which angle must the ball launcher turn from its standard orientation in fixed position B to throw a ball towards G9, and what is the horizontal distance the ball must travel? Incorporate this calculation in a spreadsheet.



Teaser: How does initial velocity play a role in the model of the projectile motion, and how do we control it so the ball will land on a desired grid cell?
→ syllabus 'Experiments projectile motion' (deduction of the equation from the graph of the acceleration as a function of time, independence and composition of motion components)
Recap and synthesis:

- Deduce the motion equation that shows the influencing parameters.
- Deduce the formula of the inital velocity as a function of the ball's horizontal travel distance.
- Determine the formula for the related motor PWM values.
- Apotheosis: bring all previously designed codes together in a master code.



Syllabus finalization (SF)

In each case, the teachers now finalized (i.e., finished and formatted) the learning materials and documents with information they had been gathering during the previous step (see step 'EPD'). The teams uploaded their documents to a shared file (in cases C2 and C4) or e-mailed them to their coordinator (in case C3).

At the end of this step, in case C2, the materials sent by the team members contained theory, but also exercises on programming, and experiments on kinematics and functions. The documents the team coordinator received in case C3, were 2D and 3D drawings, a program code, a software manual, and web links to order the electronic components: all documents with useful information for the teachers, but no learning activities for the students. In case C4, the teachers delivered a lot of theory, or references to relevant theory, but also descriptions of experiments. Some team members of case C4 sent separate syllabi for the separate STEM courses.

Learning-material bundling (MB)

In this step, the script and the learning materials and documents, supplied by the team members, were bundled by the team coordinator to a coherent syllabus in the defined layout. The coordinator checked the syllabus for gaps and included extra information when necessary. This step did not take place in case C2 because all learning activities were already gathered in one document. Neither did the step take place in case C3, because no learning materials were sent to the team coordinator to bundle.

In case C4, some team members were of the opinion that the discipline-specific learning contents should remain in the separate syllabi for the separate STEM courses, for the ease of classroom implementation. The coordinator argued that this would contravene the idea of integration and chose to integrate the learning activities from the separate syllabi into the other materials, so that e.g., the math exercises immediately followed the related scientific experiments.

Syllabus review & finetuning (SRF)

In cases C1 and C4, the bundled learning materials were finally checked by all team members. The coordinator gathered the feedback via e-mail and incorporated the suggestions into a final version. In case C1, the materials were also checked by physics education expert Prof. Mieke De Cock, who suggested to add the targeted learning goals to the activities and to adapt some activities so they would better correspond with these goals. This was done accordingly by C123_Physics and C123_Coordinator, for example, by incorporating more thinking exercises into the activities. In cases C2 and C3, no time was left for revision within the same design year.

The design process of the teacher teams was concluded with these last steps. In the school year following the design phase of each case, the learning materials were put to the test in the classrooms. The experiences and remarks of the teachers implementing the designed materials were gauged at regular resonance meetings during that school year, and were taken into account in the review of these materials. This review process fell out of the scope of this study, as it was merely conducted by the team coordinators alone.

During the course of the case study presented here, a comparable study was conducted by McFadden and Roehrig (2017) with a very similar setup: design-based case-study research. McFadden and Roehrig studied the process of two cases, in which two teacher teams embarked upon the design of an elementary-focused iSTEM learning unit. Coincidentally, McFadden and Roehrig also visualized the observed design process in a flowchart (two different flowcharts for the two teams). However, this flowchart contained detailed, case-specific dilemmas and questions instead of steps (or activities). From analyzing these decisions, it could be inferred that the teams engaged in some steps that much resemble the ones identified in the study presented here: gathering entertaining learning activities (see 'DLA'), but also brainstorming on a central theme (see 'BCT'), formulating a challenge (see 'CF') and establishing the requirements and constraints of the challenge in terms of desired student products (see 'RFS'). During these steps, however, the teams in McFadden and Roehrig's study bumped into new curriculum design principles and good practices, as well as into different possibilities posed by an open-ended student challenge. Unfortunately, they did not show any readiness to further examine these different options and even blocked further discussions on the topic. Rather, they tended to stay in their comfort zone. This finding was not so much prevalent in the study presented here. In steps 'RFS' and 'EPD' of case C4, the teachers even explored the different possible experiments and applications of algae without knowing where this exploration would lead them.

To verify the *veracity* of the identified steps as they are explained before and presented in Figure 3.1, they were checked with the impressions of a participant of the case study. Independently of the case-study findings, teacher C123_Physics was asked to draft a model of the design process as he had experienced it. C123_Physics was selected because he had been involved in three of the cases. The question to sketch a model of the design process would stimulate him to make abstraction of the actions taken by his teams, to identify types of actions that he had seen returning in each of the cases, and to categorize them into overarching steps. The electronic model he made is shown at the left of Figure 3.10. He provided an explanation with each step, which facilitated comparison between his model, and the one extracted from the case study.

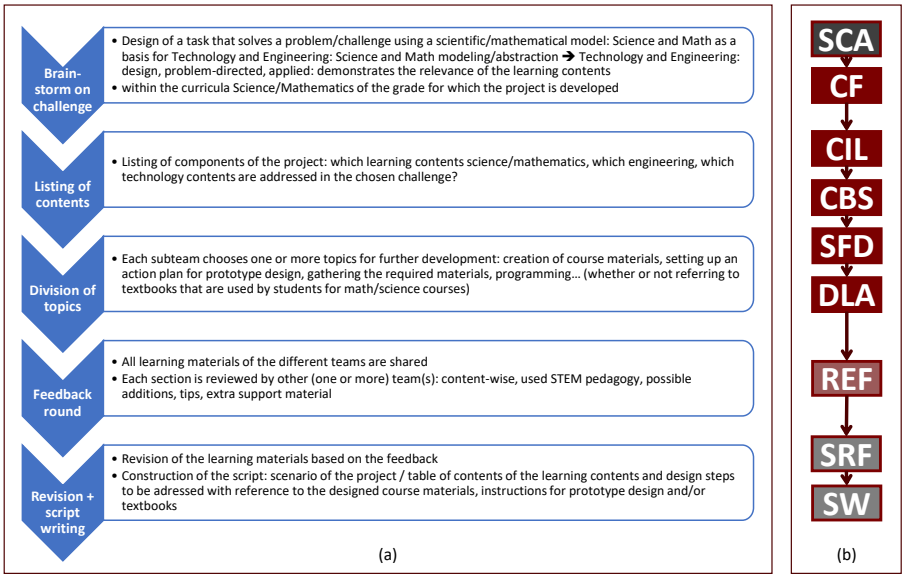


Figure 3.10: Teacher C123_Physics' impression of the design process steps (a), and matching steps identified in the case study (b)

The first step, which he called 'brainstorm on challenge', perfectly matches the step 'challenge formulation' (CF). However, a closer look to the accompanying text reveals that his first step also implies a preceding step in which the curricula of the target group are explored, such as the step 'specific-context analysis' (SCA). His following two steps, 'listing of contents' and 'division of topics' are a blend of the steps 'learning-content identification' (CIL), 'challenge breakdown into subproblems' (CBS), 'subteam formation and content division' (SFD), and 'design of learning activities'. In the 'feedback round', the step 'reporting and exchange of feedback' (REF) is reflected. Finally, his last step, 'revision and script writing' reveals actions classified by the steps 'syllabus review and finetuning' (SRF), and 'script writing' (SW). Although the sequence of the steps identified by C123_Physics does not resemble any of the three cases in which he participated in particular, his steps appear in the same successive phases that were identified by the case study. The correspondence between the steps identified by this participant and those identified in the case study suggests that the case analysis produced a representative and even more finegrained abstraction of the design process.

3.3.2 Important, unimportant, and missing steps

As a next step in this study, the important, unimportant, and missing steps of the observed design processes were determined (RQ1), in order to ensure that the important steps are definitely incorporated into the support model (RQ2 and Section 3.4). To this end, three types of data were collected:

(a) the learning materials designed by the teacher teams of each case,
(b) the requirements for high-quality iSTEM education from the literature study elaborated in Chapter 2 (see Figure 2.6), and
(c) a list of the steps identified in the case study (see Figure 3.1) together with a short description of the actions observed in each of these steps (see Appendix D).

For each case, the designed learning materials (a) were evaluated against the requirements for high-quality iSTEM education (b). This was also done by two researchers affiliated to STEM@school: by the project leader of STEM@school (Prof. Dehaene), and by C4_Coordinator (team coordinator of case C4). The mutually agreed-upon evaluation can be found in Figure 3.11.

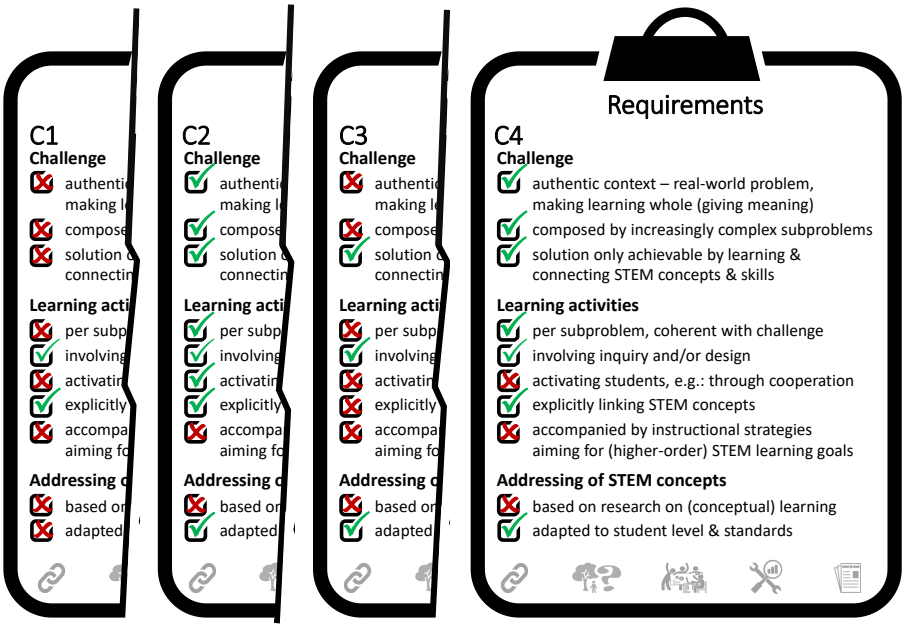


Figure 3.11: Evaluation of the learning materials designed in cases C1, C2, C3, and C4 against the requirements for high-quality iSTEM education

As another part of the analysis, regardless of this evaluation, the steps identified in the case study (c) were linked to the requirements of the list (b). To this end, for each step, the main researcher considered whether the actions observed in the step, could 'somehow contribute to' the fulfillment or failing of the first requirement, of the second requirement, ..., and finally of the tenth requirement. Another researcher was asked to do the same thing, based on a list of the actions per step as shown in Appendix D. This researcher was not related to STEM@school and, therefore, his perspective would not be biased by experiences or feelings about the design processes or learning materials delivered by the observed cases. The resulting links were compared and discussed, and a consensus was found in the associations shown in Figure 3.12. A few interdependencies among the steps were identified as well (shown at the left of Figure 3.12).

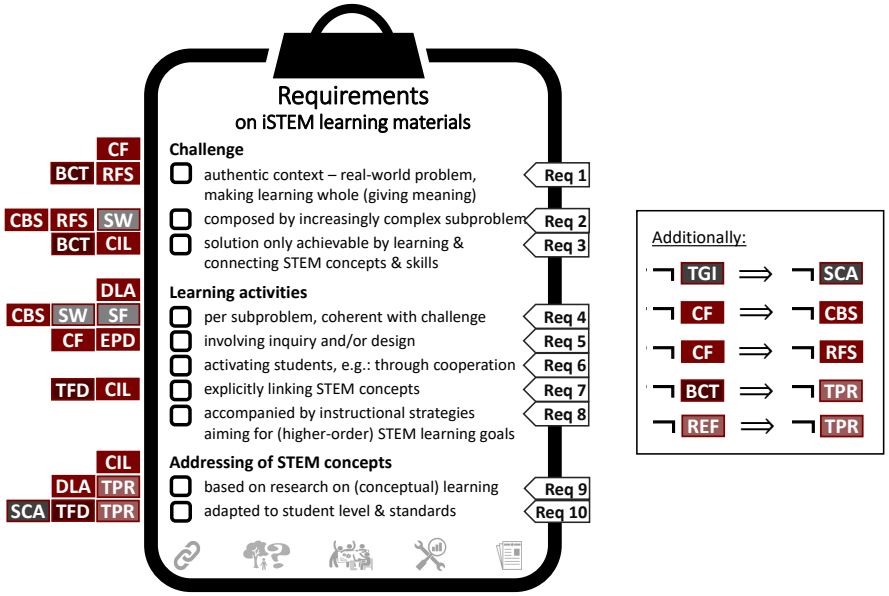


Figure 3.12: Requirements for high-quality iSTEM education and the steps that could be associated to each of them

These two parts of the analysis were then brought together. Figure 3.13 shows the result of this combination: the fulfillment of the requirements in each case, together with the contributing steps that were observed in that case. This formed the basis for analyzing the importance of each step.

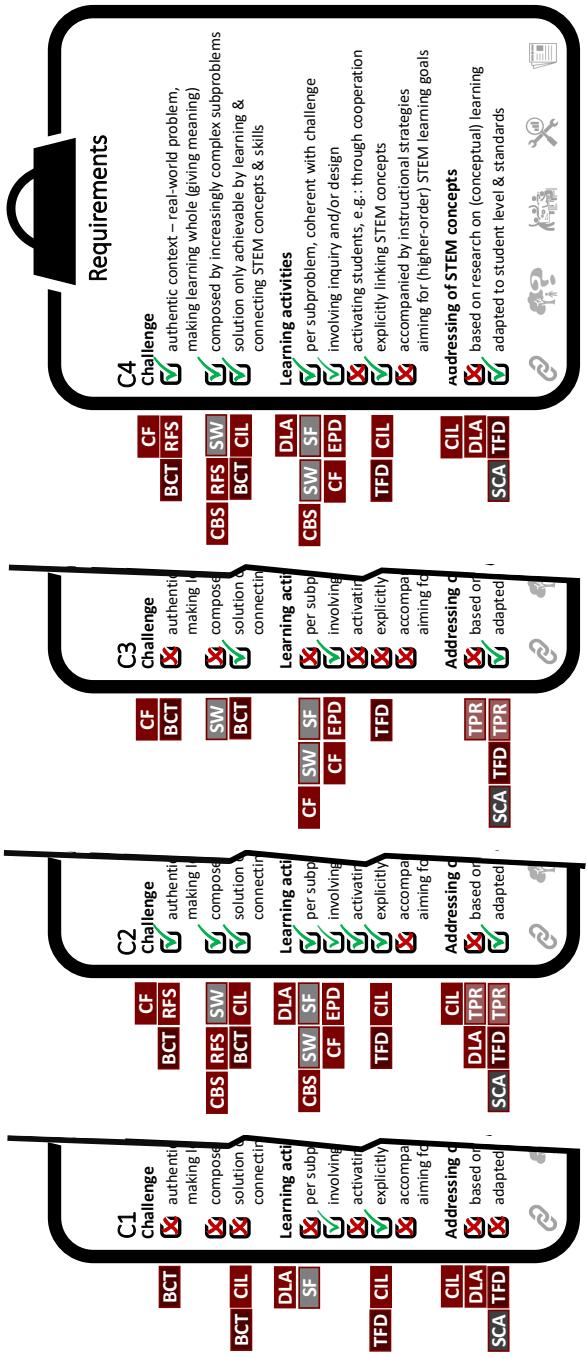


Figure 3.13: Occurrence of the associated steps and evaluation of the learning materials per requirement and per case for cases C1, C2, C3, and C4

First of all, the steps were analyzed in function of the fulfillment of the requirements. Table 3.4 shows the result. This analysis was made based on Figure 3.13 without taking into account the possible contribution of other, unidentified steps, and without considering or comparing the quality with which the steps were carried out by each team.

Table 3.4: Requirements for high-quality iSTEM education and insufficient, sufficient, and necessary steps for their fulfillment (✓), derived from Figure 3.13

for ✓	insufficient	sufficient	proven necessary
req 1	BCT CF	BCT CF RFS	RFS
req 2	CF SW	CF CBS RFS SW	CBS / RFS
req 3	BCT CIL	BCT CF	CF
req 4	DLA SF CF SW SF	CF CBS DLA SW SF	CBS CF / DLA / SW
req 5		DLA CF EPD	
req 6	DLA		?
req 7	TFD	TFD CIL DLA	CIL / DLA
req 8	DLA		?
req 9	BCT CIL DLA REF TPR		?
req 10	TGI SCA TFD CIL	TGI SCA TFD CIL REF TPR	TPR

Table 3.4 shows the steps that are necessary for meeting some of the requirements, and which were thus *important* steps in the design process:

- 'challenge formulation' (CF),
- 'challenge breakdown into subproblems' (CBS),
- 'requirements and feasibility study' (RFS), and
- 'theme-planning revision' (TPR), and therefore (as important preconditions, see Figure 3.12):
  - 'brainstorm on learning content and themes' (BCT), and
  - 'review and exchange of feedback' (REF).

These steps must therefore be incorporated into the support model.

Furthermore, it is clear that one or a few steps are *missing* in order for requirements 6, 8, and 9 to be met. More precisely, some actions should be taken in the design process to make sure:

- that students are activated and in control of their own activities and learning (and not, e.g., just have to listen to lectures or execute stepwise plans), e.g., through constructive student cooperation;

- that the classroom activities primarily and directly aim for the learning goals that need to be achieved by the students; and
- that students' conceptual difficulties and misconceptions are taken into account in the choice and setup of the classroom activities.

Therefore, this work advocates including an extra step in the support model: a step that encompasses all of these concerns. As these concerns address the approach to the classroom activities (i.e., how these should take place, what must be taken into account), the extra step will be called 'learning-activity accompaniment with instructional strategies' (AAS) and should include actions such as defining the setup of each learning activity.

However, in turn, this extra step, AAS, requires three inputs:

- a set of precisely defined learning goals that need to be achieved in each learning activity;
- knowledge of students' conceptual difficulties, and effective strategies to tackle them; and
- evidently, the learning activities themselves.

These preconditions raise the need for other steps, that should have been performed earlier in the design process, some of which were indeed observed in the cases:

- a step in which the learning goals are defined per learning activity;
- a study of the educational research literature on the conceptual difficulties; and therefore (as an important precondition):
  - a step in which the concepts that need to be learned are identified (i.e., CIL); and
- a step in which the learning activities are designed (i.e., DLA).

The first two step descriptions do not match any of the actions observed in the case study. Therefore, this work advocates including two extra steps in the support model, called 'learning-goal refinement per subproblem' (GRS) and 'learning-content literature study' (CLS).

Furthermore, the step DLA should be more focused on learning goals and learning opportunities for the students, than on gathering activities that are merely entertaining, as was often the case (e.g., developing a prototype). Consequently, to check students' attainment of the learning goals, also the design of assessment instruments should be included in this step (an action not observed whatsoever in the case study). This finding was corroborated by McFadden and Roehrig (2017):

> [A]nalysis activities are often overlooked by teachers. ... Instead, design conversations remained geared around what types of experiences students should be engaged in and not how students learn best during integrated learning experiences. (McFadden & Roehrig, 2017, p. 13)

But what about the other steps that were observed in the case study: should they still be included in the support model as well? To examine this, the data were also regarded from the reverse perspective. Based on the data in Figure 3.13, the requirements that were met or failed were tallied per step to which they were associated and per case. This was also done for the steps that had not been observed in certain cases. The summary of these results is shown per step in Table 3.5. These data could not be examined quantitatively because of the small sample of cases. However, the weighing of the numbers could give an idea on which steps are rather *fruitful* (i.e., positively contributing to the majority of the associated requirements) or rather *detrimental* (i.e., negatively contributing to the majority of the associated requirements). This analysis did not take into account the possible contributions of other, unidentified steps or the quality with which the steps were carried out by the teams.

Table 3.5 suggests that, overall, the observed steps did not have a predominantly negative effect on the requirements. It would therefore not be harmful, and for the most part even fruitful to incorporate these steps into the support model.

The steps 'target-group identification' and 'specific-context analysis' (TGI and SCA) can be of particular importance when the designers want their learning materials to be standards-based (Sahin & Top, 2015). The actions comprised by the steps 'brainstorm on content and themes' and 'team formation and theme division' (BCT and TFD) prepare the setting for the learning materials and facilitate the design process (Satchwell & Loepp, 2002). Therefore, they will be included in the support model.

The insertion of the step 'reporting and exchange of feedback' (REF) by the team coordinators was much valued by several teachers. C4_Bio/Chemistry2 was seen to actively grab this opportunity to ask around for feedback. In an interview in the scope of another study in this work (see Chapter 4), teacher C123_Physics testified: "[P]resenting to each other, and feedback ..., that must be part of it for sure." During one of the design meetings observed in the case study, teacher C4_Physics was recorded saying:

> Actually, I find it quite important: explaining what we want to do, and that [other teams] can say: yeah, that is maybe a bit odd, or that can be done better like this, or I would put more emphasis on that. So that we can take this into account *before* we start to develop, 'cause... yeah, if we would already have developed everything, and *then* they [would come up with] a lot of comments, that [would be] quite annoying. (C4_Physics)

Also Satchwell and Loepp (2002) found that collecting feedback is an essential part of producing high-quality iSTEM materials. All of this suggests that REF is an important step in the design process.

Some steps raise doubts about whether they would engender a useful and positive contribution to the fulfillment of the requirements:

- 'learning-content identification and linking' (CIL),
- 'design of STEM-linking learning activities' (DLA),
- 'theme-planning revision' (TPR).

The previous analysis, however, shows the necessity of each of these steps, often as precondition for other steps (in case of CIL and DLA). Furthermore, Table 3.4 suggests that the absence of DLA counteracted the fulfillment of several requirements, a reason to keep the 'design of STEM-linking learning activities' in the support model.

The step 'identification and linking of STEM learning contents' (CIL) is a step that does not only appear necessary for other steps (see previous analysis), it is also one of the key activities that discerns the process of designing iSTEM learning materials from any other instructional design process. In this step, the bridges between the STEM disciplines are forged, and it provides a solid basis for the design of learning activities that explicitly link STEM concepts and skills.

Some steps appear to be *unimportant* for meeting the requirements for iSTEM education. These steps must be inspected in the light of their contribution to the design, before they are incorporated into the support tool:

- 'subteam formation and content division' (SFD),
- 'material bundling' (MB), and
- 'syllabus review and finetuning' (SRF).

Both the steps MB and SRF will not prevent the design process from outputting useful learning materials. On the contrary, they enhance the coherence and quality of the learning materials. Thanks to these steps, some mistakes, which might otherwise hamper the practices in the classroom, might be detected and removed before implementation.

The step SFD only emerged in case C3. In this step, the multidisciplinary team of STEM teachers split up in smaller, monodisciplinary subteams. The learning contents related to the central theme were decomposed into discipline-specific contents (i.e., course contents), around which the subteams produced some information and documents. The produced information contained no link with contents from other STEM disciplines and did not contribute to solving the challenge. These findings emphasize the importance for iSTEM education of crossdisciplinary collaboration and of thinking in terms of learning activities, instead of in terms of courses. The step SFD seems to have been detrimental for the design process and will, therefore, not be incorporated into the support model.

Table 3.5: Steps observed or skipped (¬), number of requirements fulfilled (✓) or failed (✗) to which they might have contributed, and assessment of their contribution, based on Figure 3.13

step	# cases	# requirements ✓	# requirements ✗	step assessment
TGI	4	3	0	rather fruitful
¬ TGI	0			
SCA	4	3	1	rather fruitful
¬ SCA	0			
BCT	4	7	3	rather fruitful
¬ BCT	0			
TFD	4	6	2	rather fruitful
¬ TFD	0			
CIL	3	7	5	
¬ CIL	1	2	2	
SFD	1	0	0	rather unimportant
¬ SFD	3	0	0	
CF	3	17	3	rather fruitful
¬ CF	1	1	7	
RFS	2	2	0	rather fruitful
¬ RFS	2	0	2	
CBS	2	4	0	rather fruitful
¬ CBS	2	0	4	
DLA	3	9	9	
¬ DLA	1	1	5	
EPD	3	3	0	rather fruitful
¬ EPD	1	1	0	
REF	4	2	0	rather fruitful
¬ REF	0			
TPR	2	2	2	
¬ TPR	2	1	3	
SW	3	4	2	rather fruitful
¬ SW	1	0	2	
SF	4	3	1	rather fruitful
¬ SF	0			
MB	1	0	0	rather unimportant
¬ MB	3	0	0	
SRF	2	0	0	rather unimportant
¬ SRF	2	0	0	

For the support model, some steps will be added, recombined, or displaced. A step 'learning-goal definition per theme' (GDT) will be added, on top of the step "learning-goal refinement per subproblem" (GRS). When the designed learning materials must be standards-based, this step is particularly important for teachers who are not very familiar with the STEM-course curricula (Deboer, 2002). Also for more experienced teachers, this step might be helpful, in order to define more holistic learning goals (e.g., in terms of student attitude, or 21st Century competences).

The steps 'experiment tryout, prototype design, and documentation' (EPD) and 'syllabus finalization' (SF) will be merged and moved to the Development phase. This has a particular reason: in the cases in which the step 'EPD' emerged, the teachers devoted a major part of their design time to building a prototype or trying out experiments, with often merely information (technical drawings, stepwise plans, images of circuits or programs) as a result. Although this information might be useful for the teachers, it does not contain actual learning activities. Therefore, it seems appropriate to first make the teams thoroughly think about what and how they want their students to learn (through the steps 'GRS', 'DLA', 'AAS') in the Brainstorm phase, then make them discuss this outline with the other teams (through the step 'REF') in the Reporting phase, and finally try out the prototype and/or experiments (EPD) in function of these learning activities in the Development phase. This tryout will then get the purpose of detecting extra conditions and learning opportunities for the students. In the support model, the teachers will thus spend much more time on the Development phase, but will do the preparation and heavy thinking during the Brainstorm phase.

The materials designed by the teams of the case study were finally bundled by the team coordinators (in case that had not been done during the design process) and supplemented with learning goals and instructional strategies. These materials were revised after a year of implementation. The resulting learning materials, together with the other materials designed within the STEM@school project, can be found at `http://www.stematschool.be`.

3.4 Model to support the iSTEM design process

In order to answer research question RQ2, a model was constructed. This model is conceived as a tool to support multidisciplinary teams of STEM teachers who embark upon the design of high-quality iSTEM learning materials. For constituting the model, the steps observed in the case study were subjected to critical scrutiny, in which their importance and contribution to the designed learning materials were assessed (see Section 3.3.2). Important steps were incorporated into the model, detrimental steps were discarded (see Figure 3.14). Important steps that had not been carried out by some of the studied teams, were considered pitfalls. To obviate these pitfalls and to ensure iteration, some quality checks (in the form of conditions) were included in the model. As a result, the model looks like a flowchart. Ideas and strategies from the observed cases were integrated in the step descriptions, as they provide practical examples (Singer et al., 2000). Furthermore, from a comprehensive review of the existing research literature on instructional design (see Chapter 2), argumentation to perform certain steps, and several instructional tips were extracted. They were included in the step descriptions. As such guidelines form the transitions between the stages of the process and make the design activities more transparent, including them has proven a necessary part of the support (Stolk et al., 2016). The resulting model is named '**CODEM for iSTEM**': Collaboratively Organized Design of Educational Materials for integrated STEM. The second part of this section verifies the completeness, comprehensibility, and suitability of CODEM for iSTEM by means of outsiders' perspectives.

CODEM for iSTEM is directed to *teams* of STEM teachers. Unless explicitly mentioned, the guidelines in each step are directed to the whole team. In the idea that 'the whole will perform better than the sum of its parts', the team members are expected to join forces, collaborate and exchange ideas and materials. Exploring crossdisciplinary links and mutual applicability can only be ensured by instantiating crossdisciplinary dialogue within the team, and maintaining this dialogue throughout the design process and implementation phase (Fulton & Britton, 2011). Throughout the design process, CODEM for iSTEM instantiates and maintains these crossdisciplinary discussions.

Team coordinators should be assigned to facilitate the design process and communication among the team members, verify teachers' goals, detect problems, plan team meetings, keep an overview of the different actions, and provide support on content and/or equipment (Thornton & Bell, 2015; Stolk et al., 2016; Huizinga et al., 2015). These coordinators must have considerable expertise in the subject matter or be able to rely on a network of experts, since they will be performing the quality checks in the design process and keep track of the learning units' scenario.

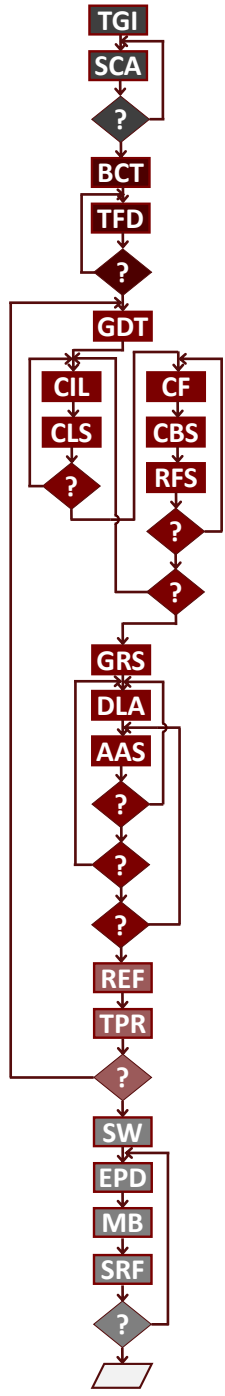


Figure 3.14: Support model CODEM for iSTEM

3.4.1 CODEM for iSTEM

CODEM for iSTEM is conceived as a flowchart that will guide you through the process of designing iSTEM learning materials. It is composed of five phases, each consisting of several steps and conditions. Have a closer look at the figures representing the phases: with each step, several 'inputs' and 'outputs' are associated. Each step requires a certain output, shown at its right. Such an output consists of decisions, information, ideas gathered in that step. Within the step, scaffolding questions (indicated by ▷) will support your team in producing these outputs. To carry out a step, your team will have to rely on one or more inputs. These inputs, that are shown at the left of the step, are the outputs of one or more previous steps. The input names tell you from which step(s) to retrieve the outputs. Throughout the process, several conditions are included. These are questions to verify and/or improve the quality of your work. Figure 3.15 shows the representations of a step, an input/output, and a condition.

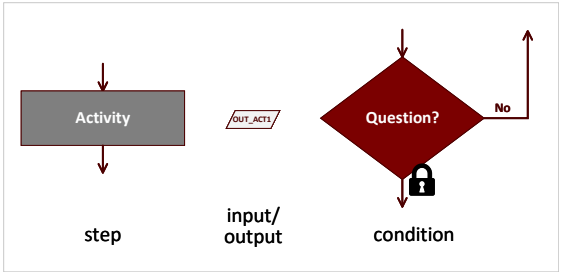


Figure 3.15: Representation of a step, an input/output, and a condition in CODEM for iSTEM

CODEM for iSTEM should not be regarded as a stepwise plan, as designing iSTEM learning materials is not a linear process. It should rather be perceived as as an action plan, containing all the necessary ingredients for a productive and efficient design process.

A team coordinator will be assigned to your team, who will schedule team meetings, mediate in case of problems, and provide information. S/he will also check the intermediate results for quality by means of the conditions. If the answer to the question of the condition is negative, the team coordinator will sent your team back to a previous step to revise the actions and outputs. If the answer is positive, your team can proceed to the following step.

You start the design process together with other teachers and enthusiasts, possibly from other schools, who are open to developing the iSTEM education at their school(s), and who want to brainstorm together on how to do so. This group will, from from this point onwards, be called 'the STEM group'.

Context analysis phase

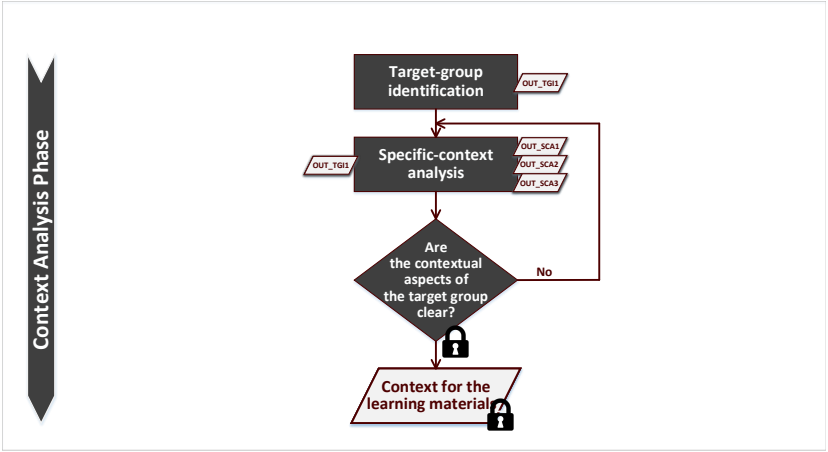


Figure 3.16: Context analysis phase

In the Context Analysis Phase, together with the other teachers of the STEM group, you figure out the constraints or conditions of the design process. In this phase, you will determine the target group of the learning materials. You will furthermore examine the interests of this target group, as well as the prerequisite and new knowledge students of this target group are supposed to possess.

This phase is optional if you already designed course materials for the same target group. The schematic overview of the Context analysis phase can be seen in Figure 3.16.

Target-group identification (TGI)

In this step, you gather in the STEM group to determine the target group of students for whom you will design the learning materials. Try to find an answer to the following questions:

- ▷ What is the age of the students who will get to work with the learning materials?
- ▷ In which study option will the learning materials be implemented?

Specific-context analysis (SCA)

Together with your colleagues of the STEM group, try to find out the background conditions of this target group. For this step, the following questions need to be answered:

- ▷ What is the prior knowledge of these students?
- ▷ What are the daily concerns and activities of these students?
- ▷ Where do the interests of these students lie?
- ▷ Which learning goals do these students need to achieve according to the national curriculum standards?

Instruction that is centered around students' interests, will be more easily perceived by them as 'meaningful', and will, consequently, be more easily retained and retrieved (Felder & Brent, 2016). The **interests** of the target group can be gauged by means of an oral or written survey. You might discover, that, for example for girls, the interest goes out to topics in the social sector (e.g., health care and education), ethics, and ecology (Sjøberg & Schreiner, 2010). When you administer a survey among the students of the target group to find out their interests, you might additionally ask what draws their attention to these topics. This will help you to identify common aspects from the students' broad list of interests afterwards (Jones, Howe, & Rua, 2000).

On the websites of educational umbrella organizations, the **national curricula** for the different student levels and types of education are published. These curricula provide an overview of the standards to be achieved, and the knowledge to be acquired by the students throughout the years of secondary school. These curricula are discipline-specific and their guidelines are based on discipline-specific research that has been conducted on student learning in the past. The umbrella organizations thus offer a framework with standards and guidelines that should be taken into account while designing the learning materials.
Therefore, gather the national curricula of the different STEM disciplines to get a grasp of the prior knowledge and the national standards of the chosen target group of students:

- Mathematics,
- Natural sciences, or
- Physics,
- Biology,
- Chemistry,
- Earth science,
- Technology, or
- Engineering, and/or
- Applied sciences, and
- Computer science

Are the contextual aspects of the target group clear? (ph1C1)

- In case the answer is 'no', the STEM group is redirected to the step 'specific-context analysis'.
- In case the answer is 'yes', the STEM group proceeds to the next step.

Theme selection phase

In the Theme Selection Phase, together with the other members of the big STEM group, you will search for crosscutting themes to frame the desired STEM learning contents. Then, the group will split up into smaller teams to further elaborate these themes. A schematic overview of the Theme selection phase is shown in Figure 3.17.

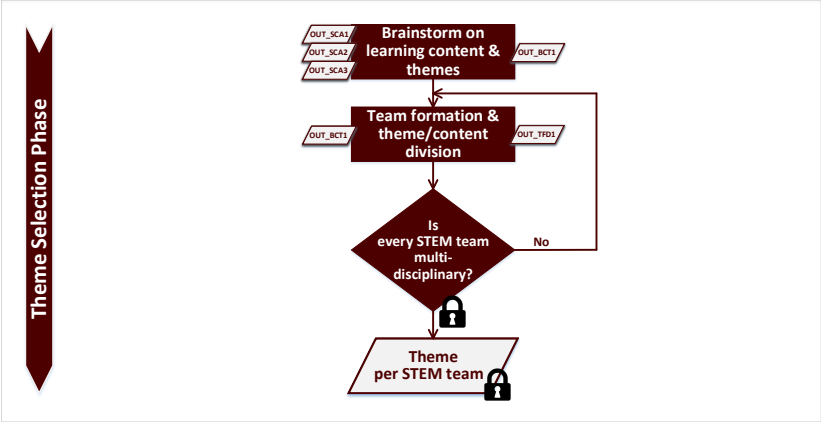


Figure 3.17: Theme selection phase

Brainstorm on learning content & themes (BCT)

In this step, together with the colleagues of the STEM group, you will choose the **themes** around which the learning materials will be designed. If the STEM group aims to cover a whole school year, you should select as many themes as learning units to be designed.

Research suggests choosing themes that strongly relate to students' interests and/or have a societal or ecological value (Stolk et al., 2016; Hidi, 1990; Felder & Brent, 2016). However, grounding a problem context on students' interests is not so evident, since not all of these interest contexts lend themselves to the deep learning of concepts that are comprehensible for students at that age. For example, the theme 'sailplaning' might sound attractive for students aged 13, but is hard to address without studying the rather complex law of Bernoulli. Consequently, the learning unit becomes merely descriptive, with small learning gains as a result.

The discipline-specific curricula of the different STEM courses, published by the educational umbrella organizations, also provide general and sometimes shared themes (e.g., 'energy', 'materials', 'algebra', 'electromagnetism', etc.). These themes cover specific learning contents: the STEM concepts and skills to be learned (Satchwell & Loepp, 2002). However, the structures of these separate curricula do not call for

making links with learning contents of other STEM courses. The key to integration lies in identifying common themes that encompass matching learning contents.

Therefore, you should first scan the discipline-specific curriculum of your own STEM course, together with other group members teaching the same course. Simultaneously, the other group members do the same for their courses. When you have a clear overview of the discipline-specific curriculum standards and the learning contents that are addressed in them, you gather again with the whole STEM group. Within this group, try to identify crossdisciplinary applications or contexts that capture some learning contents from each of the STEM-course curricula (or from as many as possible). These contexts provide suitable themes. As such, the designed learning units can cover multiple curriculum standards (Sahin & Top, 2015). Make sure that the different themes do not have too much overlap in learning contents, in order to maximize the amount of contents that can be addressed in one school year.

To select suitable themes, ask yourself the following questions:

- ▷ Which themes encompass learning contents from multiple STEM-course curricula?
- ▷ Which themes strongly relate to the target group's interests and/or societal or ecological issues?
- ▷ Can enough aspects of technology/engineering, math, and science be linked to these themes?
- ▷ Is there not too much mutual overlap between these themes in terms of learning contents?

Examples of suitable themes are: 'food', 'water', 'energy', 'biomedical systems', 'communication', 'production technology', 'music', 'biofuel', 'transportation', or 'mobility' (Rossouw, Hacker, & de Vries, 2011; KathOndVla, 2016b), 'kinematics', 'optics', 'cartography', 'heat transfer', 'immune system', 'astronomy', 'robotics', 'revalidation', 'security', etc.

If the STEM group members have decided upon some suitable themes, they should rank these themes in such a way that the related learning contents will be addressed with a steadily increasing complexity throughout the students' school year.

Team formation & theme/content division (TFD)

In this step, the STEM group will be divided into smaller **teacher design teams**, as to facilitate the design work (Morgan, 2015). This process can be facilitated by the team coordinators, who will be divided among the teams afterwards.

Every team should be **multidisciplinary**, consisting of teachers with differing discipline-specific knowledge, and differing classroom or practical experience in one or more of the STEM disciplines (Shernoff et al., 2017). The engagement of a technically skilled teacher is as indispensable as the commitment of a math teacher for a productive design process and an effective implementation of iSTEM education (Wang et al., 2011; Stubbs & Myers, 2016).

Ideally, a team also consists of members teaching in different grades of secondary education (often because of differing training level: bachelor versus master) (Vangrieken, Dochy, Raes, & Kyndt, 2015). Furthermore, forming teams of teachers from multiple schools will help the discussions to transcend contextual specificities, which facilitates cross-fertilization (Huizinga et al., 2015; Shernoff et al., 2017). A STEM design team has a minimum size of three teachers (S, TE, and M), and an optimal size of five to seven teachers. The design teams can be formed with the chosen themes in mind, in order to align the themes with the interests and expertise of the STEM team members as much as possible.

The chosen **themes** are then **divided among the different design teams**. Therefore, the preference, expertise and/or experience of the members of each team should be taken into account as much as possible.

Is every STEM team multidisciplinary? (ph2C1)

- In case the answer is 'no', the STEM group is redirected to the step 'team formation and theme/content division'.
- In case the answer is 'yes', the design teams proceed to the next step.

Brainstorm phase

The Brainstorm phase forms the core of the design process. The central part of this phase is analogous to a student's learning process, as shown in Figure 3.18.

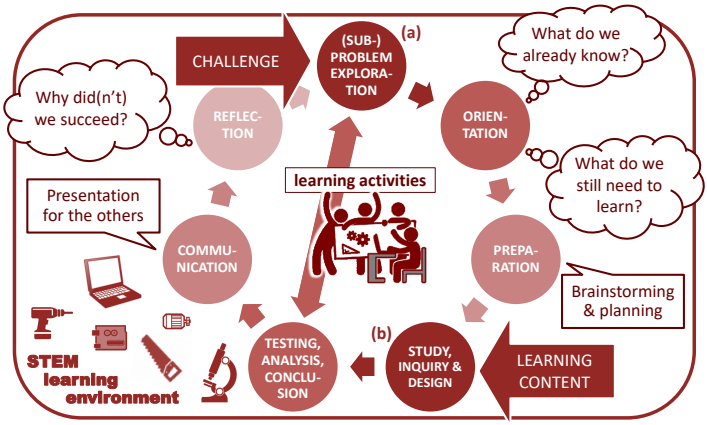


Figure 3.18: Representation of a learning cycle based on Schwartz et al. (1999); Klein and Sherwood (2005); De Groof et al. (2012); Elen (1995); Strubbe et al. (2012)

The brainstorm elaborates on two steps of this learning cycle: '(sub)problem exploration' and 'study, inquiry and design', and translates these to two focal steps in the design process. This translation is pictured in Figure 3.19. The student's exploration of the subproblem (a) then becomes your team's formulation of a problem statement or challenge (a'). The students' study, inquiry and design (b) then becomes your team's identification and linking of learning contents (b').

When students are given a certain problem statement, they will explore it (a), and ask themselves: "Given this challenge: what do we already know, what have we still got to learn to solve this problem?". Then, they will engage in learning activities that help them acquire the knowledge that is needed to proceed (b). Afterwards, they will have to relate what they have learned back to how it can help them solve the challenge.

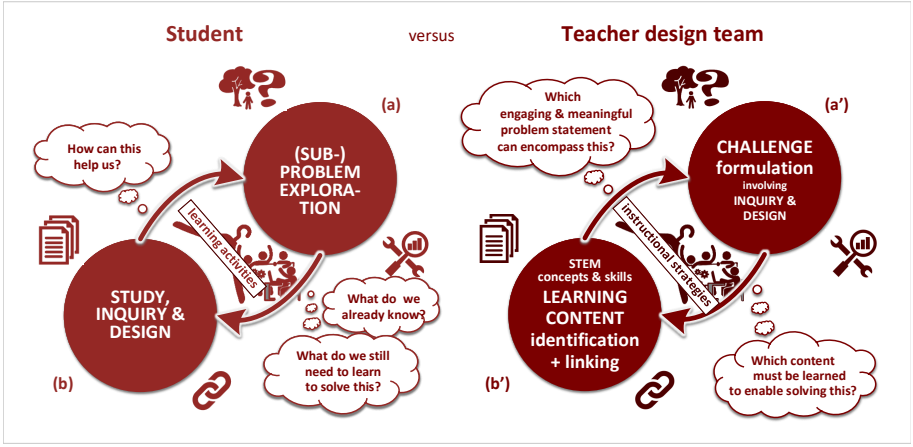


Figure 3.19: Students' learning process versus your team's design process

In the Brainstorm phase, which is fully depicted in Figure 3.20, your team will iterate between (a') some development, i.e., searching for a problem task that is meaningful and challenging to students, and (b') some research, i.e., determining the contents students are supposed to learn, and strategies that guide this learning. Since this is a cyclic process, theoretically, it does not matter where you begin: with the 'learning-content identification and linking', or with the 'challenge formulation'.

The five key principles of iSTEM education are addressed in this brainstorm process. The learning contents will be identified and linked in a crossdisciplinary way (*integration of STEM learning contents*). Your team will then dig into the extant research literature about student learning with respect to these contents (*conceptual learning*). And you will formulate a challenge around which you will construct the activities that address these contents (*problem-centered learning*), including design and/or inquiry (*inquiry- and design-based learning*) and student team work (*cooperative learning*).

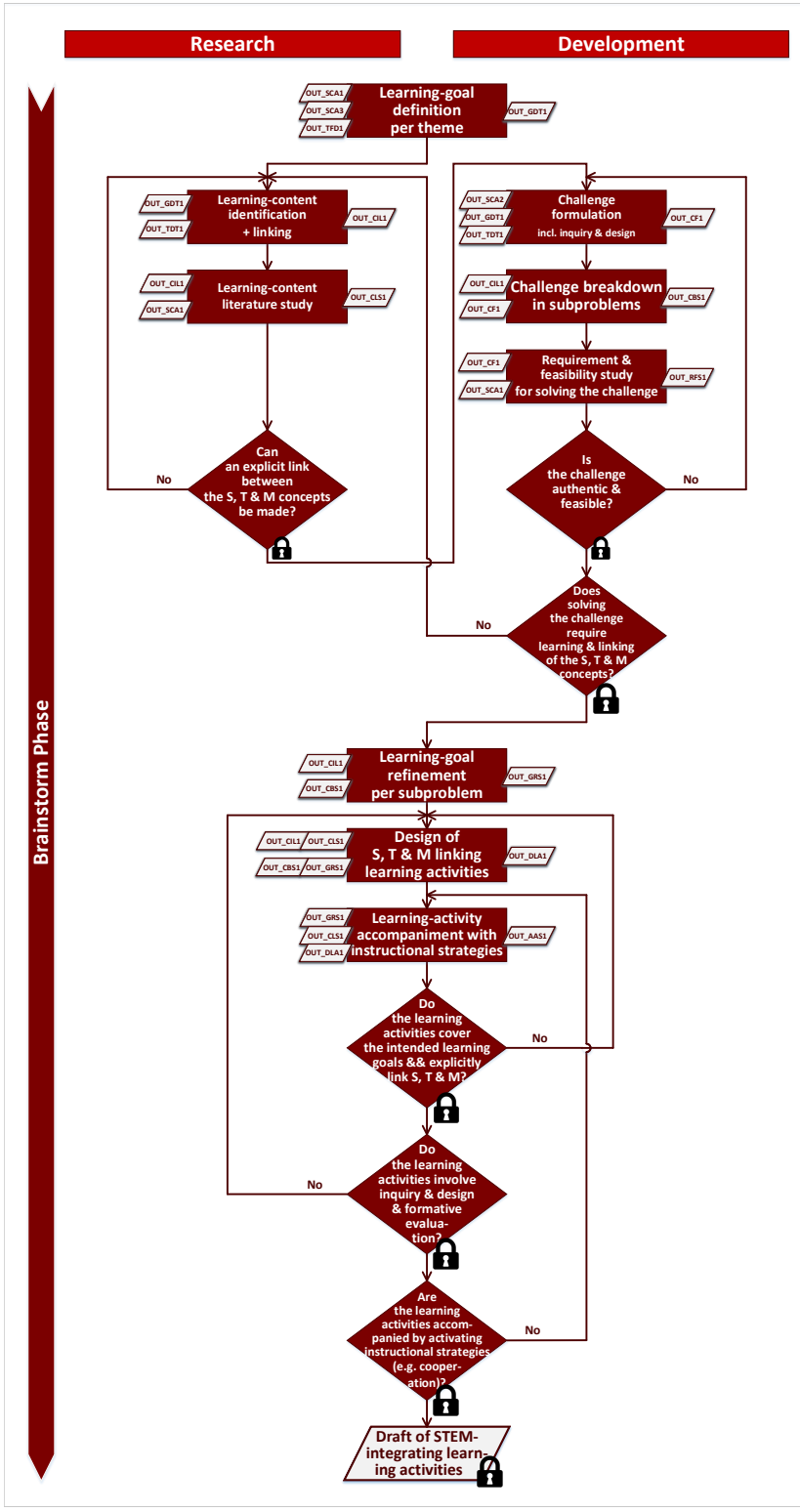


Figure 3.20: Brainstorm phase

The steps in the Brainstorm phase will ask you to merely prepare an outline of the learning activities. This outline will be reviewed by the other design teams in the following phase, before you further develop and try out the learning activities. This sequence allows you to take into account their feedback.

Learning-goal definition per theme (GDT)

One of the important questions in curriculum design is: which contents lead to the highest cognitive gains in understanding (Hattie, 2012)? As in every educational activity, the first step is to list the **learning goals**. Although you might be tempted to directly start searching for an exciting STEM challenge, it is important to first define the learning goals, as achieving these goals is what actually matters. Constructive alignment is necessary: when you think about learning objectives on beforehand, you will more likely design your instruction and assessment in a way to achieve these objectives (Felder & Brent, 2016).

Given the number of standards imposed by the national STEM-course curricula of the target group, you should first regard these standards when determining the learning goals you want these students to achieve. Select those standards that can be linked to the theme that was assigned to your team. The more **curriculum standards** that can be covered by the learning materials you are designing, the better. However, curriculum standards are often defined in a very restrictive way. If a certain standard will not contribute much to STEM integration in particular, or to students' understanding in general, and if it leaves no space for a creative, integrative approach, you should consider whether or not to include the particular standard.

Box 3.2 Standards for Engineering (KathOndVla, 2016b, 2016a; GO!, 2015)

Students can:

- ☐ engineer in team (listen to each other, be constructive, take initiative and responsibility, keep track of timing);
- ☐ collect and structure information about a physical phenomenon
- ☐ transform a technological problem into a research question or hypothesis;
- ☐ discuss a solution using technological-scientific arguments;
- ☐ construct a solution strategy to study a research question;
- ☐ work out the solution strategy, thereby observing accurately during inquiry/design;
- ☐ apply safety precautions, work responsibly;
- ☐ evaluate the results of inquiry/design;
- ☐ design a prototype;
- ☐ reflect on and communicate about the result and the engineering process.

When formulating extra learning goals, you also might want to consider the '**21st century competences**' (Ananiadou & Claro, 2009):

- ☐ creativity
- ☐ critical thinking
- ☐ problem solving strategy
- ☐ systems thinking
- ☐ metacognition
- ☐ decision making skills
- ☐ digital literacy

Also the standards of the curricula of Engineering provide some inspiration, see Box 3.2. An example of more general learning goals that can be formulated in this stage of the design process is given in Box 3.3.

Avoid being too generous in listing the learning goals. Less is more: you can better aim for a fewer amount of learning objectives that are achievable and match the chosen theme, than to make an exhaustive list of objectives without having the time or resources to thoroughly address them all (Deboer, 2002).

Box 3.3 Example of some learning goals for students of grade 9

Students can:

- ☐ switch between different representations,
- ☐ analyze and adapt a program code,
- ☐ formulate a hypothesis and setup an experiment to formulate an adequate conclusion,
- ☐ break down a problem into subproblems,
- ☐ work in a systematic, analogical way, relying on prior knowledge,
- ☐ propose ideas to solve a problem,
- ☐ build a working prototype that meets the requirements,
- ☐ take initiative to correct own thinking.

Learning-content identification + linking (CIL)

From the learning goals you defined in the previous step, you will now extract the **learning contents** you want to integrate in the learning materials. Make a list of **S**(cientific) **contents**, a list of **T**(echnological) **contents**, and a list of **M**(athematical) **contents** from the learning goals and arrange them next to each other. **E**ngeering encompasses the combination of these contents for solving a problem. Organize these learning contents into **concepts** and **skills**. Eligible for this step are crosscutting concepts, i.e., concepts that have applications in different STEM disciplines (National Research Council, 2012b).

Examples of crosscutting concepts are: 'variable', 'change', 'function', 'slope', 'integral', 'system', 'velocity', 'force', 'heat', 'flow', 'atom', 'potential', 'resistance', 'induction', 'wave', 'frequency', 'refraction', 'transformation', 'reaction', 'cell', 'energy', 'inheritance', 'algorithm', 'cycle', 'leverage', 'feedback', etc. (Hanesian, Burr-Alexander, Kimmel, Kisutcza, & Tomkins, 2003; De Poorter, De Lange, Devoldere, Van Landeghem, & Strubbe, 2016; Lichtenberger, Wagner, Hofer, Stern, & Vaterlaus, 2017; Fortuin et al., 2013).

Try to list STEM concepts and skills per STEM discipline, and establish crosscutting links between them, by means of the following questions (Stohlmann et al., 2012):

- ▷ Which concepts and skills can be identified in the intended learning goals per STEM discipline that can possibly be connected to the other disciplines (Perkins & Unger, 1999)?
- ▷ Which patterns (analogies, relations, or common characteristics and representations) can be identified among the concepts of the different STEM disciplines in the light of the chosen theme?

First time you encounter this step? When you encounter this step for the first time, you might find it hard to list and identify the possible connections among the concepts and skills right-away. In a later step (CF), you will try to formulate a problem statement ('challenge'), after which you will revise the listed concepts and skills. So, you will get back to this step. However, a first trial in listing the key concepts and skills is an important start. See Figure 3.3 for an example (in the theme 'mobility') on how to do so.

Not the first time you encounter this step? When iterating this step, you might find it helpful to construct a concept map, with the formulated challenge in mind. Concept maps are visual representations in which concepts and their mutual relations are outlined by means of frames and arrows respectively (Novak & Cañas, 2008). Therefore, they are a powerful tool in integration and the search for links between discipline-specific concepts. Furthermore, concept maps structure what is to be learned, allow to detect gaps in the list of concepts, and visualize the abstraction levels at which the learning contents will be addressed (Westbrook, 1998). In this way, you collaboratively establish the possible **crossdisciplinary links between the STEM concepts**, a key action in STEM integration! An example of such a challenge-based concept map is shown in Figure 3.21.

Given the formulated challenge, you can now strike out the contents that are no longer relevant, and add extra concepts and skills students need to learn to be able to solve it.

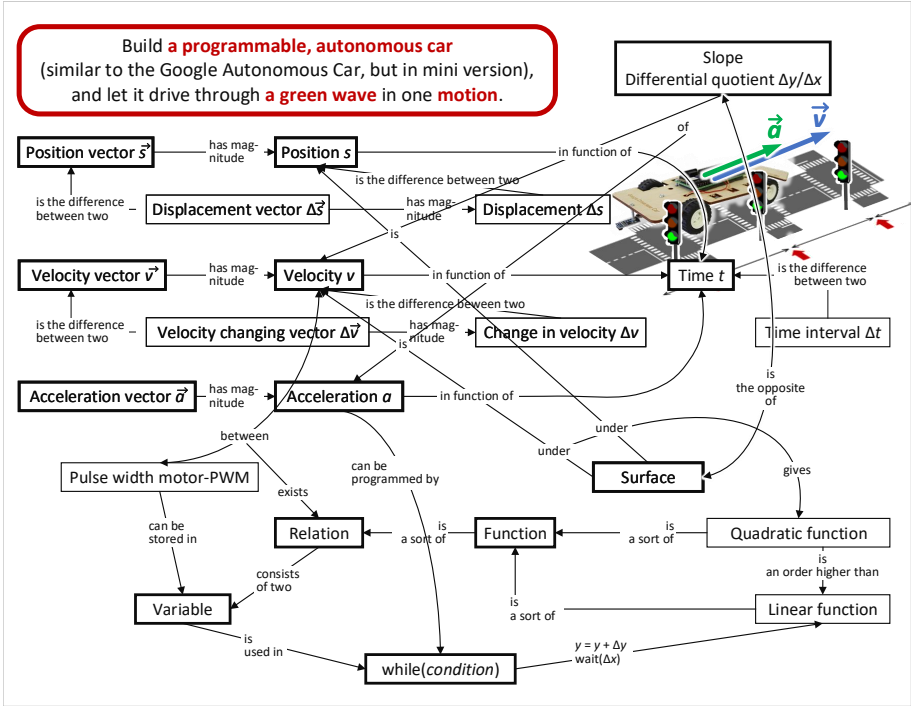


Figure 3.21: Example of a challenge with concept map, based on STEM@school designed learning materials around the theme 'mobility'

Learning-content literature study (CLS)

In this step, you will dive into the **discipline-specific educational research literature** on the listed STEM concepts and skills, because "[e]ach discipline comprises a knowledge base, specialized practices, and particular habits of mind ... [and] much is to be understood about how students acquire knowledge and skills in each area" (NAE & NRC, 2014, p. 16). Years of efforts in discipline-specific educational research (see e.g., National Research Council, 2012a) can serve as support in the design of STEM integrating learning materials. The literature produced by research in students' conceptual understanding shows their recurring difficulties and misconceptions, i.e., incomplete or faulty mental schemas and relations students have constructed around certain concepts, often (mis)guided by their intuition (Chi, 2005). Moreover, the literature often suggests possible instructional strategies to address difficult concepts (Vosniadou et al., 2001).

You can search for scientific articles of educational research yourselves, using search terms like "student difficulties" or "student misconceptions" + concept. Some

education centers provide an online portal where you can ask your question to a team of educational researchers (e.g., at the website of the Netherlands' National Directory for Educational Research (NRO)). However, your team coordinator might have easy access to the literature on this matter, so do not hesitate to ask him/her for information while looking for answers to the following questions:

- ▷ Which difficulties do students have with one or more of the listed concepts and skills?
- ▷ Which instructional strategies does the literature suggest (or refute) to address these concepts?

You will find it enriching to obtain insight in the endeavors of enhancing conceptual learning (Minstrell, 1989). This literature study might deepen your discipline-specific knowledge, and broaden your knowledge across disciplines. Establishing a profound content knowledge among the students is crucial for effective STEM integration (Pang & Good, 2000; Stohlmann et al., 2012).

Can an explicit link between the S, T, & M learning concepts be made? (ph3C1)

- In case the answer is 'no', the team is redirected to the step 'learning-content identification and linking'.
- In case the answer is 'yes', the team can proceed to the next step.

Challenge formulation (CF)

You will now try to formulate an interesting and purposeful **challenge**. The challenge is a problem statement which will be presented to the students at the start of the learning unit and must drive students' learning throughout (Nelson, 1999; Jonassen, 1999). It can serve as a vehicle for addressing the STEM learning contents you listed in the step 'learning-content identification and linking' (CIL) (in case you did not start with the current step first).

Try to formulate a challenge that anchors these learning contents and check whether it meets the following criteria as good as possible:

- The challenge is authentic, i.e., its cognitive demands as well as its practical experiences are representative for what students will encounter (as a scientist or engineer) in the real world following instruction. Hence, the complexity of the problem should reflect the complexity of real-world problems (Merrill, 2002; Savery & Duffy, 1995; Jonassen, 1999), but in a junior version (Perkins, 2010). It encourages students to explore causes and effects from different perspectives (society, economy, environment, technology), and to apply integrative tools and techniques in order to develop a sustainable solution (Fortuin et al., 2013).
- The challenge activates students, so they will take ownership of the problem and become eager to know the outcome (Merrill, 2002). In the eyes of the

students, the challenge should be worthy of solving and should make the learning worthwhile (Perkins, 2010; NAE & NRC, 2014):
  - it is related to what is personally relevant to students, so it will pique their interest (Savery & Duffy, 1995; Perkins & Unger, 1999; Satchwell & Loepp, 2002), and/or
  - it is related to today's societal or ecological issues (Sjøberg & Schreiner, 2010), which are often multidisciplinary by nature.
- The challenge will evoke the need to learn and connect the intended learning contents (Stolk et al., 2016). As such, the intended learning contents become relevant to the students, as they are needed to solve the challenge.
- The challenge unites the learning contents – like pieces of a puzzle – to a coherent whole. Like the front picture of the puzzle, it presents to students the final goal of their learning process, so students get an idea of what they will be working towards (Perkins, 2010).
- The challenge consists of multiple subproblems that require increasingly complex competences (Guzey, Moore, & Harwell, 2016; Savery & Duffy, 1995; Merrill, 2002).
- The challenge gives rise to purposeful inquiry and/or design (Sanders, 2000).
- The challenge has multiple prerequisites and constraints, and multiple solution strategies that are not always clear from the beginning: it is ill-structured and open-ended (Jonassen, 1999; National Research Council, 2012a; Felder & Brent, 2016).

In theory, finding a problem statement that meets these requirements should not pose any difficulty, since scientists and engineers encounter this kind of challenges on daily basis (Shernoff et al., 2017). In practice, however, it has been proven to be less evident to formulate such a problem statement that meets these requirements and that is comprehensible and resolvable at student level (Stolk et al., 2016). A trade-off is sometimes necessary and, consequently, the challenge sometimes becomes somewhat artificial in comparison to real-world problems.

The final goal of a challenge could be: designing and conducting an experiment and analyzing the data, or designing, building and programming a prototype to meet a specific need. Along the way towards the solution, students might have to carry out a series of smaller experiments or designs to serve the overall goal.

Examples of challenges are: 'Create a security system: place and orient mirrors and sensors in a museum chamber so that the art pieces can be protected from burglary by a laser beam and an alarm,' 'Design a rehabilitation aid to train the biceps of Mathew after his car accident,' or 'Build a scale model of a house with a sun boiler and floor heating, and control the indoor temperature with an on-/off-control loop.'

First time you encounter this step? Do not worry when you do not get the problem statement straight from the start. You will iterate this step at least once more to check if all the intended learning contents (identified in step 'CIL') will be covered by the challenge in its current formulation. A first trial can however set the scene.

Not the first time you encounter this step? When iterating this step, you can expand the problem statement with extra elements that require the intended concepts and skills that are not yet covered by the current challenge formulation. Next, you should examine if the problem-solving process is clear for all team members and if it addresses the intended learning contents. This does not mean that for the students this process should be clear from the beginning. Highlighting its critical factors for the students is not desirable. Either you provide the students with the full problem context, from which *they* should extract the important aspects and conditions, or you provide them with a very basic question, on which they will gather more information while progressing in the problem-solving process (Savery & Duffy, 1995).

Challenge breakdown in subproblems (CBS)

Although real-world problems are often ill-structured, with multiple (often conflicting) goals and constraints, they often consist of multiple, well-structured, smaller problems (Jonassen et al., 2006). In this step, you will try to determine these different **subproblems of the challenge**. While doing so, keep in mind the suggestions from educational research regarding the preferable sequence in which to address the concepts (in case you already executed the step 'learning-content literature study' (CLS)). Maybe the inspiration and brainstorming techniques provided by 'Innowiz' can help your team to identify subproblems and generate ideas for their possible solutions (see `http://innowizonlinetool.blogspot.com/`) (Michiels, Verthé, Saldien, & Versluys, 2012).

Try to identify the different steps in the problem-solving process by subsequently answering the following questions:

- ▷ What is the next subproblem students will encounter?
- ▷ Which prior knowledge or understanding will students need to employ in this subproblem?
- ▷ Does this prior knowledge match the knowledge that was constructed in the previous subproblem(s)? If not, which extra subproblem precedes this one?
- ▷ Which concepts or skills are new to the students and should be learned in order to successfully solve this subproblem?
- ▷ What will students need to do for solving this subproblem and learning these contents?

See Figure 3.6 for an example of the subsequent subproblems of a challenge within the theme 'mobility' (Figure 3.4). Another example, within the theme 'internet security', is presented by Gramm et al. (2012).

Requirement & feasibility study for solving the challenge (RFS)

Based on your overview of the different subproblems that constitute the challenge, you can now formulate the output you expect from the students: the **requirements**

and constraints on the data or prototype you want the students to produce while solving the challenge.

Analyze these requirements to detect which **accommodation** (tools, lab materials, ICT, space) and **learning materials** (resources to scaffold the learning) students will need to conduct the inquiry and design comprised by the challenge. For the accommodation, you might find support in the following resources:

- a visit to research centers or enterprises with expertise in the field,
- your school's technical support staff, or
- the web page `wiki.stematschool.be/readonly` (Vanbiervliet, Goovaerts, De Meester, Theunis, & Dehaene, 2017) on electronic components.

In this step, you might discover that not all the necessary equipment is at your or the students' disposal, because it is inconvenient, not affordable, or not available. In that case, examine whether or not these impediments can be circumvented. You could, for example, block some of the degrees of freedom in the challenge formulation, by presenting them as **extra data or constraints**. Make sure that the obstacles you encounter in this step do not harm the consistency, feasibility, or credibility of the challenge too much.

Is the challenge authentic & feasible? (ph3C2)

- In case the answer is 'no', the team is redirected to the step 'Challenge formulation'.
- In case the answer is 'yes', the team can proceed to the following step.

Does solving the challenge require learning & linking of the S, T, & M concepts? (ph3C3)

- In case the answer is 'no', the team is redirected to the step 'Learning-content identification + linking'.
- In case the answer is 'yes', the team can proceed to the next step.

Learning-goal refinement per subproblem (GRS)

Because the learning contents have been identified per subproblem, the learning goals can now be refined. Learning goals determine the objectives of the learning activities (classroom practices), and, consequently, how these activities must be designed and evaluated (Felder & Brent, 2016; Kober, 2015).

When refining the learning goals, try to avoid general words, like 'know', 'understand', 'appreciate', or 'learn'. **Learning goals** must be *transparent and unambiguous* on the one hand, and *observable* (easy to assess) on the other hand (Felder & Brent, 2016). They must be stated in such a way that they express the desired student results, i.e.,

the competences students should have acquired after implementation of the learning materials (Wiggins & McTighe, 2005). Each learning goal starts by "Students can", and continues with observable actions, like 'explain', 'deduce', 'argue', 'analyze', etc. (Felder & Brent, 2016).

The revised version of Bloom's taxonomy (Anderson et al., 2001) shows the verbs you can use in the refinement of learning goals, depending on the thinking level you want the students to attain. The sizes of the thinking levels as they are depicted in Figure 3.22 represent the importance of the related learning goals for the learner's future life. Since iSTEM education aims for higher-order thinking and problem-solving skills, the learning goals should be adapted to the upper four levels of thinking.

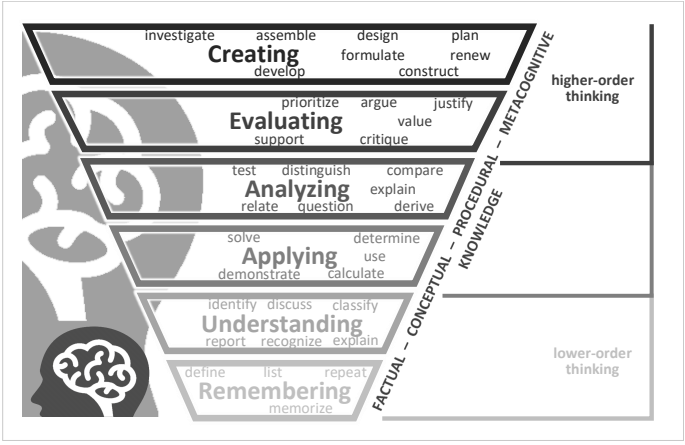


Figure 3.22: Representation of the revised Bloom's levels of thinking according to their importance for learners

Write down the discipline-specific and crossdisciplinary learning goals per subproblem, based on:

- the **national curriculum standards** of the **different STEM courses**

- **higher-order goals** (Wiggins & McTighe, 2005; NGSS Lead States, 2013; Felder & Brent, 2016): systems thinking, critical thinking and other '21st Century competences' (Ananiadou & Claro, 2009), e.g.:
  - in terms of **understanding**: 'explain in own words why . . . ', 'explain . . . for a child or a grandfather to understand', 'apply . . . to . . . ', 'formulate a problem statement about . . . ', 'estimate the time it would take to . . . ', 'phrase the different steps in . . . ', 'make a concept map of . . . ', 'formulate the prerequisites for (a good functioning of) . . . ',
  - in terms of **inquiry**: 'formulate a hypothesis about . . . ', 'argue a decision for . . . ', 'interpret the graph of . . . ', 'analyze the results of . . . by use of

scientific principles', 'explain anomalies of ... and correct the experimental setup or hypothesis', 'choose an adequate sensor for ... based on ...',
  - in terms of **modeling**: 'apply the definition of the concept ... to ...', 'graphically represent the dynamic behavior of ...', 'model the process of ...', 'capture ... in a representation', 'identify the strengths and weaknesses of a model for ... as a predictor of the behavior (of a physical, chemical, or biological system)', 'make an analogy of ... and discuss its constraints', 'control the behavior of ...', 'predict the output to ...', 'deduce the formula of ...', 'divide ... into subproblems', 'discuss the interactions between the parts of ... (what has which effect on what)',
  - in terms of **design**: 'determine priorities in the design of ...', 'develop a prototype for ... based on ...', 'choose an adequate design for ...', 'program the algorithm for ...', 'choose the adequate tools to ... based on ...', 'add an idea to ...',
  - in terms of **responsibility**: 'organize ...', 'draft a planning for ...', 'adapt the planning of ... based on sound reasons in order to meet a deadline', 'elaborate on the relevance (or possible effects) of ... for society', 'evaluate ... against ...', 'describe the (dis)advantages of ... on the environment', 'choose reliable information sources, and argue this choice', 'refer to the consulted information sources', 'use ... efficiently (or safely)', 'persevere after a failure', 'reflect on own working strategy', 'account for a decision, made for ...',

- **social skills** (Ananiadou & Claro, 2009; Wiggins & McTighe, 2005), e.g.:
  - in terms of **communication**: 'communicate orally (or on paper) in a clear manner about own progress (or results)',
  - in terms of **team work**: 'constructively contribute to a debate about ...', 'consider the perspective of other team members regarding ...', 'divide responsibilities for ...', 'integrate individual contributions in a coherent report about ...', 'take initiative in ...', 'flexibly work with ...', 'participate actively in ...',

These learning goals will not only direct the design of learning activities, they are also supposed to be communicated as **evaluation criteria** to the students (Wiggins & McTighe, 2005; Felder & Brent, 2016).

Design of S, T, & M linking learning activities (DLA)

At this stage of the Brainstorm Phase, you will create a draft of the learning activities. The **learning activities** are a means to establish the intended learning goals (Wiggins & McTighe, 2005). The activities should be connected to the challenge (Guzey, Moore, & Harwell, 2016), much like coat hangers. In turn, the activities embed the STEM concepts and skills to be learned. Each subproblem of the challenge consists of one or more learning activities.

Keep in mind the order in which the subproblems are encountered while solving the challenge, because it is the sequence in which the learning activities will be carried out. Each learning activity must rely on what students have learned in previous activities (Bransford, Brown, & Cocking, 1999; Stohlmann et al., 2012). As such, students can make connections to their mentally constructed schemas, in order to restructure and expand them with new information (Vosniadou et al., 2001).

The learning activities determine *what* the students will be doing in the classroom: as the word itself indicates, learning activities engage students to actively steer their own learning, towards the intended learning goals (Prince, 2004). They are a mixture of hands-on and minds-on activities in which students will have to employ insights of different STEM-disciplines:

- making exercises,
- processing theory,
- gathering information,
- programming,
- setting up and/or conducting and analyzing an experiment,
- designing and/or building and testing a prototype.

Modeling should definitely be part of (some of) the learning activities. Modeling encompasses several actions (Carberry & McKenna, 2014; Gainsburg, 2013; Van Heuvelen, 1991):

- capturing a phenomenon, or data, in an abstract representation (leaving out irrelevant details): a sketch, diagram, graph and/or formula;
- manipulating and/or reasoning qualitatively about the representation;
- testing the results of this manipulation or analysis against reality.

Some or more activities should involve *inquiry*. In controlled experiments, students determine the relation between (at least) one independent variable and a dependent variable, partly inductively (from data to a theory or model), partly deductively (from a theory or model to data) (Pedaste et al., 2015). The following activities are part of inquiry-based learning (Barrow, 2006):

- posing scientific questions on certain concepts (identifying a testable hypothesis and an adequate setup);
- designing an inquiry in such a way that it tries to answer these questions (or prove that hypothesis) in the first place;
- conducting the inquiry and making improvements, therefore relying on adequate measuring equipment and mathematical or scientific models;
- analyzing the data resulting from the inquiry, and reflecting on the procedure;
- formulating (alternative) explanations and models based on scientific evidence;
- constructing and communicating arguments for these explanations and/or models.

Examples of learning activities concerning inquiry-based learning are: ‘determining the relation between the duty cycle of the motors and the velocity of a car’, or ‘determining which material and which liquid in a sun boiler result in the highest efficiency’ (for inquiry-based design).

Some or more learning activities should involve *design*. Design starts with a certain question or need, proceeds with the generation and selection of possible solutions, and results in a prototype or artifact. The tool 'Innowiz' can guide the students' idea-generation and -selection process (Michiels et al., 2012). Examples of artifacts are: 'an installation out of recycled materials', 'a polymer accessory', 'a mechanical arm', 'a software application', 'an electronic alarm system', 'a computer game', etc. The following activities are part of design-based learning (Mehalik & Schunn, 2007; Gómez Puente, Van Eijck, & Jochems, 2011):

- exploring the problem from the perspective of the end user or customer;
- decomposing the problem in partial components with different functionalities;
- making a planning, and inserting deadlines;
- using (different) graphical (re)presentations;
- (re)formulating prerequisites and constraints, and estimating their impact;
- evaluating design concepts and choosing a suitable one based on scientific principles and argumentation to account for its reliability;
- developing (i.e., building and/or programming) a prototype;
- testing the prototype against the standards and requirements;
- analyzing defects, reflecting upon and iterating the design process.

Examples of learning activities concerning design-based learning are: 'programming a car so that it accelerates at a desired, constant rate', 'building a configuration with pulleys to train a biceps with a weight of 200 Newton', or 'designing a sensor that measures the concentration of algae in a solution' (for design-based inquiry).

Also *reflection* and *evaluation* are part of learning (Miedijensky & Tal, 2009)! Therefore, include exercises and discussions that provide student with the opportunity to reflect on their own or others' solution strategy and/or learning process.

Make an outline of the learning activities per subproblem. This does not have to be a final outline, as it will be reviewed by the other teams in the STEM group first. Consider the following questions for each of the learning activities separately:

- ▷ Does the activity address one or more of the intended learning goals (Felder & Brent, 2016)? If not, eliminate this activity, it will just absorb precious time that could be spent on learning.
- ▷ Will students have to use insights from two or more STEM disciplines during this activity (NAE & NRC, 2014)?

After having identified all learning activities, reflect upon the following questions:

- ▷ Are all intended learning goals covered by the learning activities? If not, evaluate the importance of the remaining learning goals and think of an extra activity to cover them if they are too valuable.
- ▷ Can some of the learning activities only be executed successfully by a *team* of students? If not, try to adapt some learning activities to ensure that students will perform some constructive team work.
- ▷ Do some learning activities require inquiry-based learning?
- ▷ Do some learning activities require design-based learning?
- ▷ Are evaluation activities built in?

Learning-activity accompaniment with instructional strategies (AAS)

The learning activities should be accompanied by appropriate instructional strategies. These **instructional strategies** determine the classroom configuration and *how* the students will carry out the learning activities. Just like the learning activities, the instructional strategies must be chosen strategically so that they activate the students (Merrill, 2002) and guide the students towards the intended conceptual understandings and skills. Although variation in instructional strategies will certainly be appreciated by students, the strategies should, above all, be chosen with the intended learning goals in mind (Felder & Brent, 2016; Kagan, 1989). Therefore, the previously defined and refined learning goals are again an important input.

One way to have students actively construct their own knowledge and skills, is by having them work together in *cooperation* (Prince, 2004). For fruitful cooperation, student teams ideally consist of four students who can pair up in subteams of two, who can alternately share their thoughts. As such, half of the classroom is actively involved at the same time, instead of only one student per classroom (i.e., the one who answers the teacher's question) (= equal participation). The students should exchange encouraging though instructive feedback (= constructive interaction) and rely on eachother to elaborate an adequate solution (= development of team skills), because it is the team score that counts! The students still need to account for their individual effort (= individual responsibility), but the team score is calculated as the sum of the progress of each team member separately (= positive mutual dependence) (Slavin, 1991; Kagan & Kagan, 2009; Johnson, Johnson, & Smith, 1998; Felder & Brent, 2016).
Examples of cooperative strategies are:

- brainstorming (Capraro, Capraro, & Morgan, 2013) and mindmapping;
- debate – reaching a consensus (Howe, Tolmie, Duchak-Tanner, & Rattray, 2000);
- *CLIM*: rotation of learning activities among teams, and rotation of roles among team members (Paelman, 2005);
- *jigsaw*: distributed learning of contents in expert teams – exchanging learned knowledge in mixed teams (Aronson, Blaney, Stephan, Sikes, & Snapp, 1978; Slavin, 1991);
- *think-pair-share*: individual reflection – exchanging in pairs – sharing with team members (Lyman, 1987);
- *thinking-aloud pair problem solving*: individual reflection – proposing problem-solving steps or asking for clarification in pairs (Lochhead & Whimbey, 1987);
- *peer instruction*: individual reflection – individual answering – classical debate – exchanging in pairs – individual answering – classical answering – extra instruction if necessary (Mazur, 1997; Dumont, 2014);
- *learning cell*: individual study – individual question-posing – in-turn question-posing and exchanging in pairs (Goldschmid, 1971); and
- programming in pairs (Williams, Kessler, Cunningham, & Jeffries, 2000; McDowell, Werner, Bullock, & Fernald, 2006; Bergner et al., 2012).

The choice or design of instructional strategies should also be informed by the literature review on how to address *students' conceptual difficulties and misconceptions*. Often, the literature suggests (1) identifying the misconception(s) by having the students articulate and explain their ideas, e.g., by having them predict the outcome of an experiment, (2) providing a demonstration or experiment that clearly contradicts the misconception(s), (3) inviting the students to reason upon why the outcome is different from their prediction, (4) creating a correct conceptualization and showing its validity by analyzing the experiment, and (5) doublechecking the students' understanding by means of additional exercises (Taylor & Kowalski, 2014).
Examples of strategies supporting students' conceptual learning are:

- concept mapping (Westbrook, 1998; Novak & Cañas, 2008);
- *concept inventory*: quiz with a multiple-choice answers (inspired by the students' misconceptions); *concepTests* (Mazur, 1997) with clickers or smartphones and automated answer logging (Quinn, 2005);
- debate on concept cartoons (Keogh, Naylor, & Wilson, 1998; İnel & Balım, 2013);
- *flipped classroom*: home study – making exercises and applying learned contents in the classroom (Bergmann & Sams, 2012);
- *conceptual understanding programme*: individual reflection – individual answering – debate and exchanging in trio – writing down the answer on a large paper in trio – showing all answers next to each other – classical debate about the differences and similarities – reaching a classical consensus (Mills, McKittrick, Mulhall, & Feteris, 1999) [specifically useful for learning activities involving modeling and graphical representations];
- *interactive lecture demonstrations*: classical experiment description – individual reflection about hypothesis – exchanging and discussion in pairs or in trio – reaching a consensus in pairs or in trio – (possibly) classical discussion – classical experiment demonstration – classical discussion about results and interpretation (Sokoloff & Thornton, 1997);
- process-oriented guidance (Moog, Spencer, & Straumanis, 2006); and
- lecturing by the teacher (for a small amount of time, and including student involvement).

Instructional strategies to address *reflection* and *formative (process) evaluation* are, for example:

- self-assessment based on predetermined criteria (e.g., in a rubric) (Sluijsmans, Dochy, & Moerkerke, 1998; Goovaerts et al., 2015);
- peer assessment based on predetermined criteria (e.g., in a rubric) (Sluijsmans et al., 1998);
- pre-lab quiz (Quinn, 2005);
- creating a portfolio (Felder & Brent, 2016);
- publishing blog posts
- *one-minute paper*: short survey concerning learning content and activities: "Which three ideas do you take home, and what is left unclear?" (Angelo & Cross, 1993);
- (poster) presentation of the results of their own inquiry

Indicate per learning activity the instructional strategy that seems appropriate and why, by answering the following questions:

- ▷ If the strategy involves team work: is the learning activity too complex to be carried out solely by one student? In other words: is success of his/her team members necessary for a student to complete this learning activity? If not, maybe another strategy is more suitable for this activity.
- ▷ Will multiple students be actively involved at the same time?
- ▷ Will the students achieve the intended learning goals via this strategy? How?
- ▷ Will the students regularly have to reflect on their own and their team's progress with regard to the objectives?

Do the learning activities cover the intended learning goals && explicitly link S, T, & M? (ph3C4)

- In case the answer is 'no', the team is redirected to the step 'Design of S, T, & M linking learning activities'.
- In case the answer is 'yes', the team can proceed to the next step.

Do the learning activities involve inquiry & design & formative evaluation? (ph3C5)

- In case the answer is 'no', the team is redirected to the step 'Design of S, T, & M linking learning activities'.
- In case the answer is 'yes', The team can proceed to the next step.

Are the learning activities accompanied by activating instructional strategies (e.g., cooperation)? (ph3C6)

- In case the answer is 'no', the team is redirected to the step 'Learning-activities accompaniment with instructional strategies'.
- In case the answer is 'yes', the team can proceed to the next step.

Reporting phase

As in each educational activity, there comes a time for formative evaluation (Wiggins & McTighe, 2005), to check if the intermediate outcomes meet the goals. The team coordinators gather all teams back again in the initial STEM group, so each team can present the ideas and the state of the design work to the other STEM teams and possibly other stakeholders. This phase builds in an opportunity for your team to **reflect** upon your work and to **share** ideas **with peers**. The purpose of this phase is to optimize the learning materials before they are implemented in the classroom.

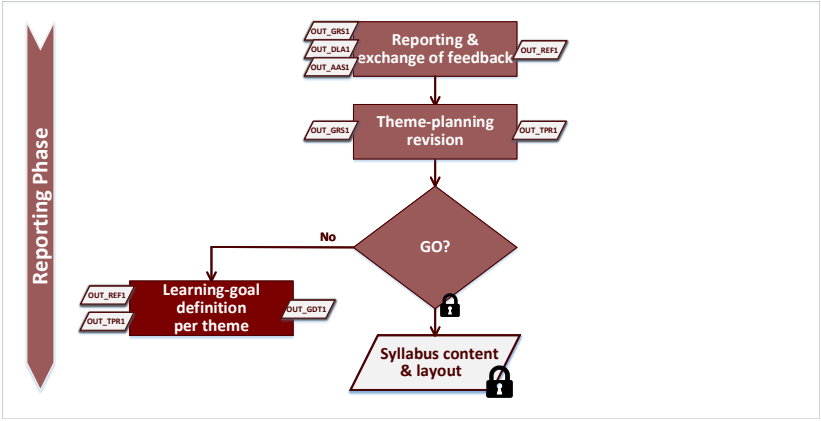


Figure 3.23: Reporting phase

Reporting & exchange of feedback (REF)

In a meeting coordinated by all team coordinators, you will be asked to **present** the **outline of the learning activities** to the other design teams involved in the STEM group. You will also be updated on the progress and ideas of the other design teams. Time is provided to exchange constructive feedback. The team coordinators moderate the discussions so that they address necessary adjustments, and – more importantly – how those adjustments should be carried out.

Also other stakeholders might be invited to this meeting (e.g., members of the educational umbrella organizations). A large support base is key to a change of mindset, and, eventually, a broad dissemination of the learning materials (Henderson, Beach, & Finkelstein, 2011; Peters-Burton, Lynch, Behrend, & Means, 2014).

Theme-planning revision (TPR)

After the presentation of the different design teams, it might become clear that a **reorganization of the theme planning** is in order. This means that the themes would better be addressed in a different sequence during the students' school year. This can be the case if, for example, one team's challenge requires quite a profound understanding of a certain concept that, according to the current planning, would only be addressed for the first time in another theme later-on in the school year. Concepts need time to grow in the students' heads (Schwartz, Bransford, Sears, et al., 2005). Therefore, together with the other design teams, you will try to find a logic sequence of the themes (and associated challenges) so that considerable time is provided for students' learning of the STEM concepts. Keep in mind that such a rearrangement of themes can sometimes also necessitate a shuffle of the learning activities.

GO? (ph4C1)

Is every team of the STEM group satisfied with the outline of the learning unit?

- If the answer is 'no', the team is redirected to the step 'Learning-goal definition per theme' of the Brainstorm phase. The coordinator will indicate which steps need revision.
- In case the answer is 'yes', the team can proceed to the next step and start developing the proposed learning activities, keeping in mind the suggestions from the other teams.

Development phase

In this last stage of the design process, you will develop the actual learning materials, in the form of syllabi and prototypes. As shown in Figure 3.24, sometimes the work is divided, for a more efficient progress.

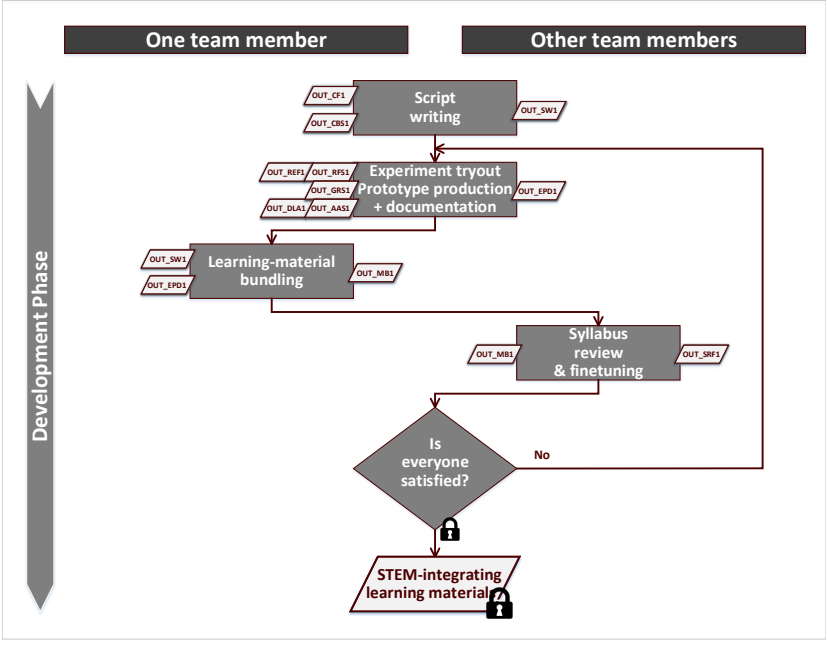


Figure 3.24: Development phase

Script writing (SW)

In this step, one or two of the team members start writing the **script**. The script is the story line or scenario. It consists of the challenge and suggests an order in which the subproblems and, therefore, the learning activities could be encountered. In the script, you consecutively present a new subproblem by means of scaffolding questions that invoke the need for learning *more*. Through these questions, the students are directed towards the learning activities in other syllabi (which are developed in the next design step: 'experiment tryout, prototype design, and documentation' (EPD)). You can opt for *just-in-time instruction*, in which you provide students with these other syllabi only at their own request (Wiggins & McTighe, 2005). After having performed a learning activity or answered a subproblem, the students are expected to return back to the script.

A script has appeared to be crucial for teachers as well as students to keep an overview on the problem-solving process. It should thus consist of:

- the challenge
- the different subproblems, each time with:
  - an introduction to the upcoming learning activities because of the need for learning new concepts and skills created by the subproblem, and
  - a reconnection from the learning activities to their use for solving the subproblem of the challenge, by means of reflective questions.

Experiment tryout, Prototype production + documentation (EPD)

The other members of the team will **elaborate the proposed learning activities**. You can choose to divide the learning materials that must be developed among duos (or trios) of team members. However, mind that, as the outlined learning activities are multidisciplinary in nature, that the developing duos (or trios) are too.

In this step, you try out one or more of the devised experiments, or prototype and/or code designs. Mind that several platforms offer easily-accessible programs and tangible devices for dummies as well as for advanced makers to start programming and building, such as Scratch, Arduino, Dwengo, Lego Mindstorms, etc. (Wyffels, Hermans, & Schrauwen, 2010; Bergner et al., 2012; Sentance & Schwiderski-Grosche, 2012; Wyffels, Martens, & Lemmens, 2014). The experimental data or artifacts you produce here, can serve as an inspiration or a model for the student products. However, the most important goal of this step is not the end result, but the pathway to reach it. Consequently, you should document this pathway for yourself or for your colleague-teachers who will implement the learning materials in the classroom. Furthermore, mistakes you make now can become learning opportunities for the students later-on.

In this **documentation per learning activity**, you gather all the information you produced in the previous steps of this design process:

- *the intended learning goals, and the STEM contents to be learned and linked;
- the prior knowledge to be retrieved;
- instructional tips (see further);
- the accompanying instructional strategy;
- the final goal: the intended results (data, prototype, solution, ...);
- the required equipment (measurement instruments, tools);
- a list of prerequisites, constraints, requirements and/or functions;
- the setup, a schematic, a drawing;
- a description of what is supposed to happen;
- *questions or instructions that guide students towards the learning and linking of the targeted STEM contents;
- the scientific theory and principles that underpin the targeted STEM contents;
- the interpretation and conclusion + reconnection to the challenge (this is important for the script as well!);
- *questions that make students reflect upon their working and learning strategy;

Not all of this information is destined for the students. If the students are expected to formulate a hypothesis, think about how to design the experiment or prototype, and identify the required equipment on their own, they should only be provided with the information indicated with '*', i.e., the intended learning goals, and the scaffolding questions. In that case, all other documentation is intended for the teachers, as a practical classroom guide to support students in their learning process. How much information or scope for creativity will be granted to the students, depends on the goals of the learning activity at hand and on the desired level of self-regulation. Keep in mind that if you incorporate scientific theory, it should aim for ***necessary* knowledge** (rather than fun facts), and for ***higher-order* insights and skills**, such as understanding, analysis and application (rather than rote learning and memorization, which can take place at home if necessary) (Felder & Brent, 2016).

Consider the following issues when gathering **instructional tips or recommendations** for the teachers who will eventually implement the materials in the classroom:

- During the design process, you might (have) bump(ed) into some *practical difficulties and obstacles*. Not all teachers are accustomed to using electronic circuits or mechanical devices. The same goes for programming or ordering components. How do/did you deal with problems related to technology? Maybe you find/found some useful information on forums or blogs. In case you do/did, make sure you document all of this information for the implementing teachers. As such, your endeavors during the design process, will not have been in vain.
- Stress the fact that the predetermined *learning goals*, which will also be the evaluation criteria, should be announced at the start of each learning activity (Felder & Brent, 2016) in order to ensure transparency of evaluation.
- Mark the parts of the learning materials that are optional (e.g., interesting for student differentiation), and the parts that are mandatory to address in order for the students to achieve the important goals.

- Document the *instructional strategies* you designed or learned with respect to the integration and modeling of STEM learning contents, the role of metacognitive monitoring and reflection for problem-solving, scientific inquiry, and technological design, and ways to support students' cooperation and conceptual learning. Indicate for future reference why you incorporated these strategies and associated them with the learning activities.
- Emphasize for the implementing teachers that their role is to *coach* the students, and to *scaffold students' self-regulated learning* (Stohlmann et al., 2012; Felder & Brent, 2016). Structure the learning materials in such a way that they allow teachers to provide just-in-time instruction (i.e., instruction on students' request), as it will urge students to take ownership over their learning (Wiggins & McTighe, 2005). Include multiple opportunities for students to try out their ideas and to learn from failure. Encourage this experimental and incremental problem-solving behavior, and scaffold it by means of regular formative evaluations that instigate reflective thinking on the part of the student and exchange of constructive feedback (praising students' efforts towards growth) on the part of the teacher (Boaler, 2015).
- You can include some *scaffolding questions* to help the students tackle the problems you encountered yourself during your design process. As such, you turn these problems into learning opportunities for the students. Formulate the questions in such a way that they stimulate the students to activate their prior knowledge and to look for underlying principles. The questions should elicit the students' metacognitive and strategic thinking.
- *Unforeseen problems* that can not be anticipated or even predicted, are inherent to *open-ended* learning activities. Their occurrence during the implementation will be a good sign: you created an authentic learning environment (Jonassen et al., 2006)! Together with the students, the implementing teachers will then have to go the extra mile and explore the possible causes of the problem. In your documentation, you can, however, propose a few tests to overcome such problems (e.g., partial debugging of the program code or electric circuit). However, as in other professional STEM environments, there is no shame in requesting the assistance of a colleague-teacher who might look at the problem from another perspective or another STEM discipline. After all, that is what you did during this design process as well. Therefore, do not hesitate to promote this transdisciplinary commitment among the teachers who will implement the learning materials.

Learning-material bundling (MB)

The **learning materials**, i.e., the script and the documented learning activities, are now **bundled** into a coherent learning unit, in the requested layout. The team member to whom this step is assigned, checks the syllabus for inconsistencies, and adds information where necessary, for instance, when the conclusion of a learning activity does not align with the related reflection exercise in the script.

Syllabus review & finetuning (SRF)

The syllabi are now forwarded to all team members for **review**. An online file-exchange service, such as a cloud storage software, is very suited for this step. All team members are asked to attentively read the syllabi and formulate manageable remarks and feedback where needed. Consider whether it is necessary to schedule an extra team meeting to discuss and implement these remarks.

Is everyone satisfied? (ph5C1)

- If the answer is 'no', the team is redirected to the step 'Experiment tryout, Prototype production and documentation'. The draft and outline of the learning materials has already been approved before, so, now, it is a matter of fruitfully implementing the suggestions of the team members and coordinator.
- In case the answer is 'yes', the team members and coordinator are satisfied by the result. The teacher team has successfully finished the design process. Besides gaining experience in crossdisciplinary collaboration, the team members also succeeded in designing high-quality, problem-centered, iSTEM learning materials. The designed learning materials are ready to be distributed for implementation, and congratulations are in order.

Online version of CODEM for iSTEM

Of the support model, also an online version was created: CODEM for iSTEM (Collaborative Online Design of Educational Materials for integrated STEM). In this online version, users are digitally linked with their team members and their coordinator(s). When they log in, they enter a home page, on which they can indicate the STEM subjects they believe to have some expertise in, and see those of their team members and coordinator(s) so they know who to consult on subject matter they are less familiar with.

Via the 'Let's develop!' button on the home page, the team members and coordinators arrive at the last step of the design process they were previously working at, exemplified by Figure 3.25.

The left side of the web page shows the schematic overview of the phase, in which the step in question is highlighted. The right side of the page contains a description of the step, as detailed in Section 3.4.1. Through a discussion forum on the bottom of the page, team members and their coordinators can exchange general difficulties or announcements concerning the step at hand.

The intermediately developed learning materials are gathered in a cloud storage folder (e.g., Google Drive), which can be accessed through a button on the web page. Such cloud storage allows to collaborate simultaneously with multiple people in the same document. In the cloud storage folder, following documents are provided to scaffold the team's design process:

- handouts of an introduction seminar;
- deliverables: input/output documents of all steps, already titled, e.g.: 'OUT_GRS1: Inventory of STEM discipline-specific and crossdisciplinary learning goals per subproblem', so the team members and coordinators would be able to directly retrace the documents they should be working on or reviewing,
- a template for meeting reports.

The list of requirements for the iSTEM learning materials (see Figure 2.6) is at the team members' disposal at any given moment in their design process via its button on the web page of each step. As such, the team members can remind themselves of what they are working towards, and the process becomes goal-oriented. The list of requirements behind this button can also be used as an instrument to evaluate and reflect upon the finally developed learning materials.


cloud storage folder of the team


schematic overview of all steps of CODEM for iSTEM


list of requirements for the iSTEM learning materials

To encourage team members to stick together during the design process, instead of splitting up in monodisciplinary subteams to carry out different steps separately, sluices are built in. As long as one or more team members have not clicked their name on the right bottom of the page to indicate that the step is finished, the team cannot proceed to the following web page, and is thus not allowed access to the description of the next step.

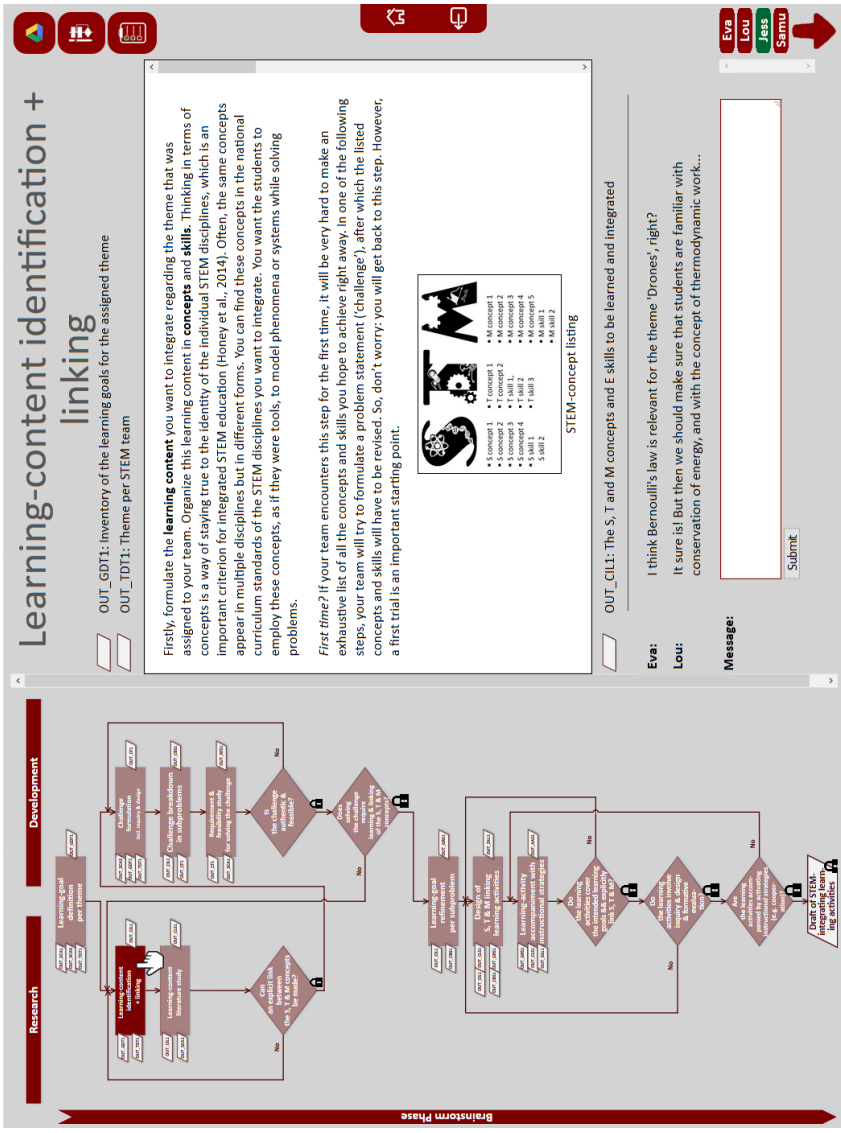


Figure 3.25: Web page of the step 'CIL' of CODEM for iSTEM

3.4.2 Model validation

The proposed model CODEM for iSTEM was evaluated by means of multiple instruments and people. One form of evaluation involved an opinion survey that was administered among a teacher and a team coordinator involved in the project STEM@school. The second form of evaluation involved tryouts of the online version among people who had not been involved in the case study or STEM@school: participants at two professional development workshops. In a debriefing discussion after these tryouts, the participants were invited to share their experiences.

Internal validation through review

To verify the *completeness* and the *coherence* of CODEM for iSTEM, and assess its *suitability* to guide teachers in their design process, two people were contacted by e-mail with the request to review the model: C4_Coordinator, the team coordinator of case C4 and researcher affiliated with STEM@school, and David, a teacher who participated as a designer in STEM@school during two years. The e-mail contained the outline of CODEM for iSTEM (i.e., the assembly of Figures 3.16, 3.17, 3.20, 3.23, 3.24), and the questions stated in Appendix G. David and C4_Coordinator sent their comments per e-mail.

A deliberate choice for David was made because of several reasons. First of all, the teacher design teams in which David had participated, had not been followed up-close in the case study. Although his teams had been part of the big group of teachers in cases C2 and C3 with whom some steps had been carried out collectively, the majority of David's design process had not been studied in depth. Being part of STEM@school though, David had the prior experiences necessary to interpret CODEM for iSTEM in view of its targeted context. Secondly, David had also participated in the teacher interviews that were conducted in the scope of another study in this work (see Chapter 4). In this interview (on the design of iSTEM learning materials), David showed remarkable insight at a metacognitive level on designing and teaching iSTEM. For a profound evaluation of CODEM for iSTEM, David therefore seemed a good candidate.

Although only the last team under her guidance was followed in the case study, C4_Coordinator had been coordinating three design processes within STEM@school. These experiences would have provided her with an idea of the overall steps and pitfalls occurring throughout the design process. Therefore, she would be able to provide valuable arguments in an evaluation of CODEM for iSTEM.

David stated that CODEM for iSTEM is "almost entirely stand-alone", and that its steps succeed one another "in a logical way". "Although," he wrote: "according to me, in practice, you go through the steps again and again, and there is not really a beginning or an end." He thought that he had experienced and carried out all steps of the model (although he was not entirely sure). During the interview in the scope of the other study in this work, however, he testified that his design team had rarely given any attention to instructional strategies ('how' to address certain contents or implement the classroom activities) (see quote 9 in Chapter 4). This reflection justifies the inclusion of the step 'learning-activity accompaniment with instructional strategies' (AAS) into CODEM for iSTEM. In addition, David seemed to much appreciate the step 'multidisciplinary STEM-team formation' (TFD), as he said: "The STEM teachers indirectly also support other courses than their own, and they learn from each other." He claimed that it is invaluable to have a great team of motivated teachers from many different STEM disciplines at school, and that teachers who embark upon this adventure need to have a profound content knowledge and confidence to teach this content. He however claimed to miss a step in which all teachers involved in the implementation make an annual planning for their own STEM course. In this annual planning, they align their instruction of the discipline-specific contents with the iSTEM activities. He argued that possibly more efforts go to the alignment of the STEM courses than to the development of the course materials. "The individual teachers must be well informed during the whole course [of the learning unit]," he wrote, "so they can connect [to the activities] and co-support the students." In his conclusion, he noted a prerequisite that is also relevant for Section 4.5 of Chapter 4:

> Gathering colleagues and getting them on the same page, does not receive attention in the schematic. However, it needs to be done, partially even before you start with this model. Maybe it should get a place here? (David)

These remarks suggest the need to allocate a significant amount of time to STEM-team preparation and STEM-course planning. Creating buy-in and a shared vision is a step that should precede the application of the support model and should possibly be carried out by the team of coordinators. To STEM-course planning, an extra step could be devoted, or this action should be incorporated into the existing steps, e.g., in the 'design of learning activities' (DLA), or in the plenary step 'theme-planning revision' (TPR).

C4_Coordinator testified that the 'challenge breakdown into subproblems' was a step that was iterated too many times by her teacher teams. She cautioned that the teams should be prevented from breaking down the challenge to the level of single classroom lessons. A more holistic view on the concept 'subproblem' is required: a subproblem occupies multiple lessons of multiple STEM courses during one or more weeks. C4_Coordinator also stressed the

importance of the step 'learning-goal refinement per subproblem' (GRS) and the fact that it should definitely precede the step 'design of learning activities' (AAS), "so teachers would think more in terms of the learning goals instead of in terms of the activities". This statement corroborates the inclusion of the step 'GRS' into CODEM for iSTEM. C4_Coordinator furthermore argued that the 'requirements and feasibility study' (RFS) is "very important":

> Teachers should also solve the challenge themselves. In this way, they will already bump into several obstacles and experience what is too complex for the students and, consequently, where they need help. Often teachers get to know their own limitations here and realize it is time to get extra help from experts. (C4_Coordinator)

About the inclusion of the conditions (quality checks) in the model, David wrote: "I think that the teams who consider these questions will automatically get to the essence of iSTEM. A very good idea." He even thought that, from the whole model, the questions of the quality checks are "the most valuable tool for the teacher teams", and should regularly be posed "by beginning, as well as experienced teachers in iSTEM". C4_Coordinator wrote:

> The [conditions] in the Brainstorm phase are of crucial importance! The foundation of the iSTEM learning materials is laid [in this phase]. So [the conditions] are at their rightful place there! Teachers do not always make this check spontaneously. It must sometimes be pointed out to them that their idea has changed so much throughout this phase that they should look back at their initial learning goals. However, when teachers were already involved several times in a design process, they do have this reflex. (C4_Coordinator)

The overall scheme seemed a bit too abstract and rigid to David and he added that it might be too heavy for teachers who start developing their iSTEM education. This might be due to the fact that the whole model was sent to him at once, while, in practice, the users of CODEM for iSTEM will be guided through the model step by step and will be provided with the necessary information just in time. David continued:

> To me, it appears to be a convenient instrument to have teachers work more independently. However, according to me, external guidance is still necessary to keep a clear overview on the challenge and to ensure that teachers will not skip steps without good reason. (David)

He stressed that the main issues and those of minor importance should be distinguishable, and that extra materials should be optional: just to help teachers and not to burden them.

When provided with information on the online version of the tool, David believed the discussion forum to be a useful feature, as it enables the team members to pose their own questions and help each other, but also to exchange information on initiatives and trainings. C4_Coordinator thought the features

of the online tool were definitely helpful, but she pointed out the importance and ease of a physical learning community for the step 'reporting and exchange of feedback' (REF), and the exchange of designed learning units with other teams. Furthermore, it will "evoke a sense of unity".

As C4_Coordinator had been consulted with respect to the observations, classification, and analysis during the case study, she concluded: "Reflecting about this model has helped me personally in guiding the design teams, because I came to see everything more clearly."

External validation through tryout

To verify the *comprehensibility* and *suitability* of CODEM for iSTEM, a proposal for a **workshop** was submitted to the international conference EAPRIL (De Meester, Langie, De Cock, & Dehaene, 2017). The limited amount of time of the workshop would, however, only allow to test the Brainstorm phase. The setup of the workshop was to create several experimental teams and one control team, each with a multidisciplinary composition, and consisting of four to five participants assuming the role of a teacher. Their task would be to design the outline of a iSTEM learning unit that would meet the requirements for high-quality iSTEM education. To control the conditions of the experiment, one and the same theme and target group of students would be specified and imposed to all teams. Furthermore, they would all receive the list of requirements (as shown in Figure 2.6). English curricula of the different STEM disciplines would be available. The experimental teams would receive the Brainstorm phase of the online version of CODEM for iSTEM as guidance, while the control team would not receive any guidelines whatsoever. The reviewers accepted this proposal because they saw great potential in it:

> This is an interesting and creatively approached submission, which addresses some key emergent themes within STEM provision. The proposed workshop provides an ideal platform by which further insight can be gained by active participation from a test and control group, the results of which would be most interesting to see. (reviewer EAPRIL)

The workshop was finally administered with two multidisciplinary experimental teams, each consisting of four members, and one multidisciplinary control team of three members. The whole group was a mixture of educational researchers and actual teachers. The workshop lasted 90 minutes. After 75 minutes, the separate team discussions were wrapped up, and a whole-group discussion about the participants' experiences concluded the session. In agreement with the participants, this discussion was recorded.

The workshop participants experienced the step descriptions in CODEM for iSTEM as very useful. They found the texts quite heavy, but stated that the descriptions could provide helpful information whenever their team got stuck in the design process.

The members of the experimental groups recognized the importance of thinking about and discussing learning goals (as suggested by step 'GDT'):

> Now that I think about it, in our context, [creating a challenge] is more interesting for us. But I don't know, for teachers really... they are much more restricted by what they need to cover from the curriculum. So looking for the learning goal[s]... What can the... The discussion you try to initiate across... eh... domains [is useful]. (experimental-team member)

On the other hand, when the members of the control team were asked which learning goals they aimed at with their design, they began deducing the goals from what they had designed, instead of the other way around:

> Ehm... They have to think about a system: how can you eh.... Like, when you're driving in a car, you have the green wave, so you have to eh... adjust your speed. So how can you do it... on a bike? (control-team member)

The participants in the experimental teams acknowledged the need for iteration of the different steps, but also struggled with defining learning objectives for a challenge that should be open-ended:

> We actually also started with the challenge, a real-life problem. And then we switched to the learning goals and then again to the challenge. It was, like, a process: switching between these two. (experimental-team member)
>
> I think it was also simultaneous. Because we read it, and then started discussing a real-life problem, and at the same time... ... But indeed, it was unnatural to completely not think about the challenge. (experimental-team member)
>
> I think it's quite hard to set your objectives, because the challenges are real problems. And real objectives and real problems are not the same side of the same coin. So it is quite difficult to set objectives for something you don't know the answer for. And I don't know if it is consistent. (experimental-team member)

These remarks suggest that the model focused the teachers' design process on learning goals and on an authentic challenge, but also that the designers struggled with the apparent paradox between these two components. The participants did, however, not get to the step 'requirements and feasibility study' (RFS), which they might have found helpful in their search to reconcile the open-ended challenge and student creativity on the one hand with the desired learning goals on the other hand. Their reflections also affirm that

teachers using CODEM for iSTEM should feel free to start with whatever focus they would like ('challenge' or 'learning contents'), *if* they make sure that they go through the iterative brainstorm cycle and address both items at least once, and preferably multiple times, to guarantee coherence and purpose. After all, if no contents from different STEM disciplines would be learned while solving the challenge, what would be the point of formulating one in the first place?

The members of one of the experimental teams had actually written down the contents and goals that came up in their team discussion. Collaboratively, they had identified learning contents from different STEM disciplines they wanted to integrate: see Figure 3.26. As can be seen from their writings, their goals are formulated in a clear and observable way, and demand students' higher-order thinking and modeling.

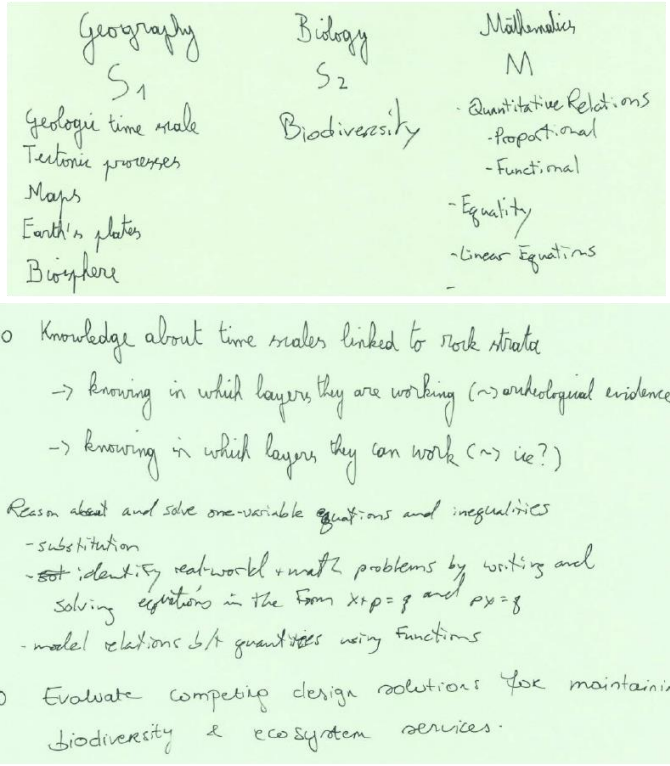


Figure 3.26: Learning contents and goals established by a workshop team who tested CODEM for iSTEM

The workshop was administered again for Flemish in-service teachers on a professional learning day, organized by a university college. In this workshop, four teams, each consisting of three to four members, also designed the outline of a learning unit, guided by the online tool CODEM for iSTEM.

In the wrap-up discussion at the end of this workshop, some participants testified that the model had helped them structure their thinking process in the design of iSTEM learning materials. One workshop participant stated:

> It was fun to work like this. You create some sort of think tank, and it goes much faster than working in pairs. The online tool is organized, it offers structure and helps you to prepare [classroom activities]. This way, you will reach the desired result much faster. (workshop participant)

3.5 Conclusion

This chapter elaborated on the process teacher teams go through when designing iSTEM learning materials, as, up until this study, no in-depth, evidence-based descriptions of the steps constituting this process were available to teams who embark upon the design of such materials. In order to model the design process, a case study was set up to capture the successive activities the teams engaged in. Four cases were examined in depth through a design-based case study. To this end, observations and documents were gathered during the design process of every case. From these data, a pattern emerged. This pattern could be modeled into five phases which consisted out of several activities or steps. In this chapter, each step was illustrated by the actions observed in the different cases. To assess the importance of the observed steps, the learning materials designed in each of the cases were collected and evaluated on the requirements for high-quality iSTEM education. For each case, the occurrence or absence of each step was then compared with the fulfillment or failing of each of the requirements that could be associated to these steps.

Important steps in the observed design process appeared to be: brainstorming on contents and themes (BCT), formulating a challenge (CF), breaking it down into subproblems (CBS), studying its requirements and feasibility (RFS), exchange of feedback (REF), and theme-planning revision (TPR). Activities that are key to the *iSTEM* design process, are the identification and linking of STEM contents (CIL), and the design of S-, T-, E-, and M-linking learning activities (DLA). The steps BCT, CIL, CF, and DLA are very similar to the steps defined by Jacobs (1989) for designing interdisciplinary learning units. Three steps were found missing in the observed processes: a literature study on students' conceptual difficulties with the STEM contents that would be

integrated (CLS), the specification of the targeted learning goals (GRS), and the inclusion of instructional strategies aiming at accomplishing these goals (AAS).

This study has some constraints. Because of differing team dynamics, teacher and coordinator attitudes, and the participation of the researcher in the design process, the possibility of bias cannot be excluded. However, complete immersion into the process enabled the researcher to experience and analyze the endeavors of the design first-handedly, and provided the opportunity to interpret the observed activities in their specific context. In turn, the fact that the findings are context-bound implies that they are possibly not generalizable to a wide range of contexts. There is, however, no reason to assume that the findings are not applicable in or extendable to other contexts. Finally, an important phase in the design process was not examined in this study: the implementation and corresponding revision of the designed learning materials (Wiggins & McTighe, 2005). It would make interesting matter for future work to have teachers perform action research to identify the effect of their iSTEM learning materials on student outcomes, and to identify required adjustments (Kelchtermans, 2001). Most models of curriculum design also include implementation as a phase (Satchwell & Loepp, 2002; Wiggins & McTighe, 2005). As such, the model would also be more in accordance with a general learning or engineering design cycle (Apedoe et al., 2008; Berland, 2013; Schwartz et al., 1999).

Some general conclusions can be drawn from this case study. Teachers manage to conduct constructive, crossdisciplinary conversations which lead to engaging student challenges and activities. The strategies they employ in establishing crossdisciplinary links, and their sharing of knowledge and materials provide interesting examples for teacher teams who are new to iSTEM design. However, teachers refrain from thinking in terms of student learning objectives. Like their students, they dive into the hands-on part (i.e., prototype design and experiment tryout) and the design of a fun challenge without setting their goals first. As a result, finding activities that are merely hands-on seems to prevail over determining essential and transferable skills that are valuable for them to learn. Paradoxically, teachers adhere tightly to the curriculum standards of their own STEM course. This is consistent with the fact that the curriculum standards are the goals they will have to account for towards the educational inspection in the end. However, when teachers decide upon an engaging student challenge, they tend to produce materials that are course-specific. This is a pitfall, because, as such, the course contents are linked to the challenge, but not to one other, while this was actually the primary purpose of iSTEM design. Since the teachers do not easily find their way to research literature, they do not tend to try out innovative or evidence-based instructional strategies. In general, instructional strategies are not a priority to them in the design of learning

materials. These results were also found by McFadden and Roehrig (2017), which corroborates the elaboration and inclusion of the steps that address these pitfalls (CLS, GRS, and AAS).

Based on what was learned from the case study, a model was constructed to support future teacher teams in their design of iSTEM learning materials. This model, called CODEM for iSTEM, consists of the important steps that had been identified in the case study, supplemented by the steps that were found lacking. To obviate the pitfalls (i.e., to prevent the skipping or poor execution of some important steps), some conditions were included to check the intermediary output and send the team back to the particular steps. These conditions need to be checked by the coordinator of the team. Furthermore, the descriptions of the steps were enriched by recommendations found in educational research literature related to the steps, and inspiring examples and strategies from the studied cases. Scaffolding questions guide the teams towards the desired (intermediary and final) outcome: iSTEM learning materials that comply with the requirements for high-quality iSTEM education. CODEM for iSTEM is conceived in such a way that it can be implemented as such in professional development programs.

CODEM for iSTEM was subjected to internal and external evaluation. It was perceived by the reviewers as helpful and resourceful, but rather rigid. And yet, TDT activities involving step-by-step guidance have proven to foster self-efficacy among elementary-school teachers (Velthuis, Fisser, & Pieters, 2014). Although this approach indeed entails the risk of micromanagement, an approach that is too open can cause the lack or failure of some crucial steps (Huizinga, Handelzalts, Nieveen, & Voogt, 2014). Nevertheless, the model should be presented with the idea that it represents an iterative process and that it does not really matter with which step one starts. One reviewer suggested to also include a step in which teachers of the separate STEM courses are urged to align their annual planning with the iSTEM activities. CODEM for iSTEM seemed to effectively obviate at least one pitfall: the users started thinking in terms of multidisciplinary learning goals, instead of merely inventing entertaining classroom activities. Also the inclusion of the other steps was justified by the reviewers. Although external guidance was claimed to remain necessary, CODEM for iSTEM appeared to structure the design process with helpful information and questions that bring a team to the essence of iSTEM design.

Chapter 4

Teacher learning for iSTEM education

4.1 Introduction

The process of designing iSTEM learning materials (see Chapter 3) encompasses many learning opportunities for teachers, which become assets during their implementation of the designed materials. Those learning opportunities translate to teacher competences, such as inquiry, problem solving, collaboration, and reflection. These are all competences the designing teachers hope to see reflected in their own students as well later-on. This chapter investigates the hypothesis that teachers who participate in the design of iSTEM education are better prepared for its classroom enactment than teachers who merely do the latter. As such, this chapter aims to inform teacher educators, school managers, and teachers about the ways STEM teachers and their classroom practices benefit from collaborative participation in iSTEM design.

The literature review in Section 4.2 shows that teacher training is needed in order to enhance student learning. Section 4.3 describes the research setup and participants, and the analysis that has been carried out as part of this work, in order to provide an answer to two research questions (RQ1 and RQ2, see below). Section 4.5 summarizes the needs indicated by the participants. Based on these needs, and on the important features indicated by the literature on teacher training, Section 4.6 proposes two formats of participation in iSTEM teacher design teams as teacher training for iSTEM education. Although teacher design teams aiming at teacher learning and reformed classroom practices have been

set up before (Binkhorst, 2017; Coenders & Terlouw, 2015; Mooney Simmie, 2007), they have rarely been employed in the transformation of separated STEM education into integrated STEM education at the secondary education level (Guzey, Moore, & Harwell, 2016; McFadden & Roehrig, 2017). The enhanced teacher learning resulting from the evidence-based teacher training via iSTEM teacher design teams proposed in this chapter, will ultimately pave the way for enhanced student learning (Fishman, Marx, Best, & Tal, 2003), and with this, the argumentation constructed in Section 4.2 will come full circle. Figure 4.1 gives an overview of the variables that are investigated in this chapter. In short, the line of reasoning in this chapter is as follows:

Question to be answered	section
How does teacher training for iSTEM education lead to enhanced student knowledge and attitude towards iSTEM?	4.2
Which methodology is used to investigate RQ1 and RQ2?	4.3
Is participation in iSTEM teacher design teams a valid form of teacher training for iSTEM education? *RQ1: How does participation in iSTEM design teams influence teacher knowledge and attitude towards iSTEM education?*	4.4
What should good teacher training for iSTEM education consist of? *RQ2: Which needs do teachers indicate as important features of teacher knowledge and attitude, teaching context, and teacher training for iSTEM education?*	4.5
Which formats of teacher training for iSTEM education does this work propose?	4.6

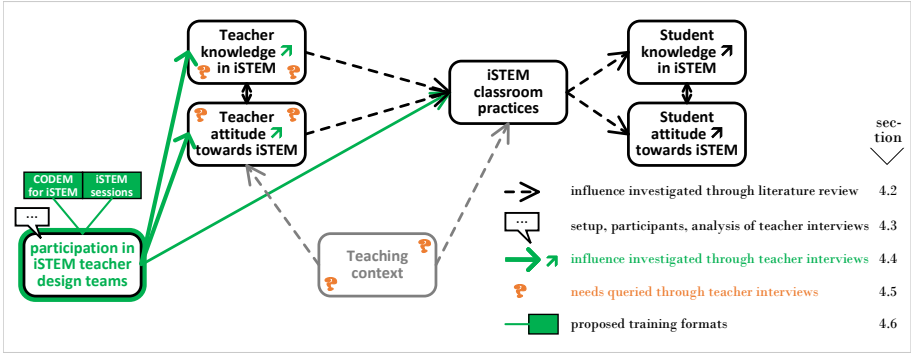


Figure 4.1: Overview of the variable relations investigated in this chapter

The coefficients mentioned in this chapter are clarified in Box 4.1.

Box 4.1 Effect size and coefficient calculation

An intervention (e.g., implementation of iSTEM education) is carried out with an experimental group (*exp*), and, often, its effects on a variable of interest (Y, e.g., math-test score) are examined before (*pre*) and after (*post*) the intervention. The results of this examination are sometimes compared with those of a group that did not participate in the intervention (*control*).

Calculation of effect size ES:

$$\text{ES} = \frac{\overline{Y}_{exp} - \overline{Y}_{control}}{SD_{Y,control}} \tag{4.1}$$

$$\text{ES} = \frac{\overline{Y}_{post} - \overline{Y}_{pre}}{SD_{Y,pre}} \tag{4.2}$$

$$\text{ES} = \frac{\left(\overline{Y}_{post} - \overline{Y}_{pre}\right)_{exp} - \left(\overline{Y}_{post} - \overline{Y}_{pre}\right)_{control}}{\frac{SD_{Y,pre,exp} + SD_{Y,pre,control} + SD_{Y,post,control}}{3}} \tag{4.3}$$

with $\overline{Y}$ the sample mean, and SD_Y the sample's standard deviation, where ES $\geq$ .20 indicates a small effect, ES $\geq$ .50 indicates a medium effect, and ES $\geq$ .80 indicates a large effect.

Often the effect of a change in a certain variable (the independent variable X, e.g., participation in an intervention - yes or no) on a variable of interest (the dependent variable Y, e.g., math-test score) is examined. In multiple regression analysis with multiple possibly influential variables, comparison of the standardized coefficients β shows which of these independent variables has the largest effect on, or the strongest relationship with the dependent variable Y.

Calculation of standardized regression coefficient β:

$$\beta = b \cdot \frac{SD_X}{SD_Y} \tag{4.4}$$

$$b = \frac{\sum_{i=1}^{N} (X_i - \overline{X}) \cdot (Y_i - \overline{Y})}{\sum_{i=1}^{N} (X_i - \overline{X})^2} \tag{4.5}$$

with N the number of participants in the study,
and b the regression coefficient, which is the change in the dependent variable Y for every change of 1 unit of the independent variable X, controlled for the other independent variables (i.e. when the values of the other independent variables are kept constant).

4.2 From teacher training and teaching context to student learning in iSTEM education

Just like in any other form of instructional innovation, the ultimate goal of efforts towards iSTEM education is to enhance student performance in knowledge and attitude. In the case of iSTEM, the aim is to improve student performance in STEM subjects and practices. Since this chapter proclaims a specific form of teacher training for high-quality iSTEM education, the link between teacher training and student performance must be understood first. Therefore, this section gathers evidence from the research literature to show how pre- and in-service teacher training ultimately leads to improved student knowledge and attitude. In this link between teacher training and student learning, several confounding and mediating factors (variables) play a role (Shernoff et al., 2017), as shown in Figure 4.2. The literature review in this section specifically focuses on student and teacher learning, training, and context with regard to the key principles of iSTEM education (see Chapter 2).

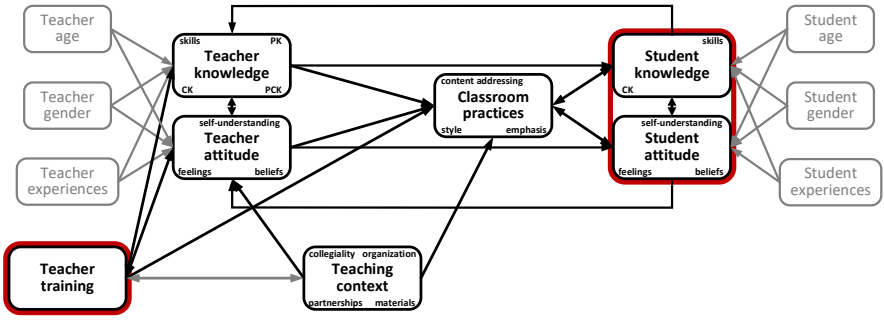


Figure 4.2: Teacher and student variables and influential variables identified by the research literature

Student and teacher learning is embodied in gains in their knowledge, and in improvement in their attitude, which is reflected in cognitive, behavioral, and affective growth (Axelson & Flick, 2010; Bransford et al., 1999; Shawer, 2017). Students' and teachers' *knowledge* is their ability to recognize, understand, apply, manipulate and reason about concepts and objects (Biggam, 2001). As 'knowledge' thus entails a theoretical, as well as a practical understanding of subject matter, it is comprised of both insights and skills (Oxford Dictionaries, 2018). Cognitive learning outcomes are categorized by Bloom's taxonomy (see Figure 3.22). Students' and teachers' *attitude* is their evaluation (perceptions,

feelings, beliefs) of subjects, which guides their thinking and actions (Perloff, 1993). Awareness and interest, perceived ability, value and commitment are important aspects of someone's attitude (Mahoney, 2010). Knowledge and attitude are subject to influences from outside, but they also mutually reinforce one another (Shernoff et al., 2017; Roehrig et al., 2007; Clark et al., 2014). For example, a student's interests play an important role in the type of information his/her brain selects and retains (Hidi, 1990).

Although students' and teachers' age, gender, and past experiences play an important role in their knowledge and attitude formation (Inhelder & Piaget, 1958; Sadler, Sonnert, Hazari, & Tai, 2012; Appleton & Kindt, 1999), also in iSTEM education (Thibaut, Knipprath, et al., 2018c; Al Salami, Makela, & de Miranda, 2017), these variables will not be considered here, since they are inherent to personality and therefore not manipulable.

4.2.1 Influence of classroom practices on student knowledge and attitude

Apart from the teachers' knowledge (Hill, Rowan, & Ball, 2005; Cohen & Hill, 1998), what and how students learn is mainly determined by the practices that take place in the classroom. Classroom practices are the integral set of activities students and teachers are engaged in at school, aimed at developing students' minds and habits. These practices entail the enacted instructional strategies (e.g., lectures or scaffolded student activation, cooperative learning, summative or formative evaluation), the way in which learning content is addressed (e.g., through isolated or integrated courses, through inquiry- or design-based learning), and the expected outcomes (e.g., lower- or higher-order thinking, cognitive or practical skills) (Loughland & Vlies, 2016; AITSL, 2017). When it comes to educational reform, such as transforming STEM into iSTEM education, the fidelity with which the new curricular materials and pedagogies are implemented, manifests itself in the practices that take place in the classroom (Pintó, 2005; Blumenfeld, Krajcik, Marx, & Soloway, 1994). As illustrated by Figure 4.3, this section reports on research that has investigated the effect of different components of iSTEM classroom practices on student knowledge and attitude.

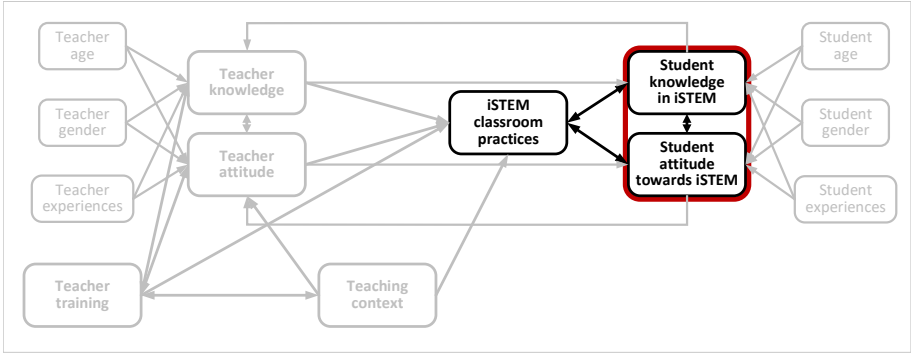


Figure 4.3: The influence of classroom practices on student knowledge and attitude investigated in Section 4.2.1

Evidence of the effect of integrated classroom practices on student knowledge and attitude

Kutch (2011) studied 47 students of grade 7 and 23 students of grade 8 who had taken an integrated math/science pre-engineering course in which learned math and science concepts were applied in an engineering design. She compared these students' scores on pre- and posttests and -surveys with those of two control groups ($N = 60$ and 85, respectively). Apart from the integrated course, the experimental group got the same Science and Math classes as the control group. The extra time spent on math and science content and application in the experimental group was not controlled for. No significant differences were found between the experimental and control groups on the tests on math and science concepts (Kutch, 2011). The seventh-graders showed no or even less interest in science or math careers after having followed the integrated course than their peers in the control group. The experimental group's perception of relevance of science, self-efficacy in science, and interest in engineering careers had however improved. The eighth-graders enrolled in the integrated course demonstrated significantly more interest in STEM careers, and perceived math as more relevant with respect to their presurvey scores and with respect to their peers in the control group (Kutch, 2011). In a longitudinal study, Gottfried and Bozick (2016) examined the effect of students' applied STEM-course taking in secondary school (grade 10) on their chosen STEM major in college ($N > 15000$). The applied STEM courses in secondary education were 'Science Research and Engineering' (SRE) and 'Information Technology' (IT), two courses with the aim to reinforce math and science learning content, foster the interest in STEM disciplines among the enrolled

students, and develop STEM skills relevant to STEM college courses. Gottfried and Bozick found a consistent, significant, positive relationship between SRE- and/or IT-course taking in secondary education and enrollment in a STEM major in college. Moreover, most of the students who had taken the SRE and/or IT course had preferred an Engineering or Technology major over a Science, Math or non-STEM major (Gottfried & Bozick, 2016). These findings suggest that applied, integrative STEM courses enhance students' interest in STEM disciplines. Ross and Hogaboam-Gray (1998) investigated the effect on student achievement of a math, science, and technology integrated project-based classroom approach in grade 9. This approach regularly involved student teamwork, application and combination of learning outcomes shared by the three STEM disciplines, and a complete alignment of the discipline-specific learning topics (geometry, forces, technical drawing, and joints), collaboratively planned by the teachers. With respect to the students who were taught these learning topics in isolated courses ($N = 21$), the students enrolled in the integrated approach ($N = 18$) exhibited an improved achievement in terms of modeling skills and application of shared STEM learning outcomes in post-instruction interviews (ES = .92). No differences were noticed on the separate, discipline-specific learning outcomes, except for the female students, who had improved on science. Ross and Hogaboam-Gray furthermore found that the ninth-graders enrolled in the iSTEM classroom practices adopted more powerful learning strategies and were more intrinsically devoted to learning than students taught through isolated Math, Science and Technology courses. Moreover, observations of students' post-instruction interactions revealed that, with respect to the pre-instruction interactions, the students who had been exposed to iSTEM practices were more involved in on-task discussions than their peers in the comparison group (Ross & Hogaboam-Gray, 1998). Satchwell and Loepp (2002) assessed the implementation of 20 iSTEM learning units designed by a team of nine competent middle-school STEM teachers (three math, three science, and three technology teachers). The learning units contained (1) themes shared by the national Math and Science standards, (2) an invigorating challenge, (3) exploration, study, and application of new concepts, and (4) authentic assessment. The students who had been engaged with these iSTEM units outperformed students in the traditional STEM curriculum on understanding, theorizing, and analyzing science processes, and on math procedures and problem solving ($N = 293$ - 246) (Satchwell & Loepp, 2002). Kiray and Kaptan (2012) implemented a science-centered, math-assisted program about biological inheritance, and statistical probability. They compared the performances of 60 eighth-graders enrolled in this program with those of a control group of 30 students, by means of a pre- and posttest on biology concepts and on biology/math integrated concepts. Where implemented properly, the program was found to positively affect student performance on integrated questions (Kiray & Kaptan, 2012).

A meta-analysis performed by Becker and Park (2011) compared student achievement on science, technology, math, and integrated concepts as a result of several types of STEM integration. As can be seen in Table 4.1, the effect sizes of the examined studies depend on the students' educational level and on the implemented type of integration. The analysis overall revealed small and even negative effect sizes on students' math performance, while medium to high effect sizes were found for science and integrated concepts (Becker & Park, 2011).

Table 4.1: Average effect sizes of S, T, E and/or M integration on student performance on science (S), technology (T), and math (M) problems, weighted over the studies examined by Becker and Park (2011)

Educational level	**student achievement on**				#
Type of integration	**S**	**T**	**M**	**iSTEM**	studies
Grades 7-8					
SM	-	-	.18	-	3
EM	-	-	.03	-	1
STE	.84	-	-	-	2
STM, STEM	.34	-.51	.23	1.76	3
Grades 9-12					
SM	.48	-	.21	-	5
SE, ST, STE	.93	3.17	-	-	4
STM	.57	-.03	-.11	-	3

Thibaut, Knipprath, et al. (2018a) investigated the pre- to posttest performances of 310 students of grade 10 on physics, math, and integrated physics/math problems. With the same sample of students, Thibaut, Knipprath, et al. also administered a questionnaire on the classroom implementation of the key principles behind iSTEM education (see Chapter 2), and performed multilevel regression analyses on the combined results. The correlations of the student-reported classroom practices and the students' performance on physics, math and physics/math integrated problems are shown in Table 4.2. Overall classroom implementation of iSTEM education was found to be significantly correlated with students' learning outcomes on math and physics/math integration.

Table 4.2: Correlation between student-reported presence of iSTEM classroom practices and student performance on physics, math, and integrated physics/math problems (Thibaut, Knipprath, et al., 2018a)

Classroom practice	**Phys problems**		**Math problems**		**Phys/Math problems**	
	β	SD	β	SD	β	SD
STEM-content integration	**.503***	.226	.319	.220	**.440***	.213
Problem-centered teaching	.333	.273	**.484***	.176	**.457***	.192
Inquiry-based teaching	-.240	.352	.271	.226	.360	.241
Design-based teaching	.067	.300	.310	.194	**.393***	.178
Student cooperation	-.151	.330	**.547***	.173	**.767***	.170
Overall iSTEM education	.152	.282	**.458***	.169	**.502***	.168

**Significant correlation*

Evidence of the effect of problem-centered classroom practices on student knowledge and attitude

By analyzing a national student assessment on knowledge and student, and teacher questionnaires on classroom practices, Wenglinsky (2002) demonstrated that classroom practices in math are at least as influential to student learning as students' background; emphasis on solving unique problems (rather than routine problems) and on hands-on learning improved eighth-grade students' performance in math ($N > 7000$, with a total ES = .56). Unlike prevalent findings from qualitative studies, however, Wenglinsky found that primary focus on authentic assessment (i.e. portfolio and project assessment) was negatively correlated with students' math achievement. Sungur et al. (2010) investigated the effect of problem-based classroom practices on the achievement of grade-10 students. Pre- and posttest scores and student essays of an experimental group of 30 students were compared with those of a control group of 31 students. Both groups were taught the same learning content (on the human excretory system) for 4 weeks by the same Biology teacher, but the experimental group was engaged in a problem-based approach. Both groups scored equally on the pretest. Sungur et al. found that students in the experimental group were more proficient in the construction, use, and organization of knowledge, showed a better acquisition of scientific concepts, and scored better on items requiring higher-order thinking. No difference was found on items requiring simple recall of facts (Sungur et al., 2010). In another study, the same setup, but with attitudinal pre- and post-instruction questionnaires, was used to investigate the effect of a problem-based approach on students' self-regulated

learning (Sungur & Tekkaya, 2006). Problem-based classroom practices had positively affected students' motivation for learning: the experimental group wanted to be challenged, showed a higher interest, perceived relevance and importance of biology. This group also showed better results with respect to the control group on the use of learning strategies involving critical thinking, application of new knowledge, metacognitive thinking, and learning with peers. The experimental group did however not outperform the control group on goal-orientation, self-efficacy, and anxiety towards learning and test-taking in Biology (Sungur & Tekkaya, 2006). A study with a very similar setup was conducted by Fatade, Mogari, and Arigbabu (2013). However, the studied unit was a 3-month Mathematics course, and the teachers in the experimental group received training in the problem-based approach. Classroom observations were made to ascertain the implementation of the problem-based or traditional approach. The findings from Fatade et al. corroborate those of Sungur et al. (2010): the experimental group scored significantly higher than the control group on critical thinking (N = 42 - 54). Ferreira and Trudel (2012) investigated a problem-based teaching approach to Chemistry among 48 students. When comparing the students' pre- and post-implementation surveys and observations of problem-solving, Ferreira and Trudel found that the approach successfully improved the students' attitude towards science, their problem-solving strategies (with the exception of retrieving and integrating known facts), and their sense of community.

Evidence of the effect of inquiry- and design-based classroom practices on student knowledge and attitude

McNeill and Krajcik (2008) observed Science teachers' practices, and they gauged the effect on seventh-grade students' construction of scientific explanations through an identical pre- and posttest ($N > 1000$). They found that students whose teachers had not explicitly addressed the rationale behind scientific explanations as part of their classroom practice, struggled with reasoning and understanding the logic behind scientific inquiry. Gerber et al. (2001) studied the reasoning abilities of 500 students from grades 7 to 10, and categorized their teachers as 'inquiry-oriented' or 'non-inquiry-oriented' based on teacher interviews. The students in inquiry-based classrooms outperformed the students taught by non-inquiry-oriented teachers in a test on reasoning abilities (Gerber et al., 2001). Inquiry-based classroom approaches have also proven to result in higher student motivation and self-confidence towards science. This was the case in a grade 9 biology unit on genetics (Madden et al., 2011) in which the lab sessions were authenticated by an assessment and planning tool for scientific inquiry (Grady, 2010). Tuan, Chin, Tsai, and Cheng (2005) investigated the attitude of eighth-grade students (N = 254) who explored topics such as light,

heat, temperature, force, and mixtures during 10 weeks (40 hours) by means of inquiry, including web search, discussion, exploration and experimentation. These students were compared with students who were subject to traditional science teaching ($N = 232$). Tuan et al. found significant increases in the experimental group's self-efficacy, self-reported autonomy, and appreciation of problem solving and scientific thinking. Furthermore, students who were performance-oriented at the start, appeared to be driven by a more learning-oriented motivation after inquiry-based instruction (Tuan et al., 2005).

The large-scale study of Mehalik et al. (2008) showed evidence of higher student conceptual knowledge through a system-design approach to addressing learning content, in which students of grade 8 could investigate their own ideas and questions through the design of an alarm system. The pre- and posttest to measure gain in knowledge of electricity concepts, revealed that the system-design students outperformed students who were exposed to a scripted-inquiry approach, in which step-by-step instructions were provided ($N = 587$ - 466, ES = .89). Also Fortus et al. (2004) and Wendell and Rogers (2013) found evidence of student gains in scientific knowledge and application in problem solving as a result of the implementation of design-based science units. In the study of Wendell and Rogers (2013), third- and fourth-grade (elementary) students were introduced to scientific ideas through four engineering units, each requiring around 10 science lessons and including artifact construction, student collaboration, and design discussion and revision. With respect to a comparison group, the experimental group significantly improved from pre- to posttest on the scientific, analytical learning objectives of two units (ES = .83 and 1.12 respectively, controlled for pretest scores) (Wendell & Rogers, 2013). In the study of Fortus et al. (2004), 92 students of grade 9 took part in three learning units containing a cyclic process of context identification, background inquiry, idea development, artifact construction, and exchange of feedback. The learning units had a time span of 3, 6, or 8 weeks. The effect sizes of posttest versus pretest on student understanding of the addressed science content were 1.9, 2.7, and 2.1, respectively (no control group was administered). Apedoe et al. (2008) introduced the concepts of chemical interactions and energy through an 8-week learning unit in which students had to combine inquiry and design. Besides low scores on the pre- and postunit assessments conducted among students of grades 9 to 12 ($N = 271$), Apedoe et al. still found an increased understanding of fundamental scientific concepts (ES = .31). This design-based chemistry unit even improved students' interest in and aspiration of engineering careers ($N = 79$, ES = .49 when compared to a control group of $N = 58$).

Evidence of the effect of cooperative classroom practices on student knowledge and attitude

Through a pre- and posttest on students' physics knowledge, and a student attitude questionnaire, Hänze and Berger (2007) compared performance and self-concept among 137 students of grade 12 who either engaged in cooperative learning through the jigsaw method (Aronson et al., 1978) or were subject to traditional direct instruction of learning units on electromagnetism. Students in the jigsaw method did not outperform students in the traditional teaching on physics knowledge. When controlled for performance, the jigsaw method however strongly favored students' self-efficacy, feeling of social relatedness to peers, and interest in physics subjects (Hänze & Berger, 2007). Kistner et al. (2010) investigated 538 ninth-graders' math performance before, during, and after a 5-week instruction of the Pythagorian theorem, in relation to classroom observations on student self-regulation. Students' mathematical knowledge and skills were improved by the explicit instruction of organization strategies, and by a constructivist learning environment. Other kinds of strategies, such as systematic planning, self-monitoring, resource management, and student cooperation were not found to affect student performance, possibly because they were rarely observed in the classrooms (Kistner et al., 2010). Explicit instruction of self-regulatory strategies appeared to be effective for student learning, as opposed to implicit instruction of these strategies (Kistner et al., 2010). Urdan and Schoenfelder (2006) performed a meta-analysis and saw that students exhibited a higher motivation for learning when they engaged in student-tailored tasks and student cooperation with peers, while being scaffolded by their teachers with constructive criticism that allowed for mistakes. The study of Humphreys, Johnson, and Johnson (1982) showed more positive attitudes towards cooperative learning compared to attitudes towards competitive and individual learning among students of grade 9 in Physics class ($N = 44$).

Evidence of the effect of practices promoting conceptual learning on student knowledge and attitude

Uzuntiryaki and Geban (2005) implemented instruction on chemical solutions via conceptual change texts and discussions in combination with concept mapping among 32 students of grade 8 during 4 weeks (4 class periods per week). They compared the students' pre- and post-implementation attitudes towards science and their pre- and post-implementation performances on concept tests with those of 32 students who received traditional instruction. The students in the experimental group demonstrated a more positive attitude towards science, and a significantly better acquisition of the scientific concepts and

elimination of (wrong) alternative conceptions (Uzuntiryaki & Geban, 2005). Eryilmaz (2002) found that students who had been engaged in physics classes involving conceptual change discussions and conceptual conflict (as explained in the step 'AAS' of Chapter 3) outperformed students who had merely been subjected to conventional lecturing during 8 weeks: the post- versus pre-intervention scores of the experimental group (N = 207) were higher than those of the control group (N = 189) on a force concept test and on a force misconceptions test (ΔES = .12 and .33, respectively, between the two groups). Instruction via assignments requiring qualitative reasoning had a smaller effect on students' pre-to-post performance on the force misconceptions test than instruction via standard, quantitative assignments (ΔES = -.20 between the two instruction methods, N = 203 - 193), possibly because the former type of assignments did not prevent students from reasoning with their extant misconceptions. A combination of the conceptual change discussions and the qualitative reasoning exercises however positively affected students' pre-to-post-intervention performance on the misconceptions test (ΔES = .31 with respect to the students subjected to mere conventional lecturing, N = 113 - 99) (Eryilmaz, 2002).

4.2.2 Influence of teaching context on classroom practices and on teacher knowledge and attitude

Teaching context is the social, instrumental, and organizational framework that determines the conditions under which the learning process of students and teachers takes place (Cohen, McCabe, Michelli, & Pickeral, 2009). As indicated by Figure 4.4, its effect is reported in this section.

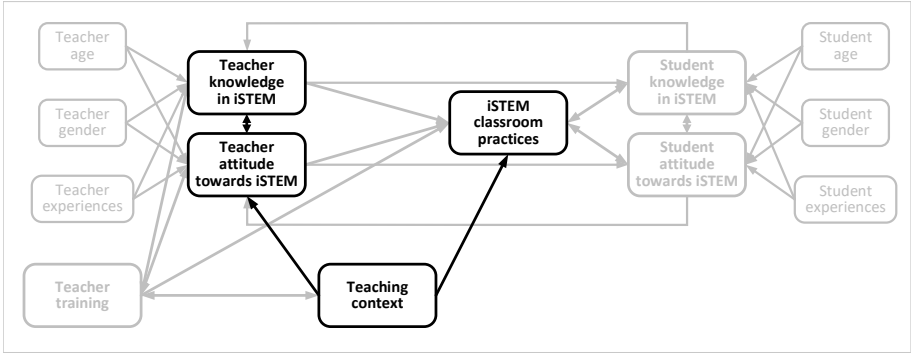


Figure 4.4: The influence of teaching context on classroom practices and on teacher knowledge and attitude investigated in Section 4.2.2

Evidence of the effect of teaching context on iSTEM classroom practices

Based on a literature review, Henderson et al. (2011) argue that policy (structures, reward systems) and vision are important change agents in facilitating STEM classroom practices. Peters-Burton et al. (2014) found literature suggesting that a well-constructed mission and curriculum, and partnerships with industry could provide an inclusive, effective STEM learning environment for students in secondary education. Individual and focus-group teacher interviews in secondary education revealed the necessity of collaborative support and adapted timetabling to effectively establish a year-long math/physics integrated approach (Ríordáin, Johnston, & Walshe, 2016). Through quantitative analysis of a questionnaire administered to 244 secondary school teachers, Thibaut, Knipprath, et al. (2018b) found conclusive evidence that opportunities for teachers to collaborate with peers, and appreciative support from the school management are positively related to classroom realization of STEM integration and problem-centered learning. Weekly subsequent class periods especially dedicated to iSTEM, and facilitation of co-teaching seemed to stimulate cooperative student learning in the classroom (Thibaut, Knipprath, et al., 2018b). Hewson, Tabachnick, Zeichner, and Lemberger (1999) argue that breadth of curriculum contents, non-constructivist behavior of colleagues, and too little time to reflect prevent teachers' classroom practices from fostering conceptual change among students.

Teaching context impacts classroom practices indirectly as a confounding variable through its influence on teacher knowledge and attitude (Flores & Day, 2006) as it can provide or hamper opportunities for teacher learning (DeChenne, Koziol, Needham, & Enochs, 2015). Roehrig et al. (2007) interviewed 27 teachers who had implemented a reformed, inquiry-based Chemistry curriculum embedded in a real-world context in grade 10. A supportive network at the school site was found to be of major influence on teachers' curriculum decisions and implementation: schools with an external driver for reform, or lacking a supervisor and/or facilitation in terms of scheduling, did not provide teachers with the attitude necessary to change their classroom practices (Roehrig et al., 2007). Such a collaborative network should be initiated and maintained by the school management, should be informed by data on student performances, allow for risk taking, and, above all, focus on teacher and student learning (Thompson, Gregg, & Niska, 2004). These were the reflections of the interviewed principles of six middle schools, which were confirmed by their teachers in individual and focus-group interviews in Thompson et al.'s study. Ingvarson, Meiers, and Beavis (2005) also stress the importance of educational policy and administration that act upon teacher learning and evidence of student performance.

Evidence of the effect of teaching context on teacher knowledge and attitude

A teaching context fostering teacher collaboration, with the aim of learning together and increasing student learning, can positively impact teachers' pedagogical content knowledge and practice, and students' performance (Bakkenes, Vermunt, & Wubbels, 2010; Voogt et al., 2011). From their meta-analysis, Fulton and Britton (2011) extracted several features necessary for an effective collaboration of STEM teachers: school support, time, shared values and goals, a collective responsibility, peer classroom observation, self-directed reflection, authentic student assessment, and coaching. A comparative, observational case study of five secondary-school teacher teams and additional teacher surveys demonstrated that teacher collaboration in which alternative instructional practices are discussed and tried out, positively contribute to a change in teachers' beliefs towards more student-activating approaches (Meirink et al., 2010). In their meta-analysis, Vangrieken et al. (2015) argue that "when teachers collaborate, the educational performances of students progress . . . [but] teachers appear to profit [the] most" (p. 35). Vangrieken et al. caution, however, that there is a difference between mere conversations about practicalities on the one hand, and deeper discussions on classroom practices and their effect on student learning on the other hand.

Next to the opportunity to collaborate, other context factors affect teachers' knowledge and attitude. Results from the international TALIS study, which surveyed 3000 teachers in 34 countries, demonstrated that having a say in the decision-making process at the school level is associated with higher job satisfaction and higher self-efficacy among middle-school teachers (OECD, 2014). When teachers get appraisal and feedback that aims at improving classroom practice (instead of marketing strategies e.g.), their job satisfaction is increased. The relationship between teachers and their school management, colleagues and students all affect their job satisfaction and self-efficacy, even stronger than possibly difficult classroom circumstances (OECD, 2014). The study of Thibaut, Knipprath, et al. (2018b) showed that in secondary education, teachers' attitude towards the implementation of inquiry- and design-based learning is influenced by management support. Unsurprisingly, teachers' attitude towards design-based learning is also affected by technical aspects of the teaching context, such as availability of room and equipment (Thibaut, Knipprath, et al., 2018b).

4.2.3 Influence of teacher knowledge and attitude on classroom practices

Teacher learning is expressed in gains in teachers' knowledge and attitude. Gains in teachers' knowledge occurs through positive changes in teachers' pedagogical knowledge (PK), content knowledge (CK), pedagogical content knowledge (PCK) and practical skills (Fishman et al., 2003). Whereas PK and CK entail knowledge of general instructional strategies and subject-matter knowledge respectively, PCK encompasses the knowledge of student difficulties and instructional strategies inherent to specific learning content (Schmidt et al., 2009; Darling-Hammond, 1998). Additionally, teachers should have some practical skills, for example in using technology to enhance the learning environment (Schmidt et al., 2009). Besides through gains in knowledge, teacher learning also occurs through positive changes in their attitude. Teachers' awareness of the impact of their beliefs on the decisions they make in the classroom, is one of the many facets of teacher attitude that affect classroom practices and are prone to teacher learning (Stuart & Thurlow, 2000). Successful implementation of an educational reform requires participating teachers to adjust their educational beliefs and to support the underlying ideas of the new pedagogies involved in order for them to change their classroom practices (Meirink et al., 2010; Roehrig et al., 2007). As illustrated by Figure 4.5, this section reports on research that has investigated the effect of teacher knowledge and attitude on different components of iSTEM classroom practices.

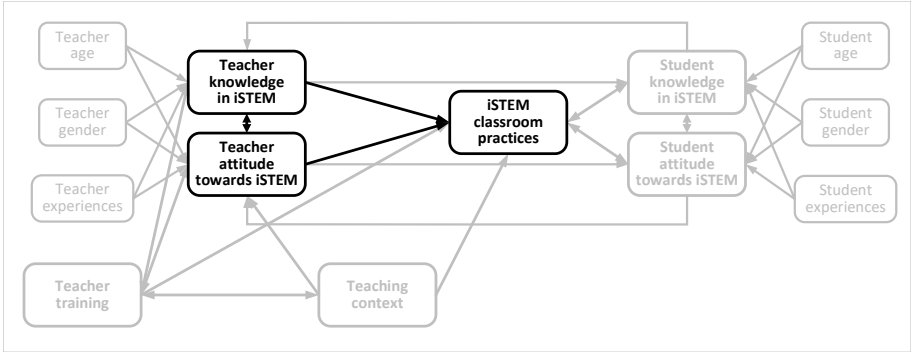


Figure 4.5: The influence of teacher knowledge and attitude on classroom practices investigated in Section 4.2.3

Evidence of the effect of teacher knowledge and attitude on integrated classroom practices

Savasci-Acikalin (2009) noticed that research on the influence of teacher learning on classroom practices has mainly been conducted with pre-service teachers, and that data sets mostly include teachers' self-reported experiences instead of classroom observations made by unbiased researchers. Teacher testimonies on their own learning experiences in educational reform should always be considered with caution. Although teachers often acknowledge the rationale behind the reform, a discrepancy between their beliefs and their actual classroom enactment sometimes still remains (Pintó, 2005; Singer, Lotter, Feller, & Gates, 2011), and teacher learning turns out to be ineffective. In a case study of nine middle-school Science teachers, Dare et al. (2018) did, however, use classroom implementation data and put these next to in-service teachers' reflective interviews. Dare et al. concluded that teachers' ability (PCK) of making meaningful connections between Science, Technology, Engineering, and Mathematics as well as their perception of meaningfulness of such connections determine the degree of S, T, E and M integration in the classroom. Hinde (2005) argues that students' achievement on integrated goals hinges on such teacher PCK. Based on classroom observations and reflective journals and interviews of teachers, Ríordáin et al. (2016) found that STEM integration strongly depends on teachers' knowledge of less-familiar subjects, on their technical skills, and on their ability and willingness to take risks.

Evidence of the effect of teacher knowledge and attitude on inquiry- and design-based classroom practices

Teachers' content preparation (CK and PCK) has proven to be more influential on teachers' implementation of inquiry-based classroom practices than any other teacher- or context-level variable (Supovitz & Turner, 2000; Peters-Burton et al., 2014). Also Ingvarson et al. (2005) found that teachers' self-reported knowledge (CK and PCK) correlated more with the self-reported effectiveness of their classroom practices ($N = 3250$, $\beta_{average} = .50$) than the other variables that were found to be influential, which were active learning in in-service teacher training, and a supportive teaching context ($\beta_{average} = .13$ and $.17$, respectively). Thibaut, Knipprath, et al. (2018b) examined the effect of three facets of teacher attitude towards iSTEM education: perceived relevance, self-efficacy, and anxiety ($N = 244$). Thibaut, Knipprath, et al. found that these facets strongly correlate with teachers' self-reported enactment of inquiry- and design-based learning and cooperative learning.

Evidence of the effect of teacher knowledge and attitude on student-activating classroom practices

In elementary and secondary education, teachers' self-efficacy was found to be positively related to their classroom practices: when teachers get a sense of accomplishment, job satisfaction, and commitment, this is reflected in more student-activating classroom practices (Zee & Koomen, 2016). Hashweh (1996) distributed questionnaires among science teachers in which (a) they were asked to write down their teaching approach as an answer to a fictious scenario in which a student displays a misconception in general science, biology, chemistry, or physics (according to the teachers' expertise), and (b) they were asked to indicate how frequently they implemented certain strategies (promoting students' conceptual change, as indicated in the step 'AAS' of Chapter 3) in their classrooms. Hashweh collected the answers of 35 teachers from different grade levels (6-12) with different science backgrounds. He demonstrated that teachers who hold constructivist beliefs towards teaching science, have a richer repertoire of instructional strategies and can more effectively induce conceptual change within students than teachers who believe that knowledge is static and should be imparted externally (Hashweh, 1996). Hewson et al. (1999) followed six elementary and secondary pre-service Biology teachers and found that their' lack of deep CK and their non-constructivist beliefs prevented their classroom practices from establishing the intended conceptual change.

4.2.4 Influence of teacher training on classroom practices and on teacher knowledge and attitude

Teacher training comprises the actions, strategies, and context designed to equip teachers with the knowledge, attitude and behavior they require to exhibit effective classroom practices. Pre-service teacher training is the form of higher education that trains prospective teachers. In-service teacher training, or continuing professional development (PD), is the kind of formation provided for practicing teachers. Teacher training can have different purposes, but often aims at advancing current or prospective teachers' CK, PK, PCK, self-efficacy, beliefs, or practical skills in or towards student learning, disciplinary learning, or specific classroom practices or approaches (Appleton & Kindt, 1999; van Aalderen-Smeets & Walma van der Molen, 2015; Parke & Coble, 1997). Changes in teachers' behavior (i.e., their classroom practices) and in their knowledge and attitude are important measures of teacher learning (Bakkenes et al., 2010). As illustrated by Figure 4.6, this section reports on research that has investigated the effect of teacher training on different components of iSTEM classroom practices and on teacher knowledge and attitude towards (teaching) iSTEM.

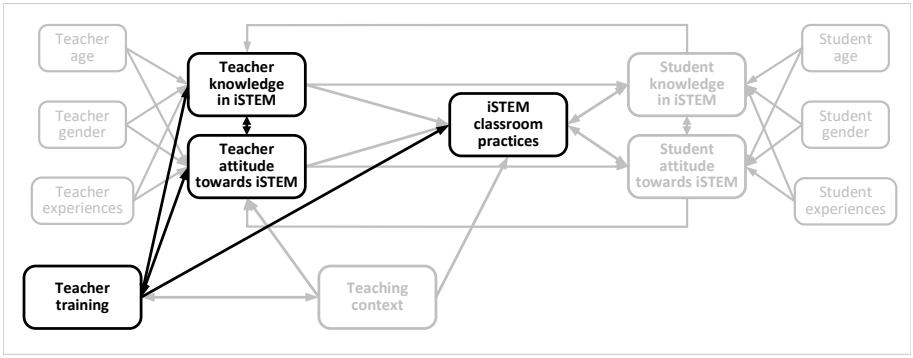


Figure 4.6: The influence of teacher training on classroom practices and on teacher knowledge and attitude investigated in Section 4.2.4

Evidence of the effect of teacher training on iSTEM classroom practices

Classroom practices are very much affected by the length and intensity of a PD program (Supovitz & Turner, 2000). In the context of educational reform, Toolin (2004) related a responsive teacher attitude to observed classroom practices, and asserted that teachers who had had no proper teacher training, fell back on a traditional way of teaching science, like the way they themselves had been taught in their own years of secondary education. Singer et al. (2011) developed a PD program, in the form of a 3-weeks lasting summer institute on inquiry-based teaching, which involved teachers in a science content lecture, controlled experimentation of the newly introduced strategies, and a critical analysis of videotaped enactments. Preselected curricular materials were used throughout the PD program. Singer et al. saw how the 13 middle-school teachers who had been enrolled in this program, successfully employed the new inquiry-based teaching strategies in their classrooms. Parke and Coble (1997) established a research-based, collaborative learning environment in which teachers engage in the research literature on science teaching and learning, and in curriculum and assessment design. Through questionnaires and state-exam results, a total of 19 middle-school teachers and 205 students in an experimental group were compared to 11 teachers and 120 students in a control group in order to investigate the effect of this PD program. Because of their participation in this PD program, the teachers in the experimental group had covered less science topics in their classes (but more in-depth) than the teachers in the control group. Hence, the students of the experimental group did not outperform students of the control group on the outdated, fact-based state exam (Parke & Coble, 1997). However, the students in the experimental group reported more frequent

implementation of in-class experiments and cooperative learning. They also demonstrated a higher interest and motivation for Science class, implying a link between teacher training and student learning through curriculum design (Parke & Coble, 1997). Mooney Simmie (2007) advocates for in-service training that challenges teachers and informs them of research findings. Windschitl (2003) observed six pre-service secondary-school teachers who engaged in authentic science research as a form of teacher training. He saw how this engagement in research, more than their promising beliefs or reflections, committed the pre-service teachers to employ open and guided inquiry in the classroom.

Evidence of the effect of teacher training on teacher knowledge and attitude

Ingvarson et al. (2005) conducted surveys with 3250 elementary- and secondary-school teachers who participated in over 80 PD programs (in total). During these PD programs, collaborative examination of student work, and feedback on classroom practices were rarely experienced by the surveyed teachers. However, Ingvarson et al. found that a focus on content, active reflection, and follow-up support positively influenced teachers' self-reported knowledge ($\beta_{average}$ = .28, .16, and .14, respectively). Intensity and duration of the PD programs deemed influential as well (Ingvarson et al., 2005). Ingvarson et al. argue that, as teacher knowledge strongly impacts the classroom practices, these features of PD indirectly determine what happens in the classroom. Content focus and active learning in PD had also positively contributed to the self-efficacy of the surveyed teachers ($\beta_{average}$ = .10 and .14, respectively) (Ingvarson et al., 2005). Based on a survey of more than 1000 elementary- and secondary-school Math and Science teachers, Garet, Porter, Desimone, Birman, and Yoon (2001) also indicated the impact on teachers' self-reported knowledge of three facets of effective PD programs: content focus (β = .33), active learning (β = .14), and coherence between PD goals on the one hand, and teachers' prior knowledge, ongoing learning opportunities, and teaching-context constraints (such as national curricula) on the other hand (β = .42). Garet et al. found that time span, and contact hours of a PD program indirectly impacted teachers' self-reported knowledge through their influence on active learning (β = .30, and .31, respectively), and on coherence (β = .26, and .16 respectively). Ingvarson et al. (2005) furthermore argue that modeling good practices and inviting teachers to try them out in their classroom is more effective than primarily trying to change their attitude.

Thibaut, Knipprath, et al. (2018c) collected the answers of 263 iSTEM teachers and reported a positive correlation between teachers' recent participation in STEM-related PD and their attitude towards all iSTEM key principles. This correlation does however not indicate a causal relationship; it is possible that

teachers who have a positive attitude towards teaching iSTEM are more likely to participate in related PD (Thibaut, Knipprath, et al., 2018c). Selçuk (2010) implemented a problem-based Physics course (on electricity and magnetism) in the pre-service training of 13 student teachers, and compared their results with those of 12 student teachers in a traditional Physics course in terms of achievement in physics, and attitude towards physics and learning in general. Therefore, she administered pre- and post-course tests on knowledge of magnetism, and questionnaires on attitude. Whereas she found no differences among the pre-course scores for these measures between the experimental group and the control group, she found significant differences between the two groups on the post-course scores. In comparison with the traditional approach, the problem-based approach had positively impacted the student teachers' knowledge of magnetism (ES = .71), their interest in physics (ES = .50), and their intrinsic motivation for learning (ES = .58) (Selçuk, 2010). Chai, Koh, Tsai, et al. (2010) examined the effect of an ICT course including meaningful problem- and inquiry-based learning, and meaningful use of ICT tools on the self-reported knowledge of 365 pre-service student teachers working towards a postgraduate diploma for secondary education. With respect to the pre-course survey, the teachers reported a higher technological knowledge, content knowledge, pedagogical knowledge and combined technological pedagogical and content knowledge (ES = .63, .65, .61, and .69 respectively) (Chai et al., 2010). Blumenfeld et al. (1994) implemented among five middle-school teachers and some university researchers a PD model which involved collaboration, enactment and reflection, from which both parties could benefit in the adoption of project-based instruction. They found that teachers' attitude changed from polite but not supportive to actively participating, steering, and acknowledging as a result of the PD model. However, practical worries among the teachers still predominated at the end of the first implementation year. During one school year, Toolin (2004) intensively followed six secondary-school Science teachers in their attempt to implement a project-based teaching approach to science. She found that teachers' willingness to enact this new approach depended on training features such as the teachers' educational degree, the amount of workshops they attended, and the opportunity to collaborate and co-teach with other STEM professionals. Hewson et al. (1999) introduced the six pre-service Biology teachers in their study to action research as part of a teacher-education program. This intervention led the student teachers to pay more attention to students' prior knowledge. It did, however, not cause a change in their beliefs about teaching, which suggests a rather small chance of long-term effects (Hewson et al., 1999). Simon and Schifter (1991) implemented a 2-year PD program with the aim to foster constructivist beliefs among 13 elementary and secondary in-service Math teachers. The program consisted of four stages: (1) a summer course, (2) follow-up of classroom implementation, (3) student-learning

analysis and lesson development, and (4) workshop coordination. The program emphasized active learning, a focus on the nature of math, and follow-up and feedback. The participants' beliefs were assessed via their logbook writings and interviews conducted after the second and fourth stage. The teachers showed deep reflections on their past and newly learned teaching approaches to promote student understanding and thinking, with which they showed that they had integrated the constructivist idea (Simon & Schifter, 1991).

Teacher knowledge and attitude can be improved by involving teachers in the design of curricular materials, for example by involving them in teacher design teams (TDTs). Through a literature review, Voogt et al. (2011) found that active involvement of teachers in collaborative curriculum design has a positive effect on their motivation and self-efficacy, and their ideas of good practice. Via focus-group interviews and reflective journals of regional team coordinators, Mooney Simmie (2007) investigated the engagement of 100 Biology teachers of grades 10 to 12 in TDTs. She reported an increase in professional dialogue and reflections among teachers on inquiry-based teaching and learning of biology, and development of their creativity. The impact on classroom practices was however not studied. By observing three experienced chemistry teachers, Coenders et al. (2010) found that, via design of chemistry learning units, the teachers had learned how to operationalize an abstract vision and translate it into concrete student learning goals. Participation in TDTs had given the teachers insights in effective instructional strategies to address learning content and new student assessment methods, indicating an increased PCK (Coenders et al., 2010). The same study found that participating teachers demonstrated a decreased feeling of anxiety, and held beliefs that were more in line with the rationale behind the design: they valued it more and earned a sense of ownership. In this way, the participating teachers were better prepared for classroom practice (Coenders et al., 2010). A later study of a TDT with a control group of teachers who did not participate in TDTs, showed that not only the teachers' PCK had improved, but also classroom implementation was facilitated by participation in collaborative curriculum design (Coenders & Terlouw, 2015). Through a questionnaire administered among 94 participating science teachers, and an in-depth case study of four teams (each consisting of around nine of these teachers), Binkhorst (2017) investigated the features of TDTs that are related to desired outcomes in terms of teacher qualities. The involved TDTs had different design goals. She found that participation in collaborative design does not automatically lead to a sense of ownership among the teachers, or to classroom implementation of the designed materials, and that much depends on the sort of coordination and support these teams receive. A combination of (a) shared leadership (leadership distributed among all team members) and (b) vertical leadership (top-down leadership by a team coordinator) appeared to favor teachers' development of a sense of ownership (Binkhorst, 2017). According

to Binkhorst, this is due to the blend of (a) the possibility to exchange ideas on an equal basis with team members, and (b) the structure and clarity about goals and progress provided by the team coordinator. Apart from coordinator support, Binkhorst revealed that also team interaction, goal alignment, and knowledge- and design-related activities within the TDTs positively interact with teachers' self-reported satisfaction, gain in knowledge, change in practice, and their perceived quality and actual use of the designed materials.

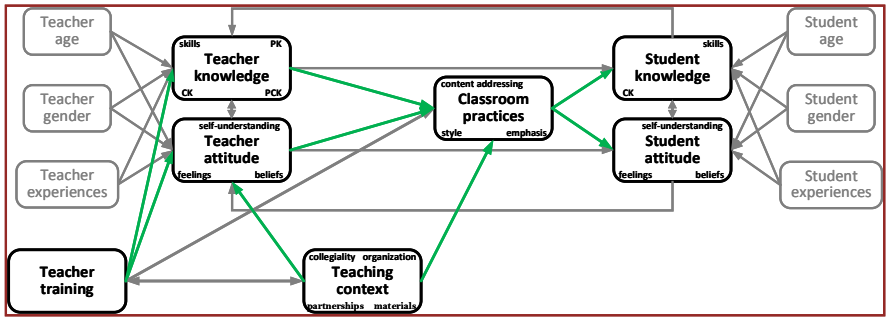
TDTs have also been implemented in the context of iSTEM education in particular. After analyzing iSTEM learning units designed by TDTs, Guzey, Moore, and Harwell (2016) stated: "[T]he strategy of teachers as curriculum designers provides teachers with rich opportunities for professional growth. . . . [W]e argue that engaging teachers in professional development of curriculum design is critical for improving integrated STEM education" (p. 14). James et al. (2000) investigated teachers' affective response to curricular reform involving integration of math and science with educational technology. The PD program administered by James et al. comprised summer courses in which the goals of the integration were examined and examples of integrated learning units and workshops on hardware and software were provided. During 2 years, the participating teacher teams designed integrated learning units, which were pilot-tested and revised with the support of classroom coaching and technical assistance. Multiple surveys revealed that teacher concerns varied with time: their strong initial concerns on the personal, informational, collaborative, and management scales diminished, and after 2 years, remaining concerns mostly revolved around finding alternatives to the PD program (James et al., 2000). The participating teachers had allegedly learned to develop a repertoire of strategies to improve students' problem-solving skills, and improved their own teamwork, technical expertise, and creativity, which they attributed to James et al.'s (2000) PD program. James et al. found that implementing TDTs had well demonstrated the importance of collaboration for instructional planning and teaching.

Conversely, teachers can bring their practical knowledge about student level and learning, curricular goals, and classroom opportunities and constraints, into a PD program that is developed with the specific purpose of designing learning units (McFadden & Roehrig, 2017; Van Driel, Beijaard, & Verloop, 2001).

4.2.5 Overview of influences on student learning in iSTEM education

The research literature provides evidence for the fact that implementation of each of the key principles of iSTEM education (see Section 2.3 of Chapter 2) indeed leads to the desired improvement in students' knowledge as well as in their attitude (see Section 2.2 of Chapter 2), such as a higher level of critical thinking, deeper conceptual understanding, and more interest in STEM subjects (e.g., Kutch, 2011; Gottfried & Bozick, 2016; Sungur & Tekkaya, 2006). For the key principles to be implemented in the classroom, differing aspects of teacher knowledge and attitude are required. For *practices involving integration of STEM learning contents*, *inquiry and design* and *emphasis on conceptual learning*, the most crucial teacher assets are thorough content knowledge (CK), pedagogical content knowledge (PCK), and (in case of design) also some practical skills (e.g., Dare et al., 2018), while for *practices involving student cooperation*, mostly specific attitudinal aspects, such as self-efficacy and job satisfaction seem to be favorable (e.g., Zee & Koomen, 2016). The literature indicates that teaching context and teacher training strongly influence the degree to which these teacher qualities and desired classroom practices are present. Availability of room and equipment, management support, having a voice in decision-making processes, and meaningful educational objectives favor teachers' (self-)efficacy (OECD, 2014; Thibaut, Knipprath, et al., 2018b). Facilitation of collaboration with peers and management support accommodate the integration of STEM contents, problem-centered practices and student cooperation (Thibaut, Knipprath, et al., 2018b), while time and a feasible amount of curriculum contents to cover promotes teaching for conceptual learning (Hewson et al., 1999). The teacher qualities needed for the implementation of the key principles behind iSTEM education all appear to benefit from collaborative curriculum design as part of pre- and in-service teacher training (e.g., Voogt et al., 2011; Coenders & Terlouw, 2015). Since (a) a focus on disciplinary (pedagogical) knowledge, (b) an active experience of the principles that should ultimately be enacted in the classroom, (c) coherence among the different goals at play, and (d) follow-up support all have an impact on teachers' (P)CK and self-efficacy, these teacher-training features positively affect practices involving inquiry and design, student cooperation and deep conceptual learning (e.g., Ingvarson et al., 2005; Garet et al., 2001). Also exploration of the educational research literature favors these practices (e.g., Parke & Coble, 1997). Although there is a large body of research on the conditions for the implementation of most of the key principles in secondary STEM education, relatively few studies were found that investigated the necessary aspects of teacher training, knowledge and attitude for *problem-centered practices* in this context. It is, however, plausible to assume that the aforementioned features,

supplemented by some authentic problem-solving experiences and structured reflection might provide a fruitful basis for teacher preparation towards problem-centered practices. The lines of reasoning that were corroborated by research findings are depicted in Figures 4.7 and 4.8.



>collaborative curriculum design	>perceived relevance of iSTEM links >PCK on iSTEM links	>opportunity to col-laborate with peers >management support	**>integration of STEM learning contents**	◻ perceived relevance of STEM subjects ◻ self-efficacy in STEM ◻ interest in STEM careers ◻ enrollment in higher-education STEM studies ◻ modeling skills ◻ motivation for learning ◻ ability to apply (i)STEM contents
		>opportunity to col-laborate with peers >management support	**>problem-centered practices**	◻ ability to apply STEM contents ◻ higher-order thinking ◻ motivation for learning ◻ attitude towards STEM ◻ ability to apply problem-solving strategies ◻ sense of community
>focus on inquiry- & design-based teaching >active engagement >content focus >collaborative curriculum design >educational research literature study >participation in scientific research	>CK in other disciplines >technical skills >risk-taking, creativity >perceived relevance of iSTEM	<availability of room & equipment <management support	**>inquiry- & design-based practices**	◻ self-efficacy in STEM ◻ higher-order thinking ◻ conceptual understanding of STEM contents ◻ interest in STEM careers ◻ motivation for learning in STEM

Figure 4.7: Features influencing iSTEM practices and student qualities (1)

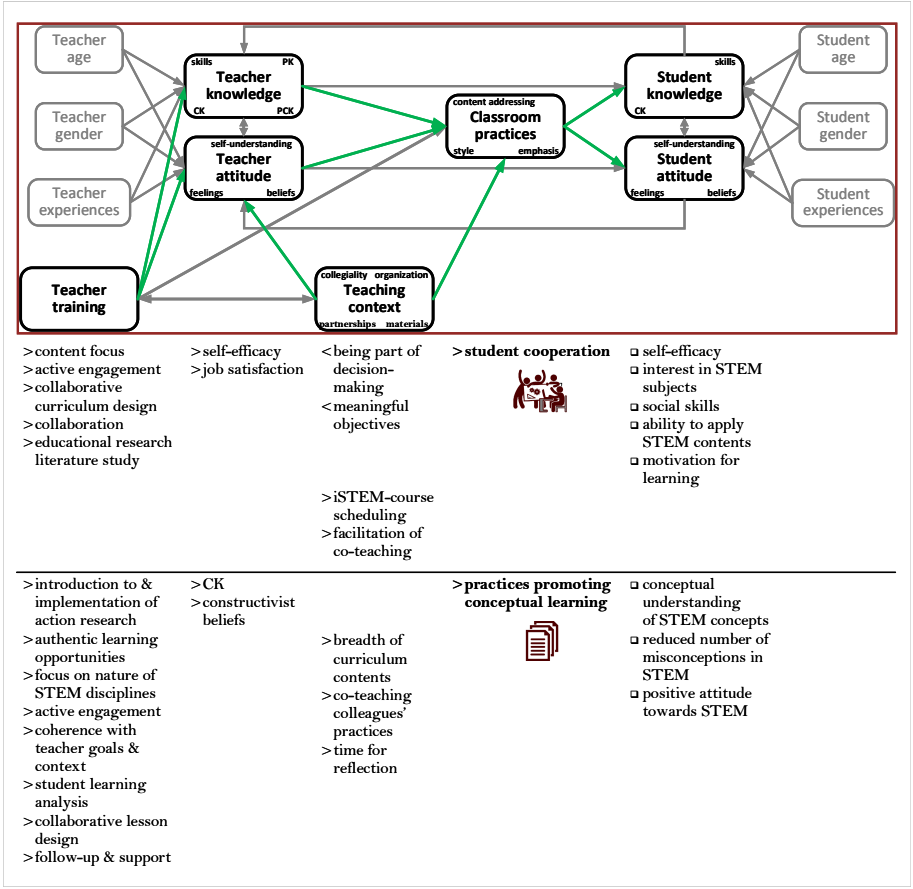


Figure 4.8: Features influencing iSTEM practices and student qualities (2)

Collaborative curriculum design, and by extension teachers' participation in iSTEM TDTs, will thus ultimately foster improved student knowledge and attitude towards STEM, as it holds promising conditions for the required teacher learning. With the aim of answering RQ1 (see Section 4.1), the underlying mechanisms and the effect of these conditions were further investigated in the study presented here.

To answer RQ2, also the required features of teacher knowledge, attitude, context, and training for succesful implementation of the key principles were examined more deeply. Some questions remain as to what constitutes effective collaborative curriculum design and ways to enhance teachers' PCK on STEM concepts and integration. Some literature suggests the inclusion of peer coaching,

micro- and co-teaching, authentic learning opportunities, and follow-up reflection into teacher training (Cochran, DeRuiter, & King, 1993): ideas that, together with the features found in the study presented here, can inspire the design of training programs (Section 4.6).

4.3 Research method

4.3.1 Setup: semi-structured interviews

To investigate the effect of participation in teacher teams designing iSTEM learning materials (iSTEM TDTs) on teacher attitude and practice, **semi-structured interviews** were chosen as data-collection method. Teacher narratives are "not only crucial for providing insight into what teachers think and do, they also help teachers to make sense of what they think and do" (Van Driel et al., 2001, p. 143). Individual interviews provide in-depth information, allow for clarification of ambiguous responses, and make interviewees elicit more information than what is possible through group interviews or questionnaires (Shernoff et al., 2017). Group interviews allow to observe interactions among the interviewees, and the dynamic generated by a group interview can converge into a shared understanding, which combines the thoughts and feelings of the separate participants (Crabtree, Yanoshik, Miller, & O'Connor, 1993; Lederman, 1990). In the case of the project STEM@school, an average iSTEM TDT had two or three members at its core: the teachers who actually implemented the designed learning materials in the classroom. Therefore, in this study, pairs or trios of teachers were contacted with the request for an interview. When a common time slot could not be found, the teachers were interviewed individually. In the data analysis, excerpts from individual interviews that significantly deviate from the lines of thought in the pair interviews must be intercepted. Conversely, pair interviews must be checked for socially desirable answers that might not be shared by the other team members.

In the interviews, teachers were asked how they felt their knowledge, attitude, and classroom practices in (i)STEM were affected by participating in the design and/or implementation of iSTEM learning materials. Furthermore, they were asked which prerequisites they saw necessary for successful design and/or implementation. Since no pre-design or pre-implementation interviews were taken, only teachers' post-implementation knowledge and attitude towards (i)STEM (teaching) were measured, by questioning their professional self-understanding (Kelchtermans, 2001) and their perception of (teaching) (i)STEM (Flores & Day, 2006). The interview questions are shown in the Appendix H.

A comparison was made (1) between teachers of TDTs and teachers who had merely implemented the materials without having participated in the design, and (2) between teachers of successful TDTs and teachers of less successful TDTs (see Section 4.3.2). These comparisons would allow to distinguish (1) the effects of participation in iSTEM TDTs, and (2) the differences in knowledge and attitude between successful and less successful TDTs.

The underlying assumption of this study was that teachers who had participated in iSTEM TDTs, would refer to the design phase as the context that provided them with opportunities to learn for the actual classroom implementation. Evidence of new or deeper insights from multidisciplinary collaboration, and an attitude or behavior more congruent with iSTEM principles would provide indications of the teacher-training potential of collaborative iSTEM design, if these signs would be more prevalent in interviews of successful iSTEM TDTs than in interviews of teacher teams who had merely implemented the materials.

4.3.2 Teacher-team selection

For the interviews, teams of STEM teachers were selected from STEM@school. These teams were observed during design or resonance meetings, in which they exchanged ideas, preparations, and classroom experiences on the design and/or implementation of the iSTEM learning units. Based on these observations and the rubric presented in Table 4.3, extreme cases were identified among the STEM@school teams (Seawright & Gerring, 2008); teacher teams that exhibited extraordinarily successful classroom practices (+) were distinguished from teams that exhibited particularly unsuccessful practices (−).

Table 4.3: Rubric for determination of extreme cases

Criterion	IMPL = +	IMPL = −
engagement of teachers of *different* STEM disciplines	delegation of at least one teacher with an S, T, or M background	rather monodisciplinary teams: only teachers with a T (or S) background
reflections indicating the incorporation of iSTEM key principles	explicit testimonies of inquiry-based design, interconnections among STEM disciplines, student-activating strategies in view of a central challenge	explicit testimonies of experiments or designs that are incoherent, not meaningful, or not mutually connected, rather teacher-centered approaches
on-schedule learning-unit implementation	on schedule: one learning unit per semester	lagging behind: learning units not finished by the end of the semesters

Of all the teams who had implemented the STEM@school learning units, a total of 20 teams were observed to be extreme cases (eight successful, 12 unsuccessful teams), nine of which had participated in iSTEM teacher design teams (TDTs) (three successful, six unsuccessful teams). The successful implementation of the teacher teams that were evaluated accordingly (IMPL = +), was confirmed by the cognitive and affective scores of these teams' students on a quantitative test within another study (De Loof, Boeve-de Pauw, et al., 2018).

From these extreme cases, teams were then sampled based on the main independent variable: participation in teacher design teams (TDT), and varied on the dependent variable: implementation (IMPL) of the iSTEM learning units. Sampling cases based on the dependent variable risks the occurrence of bias, because the selected sample of cases might not reflect the true distribution of the variable (IMPL) among teacher teams implementing iSTEM education (Kahan, 2013). For example, in a faulty setup, only a sample of successful implementation teams (IMPL = +) would be selected, and in the end, the (desired) conclusion might be drawn that participation in TDTs (TDT = 1) causes successful implementation (IMPL = +). This conclusion on the cause of this outcome would be invalid because cases are omitted in which the putative cause (TDT = 1) might have been present but did not generate successful implementation (i.e. cases of TDT = 1 but IMPL = −). Even though the dependent and independent variables in this study might be correlated, bias can be avoided by sampling cases based on the independent variable (TDT):

> If investigators have a special interest in cases that have high scores on the dependent variable, another solution may be to select cases that have extreme scores on an explanatory variable that they suspect is strongly correlated with the dependent variable. This should yield a set of cases that has higher scores on the dependent variable, and if this explanatory variable is then incorporated into the analysis, selection bias should not occur, although other risks of bias and error may arise. (Collier & Mahoney, 1996, p. 89)

When sampling on the independent variable (TDT), for both values of that variable (0 or 1), the dependent variable (IMPL) can still assume any value (+ or −), and the effect is not distorted (Collier & Mahoney, 1996). However, to avoid bias, the independent variable should be controlled for in the analysis (King, Keohane, & Verba, 1994). As suggested by King et al. (1994), the cases were thus selected based on the independent variable, while ensuring enough variation in the dependent variable.

Teacher teams who had participated in iSTEM design (TDT = 1) were distinguished from teams who had not participated in iSTEM design (TDT = 0) to identify the effect of participation in iSTEM TDTs. Next, proportional numbers of teams were chosen from the extreme cases. For enough variation on the dependent variable, two teams were sampled in the category 'IMPL = +',

and three teams in the category 'IMPL = −', proportionally to the division of teams among the extreme cases (eight successful, 12 unsuccessful). This variation must thus cancel out the possibly self-fulfilling prophecy that teacher teams who signed up for iSTEM TDTs are more likely to embody a better attitude towards iSTEM and better classroom practices in iSTEM than teams who did not sign up for it. This resulted in the contingency table 4.4.

Table 4.4: Contingency table: the number of cases to be sampled, proportional to the total number of extreme cases in the implementation (IMPL) who did (1) or did not (0) participate in the design (TDT) of STEM@school learning units

	IMPL = +	IMPL = −	% teams
TDT = 1	1	2	9 / 20
TDT = 0	1	1	11 / 20
% teams	8 / 20 = 2 / 5	12 / 20 = 3 / 5	20 / 20

Because this study was mostly interested in the attitudes of the teachers in the successful TDTs, and in how these attitudes differed from those of the other teams, an extra distinction was made: between teams who were successful in the design (TDT = +) and teams who were unsuccessful in the design (TDT = −). This distinction was made based on observations of the design meetings, by the team coordinators of STEM@school. Observations of the TDTs were evaluated by means of three criteria: the first two criteria in Table 4.3, but for the design part instead of the implementation part, and the criterion in Table 4.5).

Table 4.5: Additional rubric for determination of extreme TDT cases

Criterion	TDT = +	TDT = −
development of learning activities in function of learning goals	search for integrable learning goals in STEM curricula + development of experiments and prototypes to achieve these goals	immediate tryout of components and design of prototypes without connection to STEM-curriculum standards or other useful goals

Results from this evaluation revealed that, of the teacher teams that were successful in implementation, no teams had been unsuccessful in design, and vice versa. This is already an indication of the predictive value of participation in TDTs, suggesting that successful participation in iSTEM TDTs is a helpful, though not strictly necessary condition for successful implementation.

From the 20 extreme cases of STEM@school, a total of five teams were selected for the interviews in this study. The selection of the teams was based on representative (or typical) case sampling (Seawright & Gerring, 2008): those teams were chosen whose reflections and practices met the most criteria of Tables 4.3 and 4.5. Next to the five selected cases, two extra teams of STEM teachers were selected to gather extra information on the participation in iSTEM TDTs (as indicated by Table 4.6): one successful implementation/design team, and another team that had successfully participated in a TDT, but had not implemented the STEM@school learning units as such.

Table 4.6: Number of cases sampled from the extreme cases in the design (TDT) and implementation (IMPL) of STEM@school learning units

	IMPL = +	IMPL = −	IMPL = 0
TDT = +	1 + 1*		1*
TDT = −		2	
TDT = 0	1	1	

** extra cases for extra data*

A total of 15 teachers from the seven selected teams were interviewed, as shown in Table 4.7. Features of their profile are presented in Table 4.8.

Table 4.7: Schools and interviewed members of the STEM teacher teams selected for the study

	IMPL = +	IMPL = −	IMPL = 0
TDT = +	ASO-F(.65): *Dawson*, *Damian(.80)*, *David(.79)*, *Daphne(.95)*		ASO-A(.62): *Adrian*
	TSO-G(.26): *Dorothy*, *Donna*		
TDT = −		TSO-D(.23): *Will*, *Wilfred(.40)*, *Winston(.21)*	
		TSO-H(.79): *Walter(.00)*	
TDT = 0	ASO-I(.54): *Isaac(.29)*, *Ida(.53)*	ASO-J(.-.04): *Ray(-.16)*, *Rita(-.98)*	

(.xx) = averaged score on the school's teaching context or the teacher's attitude towards iSTEM education, retrieved from Thibaut, Knipprath, et al. (2018b) (M = 0, SD = 1)

The selected teams are named after the type of education their school provides: 'ASO-X' in case of general education, 'TSO-Y' in case of more technically-oriented education. The design process of the teams ASO-A, TSO-D, ASO-F, and TSO-G had been followed up-close in the case study presented in Chapter 3.

Table 4.8: Background of the interviewed teachers

Name	**Sex**	**Age**	**Education**	**YoT**	**Courses**	**School**
Adrian	♂	40	MSc Chem	12	Phys,Chem	ASO-A
David	♂	30	MEngTech Electromech	6	Phys,Math	ASO-F
Damian	♂	55	MEngTech Electromech	13	Phys	ASO-F
Dawson	♂	29	MSc Veterinary	5	Phys,Chem,Bio	ASO-F
Daphne	♀	58	MSc Math	37	Math,Phys	ASO-F
Dorothy	♀	47	MEng Bio	17	Phys,Chem	TSO-G
Donna	♀	36	MEng Bio	10	Math,Phys	TSO-G
Will	♂	55	BEd Electri	30	Electri,Eng	TSO-D
Wilfred	♂	48	BEd Mech	23	Mech,Eng	TSO-D
Winston	♂	51	5B Mech	18	Mech,Eng	TSO-D
Walter	♂	40	MEngTech Electro	15	Electro,Eng	TSO-H
Isaac	♂	45	BEd Math,Phys,Bio,Chem	24	Infor	ASO-I
Ida	♀	38	BEd Math,Phys,Geo	17	Phys	ASO-I
Ray	♂	40	BEd Math,Phys,Chem	18	Math,Infor	ASO-J
Rita	♀	46	MEngTech Electromech,Biomed	13	Math,Phys	ASO-J

Adrian and Walter were interviewed individually, since they were the core members of their STEM team and the most attending representatives at the design and resonance meetings which were observed. David and Daphne were also interviewed individually, basically out of convenience for their personal schedule. Will, Wilfred and Winston were interviewed together, but the lead was often taken by Will and Wilfred.

Other independent variables might have played a role in the classroom implementation by the teacher teams, such as the teachers' background (education, experiences). Section 4.2.2 of this chapter demonstrated how school context is also an important predictor of teacher knowledge and attitude towards, and classroom implementation of iSTEM education (Thibaut, Knipprath, et al., 2018b). Just like teachers' background, the teaching context of the interviewed teams could not be controlled for in this study because of the diverse school climates of the STEM@school teams. Bias could thus not be ruled out. The selection of teams for the interviews could however be crosschecked with the results of Thibaut, Knipprath, et al. (2018b), who quantitatively examined the school-context factors of 127 schools. These factors were 'support from school management', 'accomodation of collaboration', 'technical resources', and 'co-teaching and STEM-course scheduling', each consisting of multiple subscales. In Thibaut, Knipprath, et al.'s study, 269 iSTEM teachers scored the extent to which they felt each subscale was present at their school. The resulting scores of the selected teams' schools were averaged and included in Table 4.7 ($N = 127$, $M = 0$, $SD = 1$). The school scores most inconsistent with the categorization in Table 4.7 are those of successful team ASO-G and unsuccessful team TSO-H. As the teaching context influences the classroom implementation as well as the teachers' attitude, these teams' reflections must be analyzed with caution. On the other hand, this suggests that successfulness of implementation might not only be due to the presence of favorable context conditions.

Other forms of bias could occur due to suggestiveness of the interview questions themselves (Shernoff et al., 2017) or the interpretation of the teacher reflections. Furthermore, no predesign or -implementation interviews or classroom observations have been carried out, which curtails the possibility to make hard statements about teacher growth.

The (mediating) variable studied here, is not the implementation (IMPL), but the teachers' knowledge and attitude towards (teaching) (i)STEM. However, teachers' knowledge and attitude can be considered a confounding variable in the influence of the independent variable (TDT) on classroom implementation (IMPL). Since the latter remains the main target variable, the sampling for this study was not based on teachers' knowledge and attitude. The quantitative study of Thibaut, Knipprath, et al. (2018b) however examined teachers' attitudes towards the different key principles behind iSTEM education. From that study, the averaged scores of some of the teachers participating in this study could be retrieved, as shown along with these teachers in Table 4.7 ($N = 244$, $M = 0$, $SD = 1$). Teacher knowledge was not measured quantitatively. The scores in Table 4.7 suggest that no participation in TDTs and/or a badly perceived teaching context, in combination with an overall negative attitude towards iSTEM education is a predictor for unsuccessful implementation.

4.3.3 Interview analysis

The interviews were transcribed verbatim. In a first phase, called *open coding*, the transcripts were segmented into smaller chunks, which were labeled immediately (Mortelmans, 2007; Charmaz, 2006). The segmentation was determined by whether or not the teachers' reflections revolved around an idea that was different from the idea of the previous segment. A label given to a segment indicated the central idea of that segment. In case the reflections in one segment revolved around multiple ideas, multiple labels were assigned to that segment. Across the interview transcripts, reflections on the same idea were given the same label, in order to narrow down the amount of data. But whenever another connotation could be sensed, the label was nuanced with an extra description. Along the process, sometimes a more accurate label was found for a certain idea and some other labels had to be revised, causing the open coding to be an iterative process (Saldaña, 2009). After being tagged with the corresponding interviewees, these labels were gathered on one pile.

Next in the interview analysis, *focused coding* was applied, in which the piled labels were sorted into emerging categories (Charmaz, 2006; Saldaña, 2009). Following categories and subcategories emerged from the labels:

- design of iSTEM education,
- STEM subject matter,
- implementation of iSTEM education:
  - integrated teaching & addressing and assessment of learning content,
  - inquiry- and design-based teaching,
  - problem solving & investigation,
  - student coaching & activation,
  - teacher collaboration.

Reflections on the teachers' knowledge addressed their (awareness of own) CK, PK, PCK, practical skills in, and conceptions of iSTEM design or implementation. The teachers' attitudes were reflected in their (awareness of own) self-efficacy, perceived advantage or relevance, and feelings of control, interest and curiosity, hope and disillusion, resistance, courage and anxiety, dilemma, pride, and enjoyment.

Focused coding was also applied to the labels concerning the prerequisites for successful implementation of iSTEM education indicated by the interviewed teachers, resulting in following categories:

- teacher knowledge & attitude,
- teaching context: team organization, team coordination, and school management support
- teacher training

4.4 Influence of participation in iSTEM TDTs on teacher knowledge and attitude

To identify the influence of participation in iSTEM TDTs (RQ1, see Section 4.1), this section gathers and examines data from the interviews with the focus on teacher reflections on their knowledge and attitude towards several important components of iSTEM education. This examined model, shown in Figure 4.9, hypothesizes that participation in iSTEM TDTs is an effective form of teacher training for iSTEM education.

As teachers rarely answered coherently to the interview questions, and sometimes kept coming back to a fixed idea, the reflections gathered in this section are a combination of teachers' direct answers to the interview questions, and of spontaneous reflections that were unrelated to the interview question at that moment, but highly relevant to RQ1. Raw data is presented to corroborate the assertions that are made in this section on the influence of participation in iSTEM TDTs. Although inclusion of the teachers' quotes results in an exhaustive inventory, Section 4.4.6 recapitulates the most important findings.

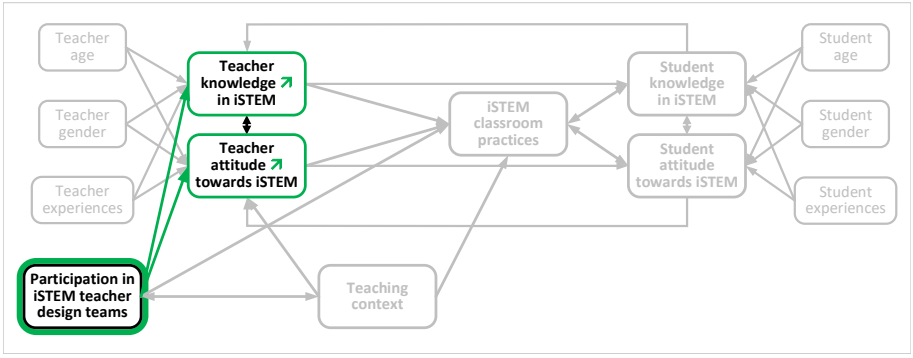


Figure 4.9: The variable relations examined in Section 4.4

4.4.1 Teacher knowledge and attitude towards iSTEM design

Conceptualization of iSTEM design

Adrian, Damian, Daphne, Dorothy, and Donna mentioned common features in their definition of iSTEM design: connecting learning contents from different STEM disciplines in extended learning units that revolve around one overarching

theme. Damian, Dawson, Daphne and David often referred to Perkins's (2010) 'playing the whole game' (see Section 2.3.2 of Chapter 2) when talking about iSTEM design, and Damian explicitly mentioned that the central theme should be interesting to students and relevant to society.

In the unsuccessful design teams, the response to the teachers' conceptualization of iSTEM design was rather dubious. When he was asked to give his definition of iSTEM design, Walter only responded that he found design interesting because, being an engineer, he has "the tendency to create new things". Will and Wilfred's answer revealed that they did not take a lead in the design process:

> Actually, *you* have developed our [i]STEM, if I can say this bluntly. ... We worked with the challenges we got from STEM@school. ... Cause if we'd have to start from nothing, we wouldn't have known how to start. ... [But] how do I perceive [iSTEM design]? A project that can grow from grade 9 to grade 12 and which you can break down into smaller projects to which you can connect your Applied Sciences. ... [For example,] in grade 9 we already [built] a museum protection, in grade 10 they will control those mirrors with a servo or a stepper motor. ... Because you can*not* address all that knowledge in grade 9.(Will) (1)

> *[T]hat*'s what I liked about *your* projects: that you constructed them by looking at the curricula: "How can we do that? Which goals can we address? How can we divide that over a year? How many projects will we do in a year?" (Wilfred) (2)

Daphne explained what constitutes a good designer, exhibiting what is referred to by Huizinga et al. (2015) as 'design expertise'.:

> A good [designer] should... should have much knowledge, but should also... be able to make it very easy! ... You have to... go further than [the students] go, to then simplify it again, because otherwise, you will start inventing nonsense, 'cause you will teach them things they cannot generalize afterwards. And you have to pay attention, to [say] it in terms of that jargon, of that book: you have to play the junior version of the real game, so that you... are not playing the junior version... of something that does not *exist*! ... We feel that now, through some [student] misconceptions; [they occur] because [students] don't know what [the concepts] will be used for later-on. And then they learn a little trick. But that trick... actually *doesn't work* for the *essence*. And then you've actually been teaching them something which is *incorrect*. And you have to guard that *very* well in [i]STEM. ... And *that*'s why you need [knowledge] experts. (Daphne) (3)

Perceived barriers in iSTEM design

Walter and Will complained about the fact that the designed projects started too much from the Science and Math curriculum, even though they had been part of TDTs and therefore had had the chance to impact the decisions made in the design process. In their opinion, the Technology curricula and design producibility were therefore often ignored:

> It *did* occur to me that your projects [from STEM@school] start from the Math and the Sciences, and then [you] say: "and *now* we will build that." ... "We will now discuss the math and the sciences and than we will build the hovercraft, and then we will give feedback." But you don't pose yourself the question: ... "Can you actually *make* that?" (Will) (4)

> In eh... the topics you develop, you will actually not get a learning trajectory of technology, more probably ... [you] follow a learning trajectory of the Physics course. And the math... yeah, is actually applied to that, causing some large leaps in math. (Walter) (5)

Both Daphne and David separately vented the opinion that it is hard to find a balance between 'getting students to learn what they need to learn', 'ensuring students' success experience', and 'finding a challenge that encompasses all this *and* is authentic at the same time':

> [T]he longer, the more I ask myself... *where* does student motivation come from. ... Shouldn't we get rid of 'being obliged to' and turn it into 'being allowed to'? But, that's again very difficult, because how far will you let them 'be allowed to', because you do want them to get a certain *minimum* [of learning content]... Yeah, that's what I find... yeah, that's very difficult... And somehow *that*'s [what student] motivation [is about]. ... Finding that balance... And I do this in my class too: lending them freedom, but you cannot let them drown! ... And also, being able to motivate them to go further than they *have* to. That is also difficult. ... And, yeah, what's the role of the teacher in this? I think it is huge. Actually, it is: making them aware that they are learning, eh... not for the teacher, not for their parents, but for *themselves*! ... And always, *that* search for compromise, I think you have that *even more* in [i]STEM. (Daphne) (6)

> What I always valued in [designing a student challenge], was that you... [create] a challenge that is not fake, that you cannot circumvent. So, that you say: "what do we want the student[s] to learn?" ... Like we did with the curricula. And then [you] say: "Can we give them a [challenge] for which they need all of that?" ... That is impossible... almost impossible. That's really weird. . . . Yeah... so that's what I find... difficult. And in the end, that's what we want [for] [i]STEM. (David) (7)

Some of the teacher-designers identified some shortcomings in the iSTEM design. By the time of the interview, Dorothy had visited the Netherlands, where she had been inspired by the lengthy design process and iterations made by the Dutch teacher design teams:

> One year of design is too short. It must be looked at from multiple perspectives. ... It's not developed well enough. ... In the Netherlands, they have teacher design teams. They work much longer - 4 hours per week, I think, that they are freed up to develop, to collaborate. And they implement it with a few test schools and then it comes back, it is reviewed *again*, and then there has been given feedback *before* it is implemented. ... [Y]ou can see that when you look at their syllabi: they put thought in them, it is well constructed. I'm not saying we did a bad job! But... it's not finished. (Dorothy) (8)

David, on the other hand, was very critical about the reflections made during their design process:

> [During collaboration with the other teams,] I had the feeling that [in] all the meetings we planned to develop together, we did not really talk about instructional strategies. ... More about: "there you can fit *that* in, and there you can..." ... But I was thinking the whole time: "why aren't we talking about the essence: what do we want from [the teachers]?" More like the book [Making learning whole by Perkins (2010)] ... there, they think about instructional strategies, instead of about details. Perkins explained a certain way of teaching and coaching. We talked too little about *that*. ... I think we should have thought more: "what do we want from the teachers?" I remember, we were... For example, the ballistic pendulum... and "does it work, or not?" What does it matter [*chuckles*]? The question is: How do you want to address that to the stu... or: Which activities do you want students to do? ... I think, within the design teams, we ... even barely talked about that, about what we wanted to do... or *why* we wanted to do that. (David) (9)

Perceived advantage of iSTEM design

Although the time-consuming character of iSTEM design was mentioned by Adrian and Dawson, all of the teacher-designers saw their participation in iSTEM TDTs as a big advantage and precondition for successful implementation:

> [The] advantage is . . . [the] feedback, from [STEM@school]. Yeah, for us, that has been... our start: our vision was developed there. . . . Yeah, the [additional advantage] is that you, because you, yeah, have the feeling you [are co-director], that... eh... [I]t's scientifically proven that that makes you happy. (Adrian) (10)

> You know what you will address, [and] you know how you will address [it]. Because you had discussions about it. Co-designing is a super added value. (Damian) (11)

> By the time you implement it, you already know where and what the pitfalls are. (Dawson) (12)

> That we knew the bottlenecks on beforehand, and that we... a year before we had to implement it, we could develop everything just as we really wanted it. And that we could order all equipment on beforehand. . . . [And] that we gathered all the background information. (Daphne) (13)

> [The advantage is] that you can tackle something. That you know *why* you do something. And that you are up against a *real* challenge, not a fabricated one. If you have the feeling: "this is something made by someone else and we have to follow it step by step," yeah, then you're not engaged in [i]STEM, I think. (David) (14)

> I'm happy we did not just... receive the learning materials [with the message]: "Start with this!" because I think that is a... eh... a very difficult task, and also... eh... because [now] you often know the reasoning behind the... *why* some features are incorporated. . . . Not only within your own developed project, but also... eh... through the plenary [design] meetings, you got an idea of the other [projects]. (Donna) (15)

> It's a good thing that you are involved, because if you have to do everything on your own, then... the wheel, they say, that you don't have to re-invent it, right. Otherwise everyone is on his island, doing things... which are now... a bit centrally coordinated. . . . It grows also. . . . [Y]ou have a year the time to get used to the idea . . . and think about it. (Dorothy) (16)

Even the unsuccessful teacher-designers seemed to be convinced of the support participation in iSTEM TDTs had given them for the implementation. Their

argument was the opportunity it had given them to get familiar with the rationale behind iSTEM education:

> Well, I think implementing is much easier when you co-designed. Because, in the end, you have a considerable head start in the thinking process. ... So if you are part of the design [teams], you will automatically achieve more. (Walter) (17)

> Actually, it has brought to me the meaning of '[i]STEM'. Because for me, it were only four letters, in a manner of speaking. (Will) (18)

> And I think it is a growth process. . . . We have maybe been more successful than schools who didn't develop because we were already involved in it for a year. We were already, like Will said, [involved] in the reasoning. (Wilfred) (19)

> They don't have to convince you, right. You yourself are pulling [the others]. ... [Also,] to see the difference between '[i]STEM' and 'working on a project' ... yeah, you cannot explain that if you're not in it. And *that*'s something you experienced as part of a design [team]. ... From the start... we entered [in this project] and we made something that suits us, something *good*. (Winston) (20)

The non-designing teachers, on the other hand, were glad that they received ready-made learning materials and that they did not have to start from zero:

> We are pretty lucky that we got a prefabricated... well, not prefabricated, but a pretty developed learning unit in which all the learning content is incorporated. Cause, basically, '[i]STEM' did not exist... Well, small, loose projects were being offered everywhere, but if you look at how they sell it.... (Ray) (21)

> For now... we are lucky with [the STEM@school materials]. Because [they] really [start] from the learning content, and I think that's good. You can see that people have put more thought in it than "we will just invent a project," which is nice, but yeah... then you still have to think of... how the math [and] how the physics [are involved]. That's a luxury, [here,] it is already incorporated. (Ida) (22)

All the non-designers convincingly denied the fact that their implementation would have run more smoothly if they would have participated in iSTEM design. Only Isaac had second thoughts:

> Conversely, I think... You're no involved party, so suddenly, you get a challenge: "Hey guys, are you up for this?" and you don't know where it will lead you! (Isaac) (23)

All teacher-designers were very enthusiastic about the collaboration with colleagues that was necessitated by their participation in iSTEM TDTs:

> In any case, you have, because of the... because of the collaborations that took place, you have different angles. ... What I also [experienced] as advantage [is] that you... ehm... You get some new ideas from the other teachers. If not for [i]STEM, then... [you can] use them in your regular courses. Ehm... Because you talk about things. (Donna) (24)

> [W]ith [the] sun collector [we were designing] back then, the handymen were allowed to help us. That was actually also very good [*laughs modestly*]. And those are... people without education in fact, well, I mean... okay, they have [an] education in their field of work, but ... they are no teachers. And they were enthusiastic, yes! They know better how something works practically. Or how it should look like. ... [And] we could use their equipment. (Dorothy) (25)

> [Through collaborative iSTEM design,] you get to know your colleagues in a fun way. (Dawson) (26)

> [I] hope that, here at school, we will have a mini STEM team to keep designing for a long while. (Daphne) (27)

> [You] also [build] good networks! ... [And] You can learn something from each school! And thus... if you only stay within your own cocoon... yeah... in the end you see nothing anymore.... (Winston) (28)

In all of the TDTs, the school management had freed up its teachers so they had common time for crossdisciplinary meetings and design; another consequence of participation in iSTEM TDTs much appreciated by Damian, Daphne, and Wilfred. Daphne illustrated how her team spent this time:

> [We discussed:] "I wrote it down like *this*, can you have a look if that's correct?" ... and then the explanation: "How do you address a certain concept in *your* course?" "Ah, but look: I can use *those* notations of yours," "Oh, I didn't know you use *that* word." ... And in two directions. Or: "I'm making a calculation here, but I don't really know what it's used for," or "I would like to make an exercise in class that can help *you*." ... Ehm... also ways to eh... to coach [student] teams: eh... how can you make sure that they will not just be wasting their time? ... And how do you evaluate that? (Daphne) (29)

Furthermore, teachers of the design teams spontaneously expressed their appreciation of the framework provided by STEM@school, and the opportunities to network. Wilfred narrated how parents also valued the fact that, through the connection with the university, the projects were scientifically underpinned.

Future efforts in iSTEM design

The interviewed teachers expressed some future perspectives with regard to iSTEM design when they were asked if they had any. The extent of their future-design plans varied from team to team. Daphne expressed the necessity of new learning units to stop the old ones of becoming too "rigid" and too predictable for teachers and students. This kind of vigilance was also exhibited by Isaac:

> I think that we... maybe later... - we already did that this year with a few things - we will also introduce new things. Cause you get used to it. I think, from the moment we're flying on auto-pilot, we will stop. When we can predict everything, we will stop. ... But yeah, designing [learning materials], I think I would like doing that as well. ... [F]or example, for the museum [learning unit] next year, we will, instead of working with one beam, I will let them work with a bar with several lasers. (Isaac) (30)

Daphne and Damian separately stated that they were planning to have a rotation system of learning units. Damian listed his team's ideas for future units: forest-impact registration and statistical analysis, and student-generated projects with the inclusion of inquiry competences. Adrian was looking for ways to incorporate programming, and experiments around eye-controlled interfaces.

The unsuccessful and non-design teams also articulated their hope for future iSTEM design, but their ideas were much less concrete, or smaller in scale. Walter merely expressed his hope for further design and an evolution in topics, which, according to him, was inherent to his background as engineer. The future design mentioned by Will and Isaac was limited to small adaptations to the existing learning units (see quote 30), such as adding or changing an electronic component. Rita nor Ray seemed to have plans for future iSTEM design.

4.4.2 Teacher knowledge and attitude towards STEM courses

Knowledge in STEM courses

The teachers who successfully participated in the design of iSTEM learning materials reported a gain in their own *content knowledge* (CK):

> You only learn *more* about your course, and [you get] new perspectives. And that... yeah... *improves* your own interest in the course; in my opinion. In physics, and in everything that comes with STEM: the mathematics and the technology. (David) (31)

Donna reported to have learned a lot about thermodynamics, a branch of her own teaching course which she allegedly was not very familiar with. Most teachers from successful TDTs however particularly improved their content knowledge of STEM disciplines other than the ones they teach. Math teacher Daphne reported an increase in her knowledge of physics and programming, and Physics teacher Damian reported an increase in his knowledge of math and computer science. Damian even mentioned that after the interview, he was going to meet up with his math colleague to get informed about theory on statistics. Veterinarian Dawson narrated that he even had hoped students would teach him soldering, but in the end that did not happen. He had however engaged in learning about programming, together with his students in class.

Conversely, the unsuccessful designers and the non-designers merely agreed upon learning "a lot", without specification:

> In the end, yes, because you collaborate more; I did learn things. (Walter) (32)

> I definitely learned new things. In *every* area... of my course! (Ida)
> ... or of the knowledge I had forgotten [*laugh*]! (Isaac) (33)

Ray stated that he refurbished his knowledge of physics, and Rita said she learned a lot about electronics. Although Will, Wilfred, and Winston acknowledged that they were now more aware of their colleagues' classroom practices, they stated that they *did* want to learn new, crossdisciplinary knowledge, but lacked the time to do so:

> No, I [did not learn things from other courses]. If I can accomplish my [own course goals], I'm already glad. I will not focus on... yeah, for example technical drawing, mechanics ... I just don't have the *time* to get involved in that. (Will) (34)

In short, all teachers declared to have increased their knowledge by designing and/or implementing iSTEM learning materials, but the unsuccessful designers and non-designers did not seem to have crossed disciplinary boundaries very often, given their educational background. Furthermore, whereas teachers of the successful TDTs explicitly mentioned they were learning from or teaching colleagues (see also quote 29), no such reference was found among unsuccessful TDTs.

Compared to the other teachers, many of the teachers of successful TDTs also exhibited a more profound or even increased *pedagogical knowledge* (PK) and *pedagogical content knowledge* (PCK) (see further reflections).

Motivation towards STEM courses

Several of the successful teacher-designers expressed an increased motivation towards STEM courses, which they explicitly attributed to their participation in iSTEM design:

> It gives an extra dimension to the job of teacher. (Damian) (35)

> My [motivation for teaching my courses] has improved. ... I have that interest for sciences and than... your course becomes broader, and then... that motivates me, compared to having to restrict yourself to your domain and the curricula you have to cover, over and over again. ... I liked designing. [It brings] new insights. ... Yeah, and the world is changing. If you now read about ... the CO_2 issues... That is going to change our society so much. ... And if we stay with our old ideas and don't think about it, we are actually not evolving, I think. ... What are all those renewable energy sources? ... I now read [articles] on those new technologies and everything that will change in society in terms of environment etcetera. And now I'm calculating how much CO_2 we produce when we take the airplane. ... [While] I'm not educated about that. And [participation in] design has made me aware of that. (Dorothy) (36)

> I'm happy that I... that I have the feeling that I'm still capable. I... I was missing... a bit... the challenge of... eh... being involved with [my] course, and not only translating [my] course to easier things. And by [designing] for [i]STEM, I'm involved again with my course because I have to think a bit further, to then make it easier again, and I like that. (Daphne) (37)

> [It] has been a challenge for me from the start, eh.... Yeah, a challenge I wanted to grasp and also wanted to realize... eh... yeah, within the school, within the [STEM@school] team. ... And it was also a challenge for myself to... retrain the technical [knowledge], under the motto 'life-long learning'. ... I [realized] that I want to be involved with the content. ... [I]t has made me realize that I... I will not let go of education, but apart from that, I have to take up other challenges. Otherwise eh... standing still is going backwards! (Adrian) (38)

No such explicit or elaborate reference to an increased interest caused by iSTEM design, or personal challenge posed by iSTEM design was made by the unsuccessful teams.

4.4.3 Teacher knowledge and attitude towards integrated teaching

Conceptualization of integrated teaching

Opinions about how learning content should be addressed in the design of iSTEM learning materials were mixed among the successful TDTs: Daphne believed that all of students' knowledge (current and to be learned) should be integrated as much as possible, while Donna felt that they had been too keen, trying to integrate as much content as possible. She said that she had noticed how the exhaustiveness had been confusing her students: they sometimes lost track of the central storyline.

The successful TDTs also expressed some reflections about student goals and assessment in integrated learning content. According to Damian, students' talent development and exploration while conducting inquiries in the iSTEM course, is irreconcilable with student evaluation. Additionally, he was of the opinion that the iSTEM course itself should not aim for students to achieve specified learning goals, let alone curriculum standards. Daphne nuanced this statement by expressing her belief that iSTEM provides the perfect opportunity to blend 'curriculum coverage' and 'contextualization' (or adding relevance to learning), hereby demonstrating that the iSTEM course in their school also played a role in addressing certain learning contents.

Perceived relevance of integrated teaching

No difference between the interviewed teams was found in the teachers' motivation towards integrated teaching. The designers and non-designers all appreciated how integration of STEM learning contents added relevance to math and science teaching, and how it broadened their own and students' scope:

> [What's] specific about that integration, is that we leave as little delay as possible between what they learn in Science and Math, and the application in [i]STEM. Things they learn in math, will get meaning in the integrated education. Then it becomes really concrete. Sometimes it happens that in the [i]STEM class the need arises to learn something more deeply in the other courses. That integration: that you use the learning content, that's an added value, ... for example: the mathematical 'function' is something we really *need*. ... [I] think we might be offering some students a nicer, more meaningful time in secondary education: they themselves feel that it's meaningful. (Damian) (39)

'[P]laying the whole game', I strongly believe in that. They use all the learning content, they better understand why they learn it. (Dawson) (40)

You wish to achieve a higher level, that students get a better understanding of the several aspects because there's a link between the different courses. (Donna) (41)

Ehm... it can - definitely for the students - come across more positively, or at least, that's what I hope. Eh... That they for example *recognize* the usefulness of math. (Walter) (42)

You can much more easily make the link, you show something, and then you'll build the theory around it. And not the other way around. And *that*'s what's so interesting for [the students]: how come this works? But we let it work first and *then* we'll engage in inquiry. So actually these are the research questions [in] Applied Sciences. (Will) (43)

And then you see that that uniform linear motion is also a [mathematical] function of the first degree. Students work with their graphical calculator. You integrate that a bit, with Physics for example: significant digits they use there, which we now use in Mechanics in our questioning. For students you should try to talk the same language. (Wilfred) (44)

[N]othing, *not one course* is regarded separately: *all* courses belong together. You cannot do anything without these courses. So . . . yeah, "I want to do something and I need a machine, so we go to the handyman, we're going to drill and saw." But also: "Yeah, but, why are we doing that? Well, have a look at the blackboard, because there's a reason for that!" Hop hop, a few formulas and an exercise. Eh... and while we're making that exercise: "what do I rely on? Yes, remember, yesterday we have seen that in Mathematics. Now it comes in handy! Pure coincidence!" But they always see: "Oh yes, well... I cannot do without." (Isaac) (45)

Students jump *straight up* when it's about their project in other courses! [And the exercise they are unable to do in Math class,] they are capable of solving [in the iSTEM course]... due to enthusiasm! . . . I don't think it's suited for *all* students, but for those who are a bit sick of school, it's *great*. We had a few of those in our first year [of iSTEM], who had a bit [the attitude]: "Pff, we don't care." But if they have to do it for their project, *that*'s another story! (Ida) (46)

[Y]ou can direct students [towards] things you advocate for, in which you have experience *yourself*: things you can *actually use*! (Ray) (47)

> I also welcome it. ... Yeah... I myself [followed a general study track in secondary education] [and] went to study [engineering in higher education] and then you see: mechanics, electricity... that was like Chinese [to me] at that moment! So [*in convinced voice*] I think it is an *added value* that you can offer that in a [general study track]. So these [students] already got a taste of it! ... [And] whether you succeed or not, you have *experienced* it, so you can also have respect for those who... *can*. ... I stand by the fact that there *are* some students who maybe... through this manner of integrated education... yeah, *did* get more enthusiasm and more... yeah.... That this is another way for some students which is *better* in line with what [they need]. (Rita) (48)

Daphne narrated how she had changed her way of teaching since she had enrolled in iSTEM design, towards more integrated teaching:

> I started to consult my Physics colleagues: "Where do you use an integral?" And I started to use *that* as an exercise for my students. While otherwise, when I look for an exercise, I will rather make theoretical... well... just exercises, and now I have placed them in a context. And I have caught myself - and I think many teachers do that - that if there are exercises in our textbooks in a context, we are tempted to just skip those because we can never test that and sometimes don't understand that context, because it is disconnected from everything. And... actually, that's a shame. . . . And I also see that... eh... those contextualized exercises are written like we as mathematicians would write them, but not like they are written in *reality*, I've realized now. (Daphne) (49)

She might have gotten her motivation for more integrated teaching from the feedback she got with respect to student learning:

> [T]here are a few statements of colleagues.... In the first year, I met my Maths colleague and he said: "I have *never* encountered *this*! The teachers ask me: 'Sir, when are we going to learn about the tangent? Cause we *really need* that'!" And now, this year, we had a student that disenrolled from [the] [i]STEM [study track] because she... found it too hard and because it was too much for her, but who kept pursuing six hours of Math, while she had gotten negative advice for it. And [her] Maths teacher said: "*She* even knows *more* of it than the other [students], because she has better remembered what she has learned." So these are two positive [reactions] which you - I think - cannot really measure: 'how does something stick?' (Daphne) (50)

All teachers thus highly valued the purpose of iSTEM education. In this regard, no effect of iSTEM design could be distinguished.

Motivation towards/through collaboration in integrated teaching

Likewise, all teachers also showed a high level of collaboration in their iSTEM implementation. With no exception, they all voiced the necessity and appreciation of crossdisciplinary collaboration with colleagues:

> [The fact that it works], is also thanks to Damian. I wouldn't have succeeded on my own! (Dawson) (51)

> I think, in the meantime, we work together *even more*! Eh... with [my] fellow colleague, who teaches a bit of math, a bit of physics, eh... I meet almost 2 hours every week. But that's about... ehm... about which materials [we] need, about all possible things. ... And in the end, by working together with other colleagues, you will get further in what you realize. (Walter) (52)

> You make a better teacher team. ... [Teachers who implement iSTEM on their own] don't get any feedback. It's *very* important that you have a sounding board, that you can consult each other. (Wilfred)
> ... And actually, someone of Math or Science should also join... in a manner of speaking. (Will)
> ... Our colleague of Physics and Chemistry comes to our meetings and sometimes visits [my] Engineering [course] ... to see what the [students] are doing. ... Now I talked with [her] and suggested... eh... that she will also adjust her curriculum. (Wilfred) (53)

> [Here,] you are really forced to collaborate. And that's a good thing, because as such, we learn from each other. You make agreements, *much* more [than] in a course-specific meeting. (Winston) (54)

> The flexibility [is very important], which is sometimes lacking [in the other STEM@school teams]. Cause we make arrangements a week on beforehand: "Who will teach this week? That is your part, this is my part. That we will teach together." ... [But] it has to be a match! ... You have to reinforce each other, also in front of the class! (Ida)
> It's also nice towards students, that they ask *me* a question, for example, and I Say: "I will play my wildcard." And then they also see: "Ah yes, about that [I] have to ask Miss [Ida]... and about that, that's more [for Mister Isaac]." (Isaac) (55)

> It's a serious search of how to align everything. ... In the first year, it was really probing: "which math [contents] will you address, what should I address? ... When do you do this, when do I do that?" ... [Now] I look at the digital agenda: "where are you [in the syllabus]?" And just like that, I know when to take over. (Ray) (56)

> Yes, we have a tandem that turns. ... [And] now, with [my other colleague], we started to co-teach a bit more. And I find *that* also a very nice experience. Cause, [it happens that] I explained something, eh... and a bit later, she refers to that [and] I hadn't thought of that.... I like that very much. That's an added value. ... And it's important that you have a good relationship and that you... both keep *searching*. (Rita) (57)

The fact that successful designers voiced fewer reflections on teacher collaboration and curriculum alignment with regard to iSTEM implementation might be an effect of successful participation in iSTEM TDTs, since most of the collaborative preparation had happened during the design phase.

4.4.4 Teacher knowledge and attitude towards inquiry- and design-based teaching

Conceptualization of inquiry- and/or design-based teaching

Most teachers exhibited a very positive attitude towards inquiry- and design-based teaching. Mostly the unsuccessful and non-designers gave detailed descriptions about the design skills they find important for students and the prototypes designed by themselves or by their students:

> [W]e make the same [car] baseplate for each student. And then ... they can 'pimp' it every time. [They] can finish it as [they] wish. And there were nice [products] among them! Cause at the opendoor event... eh... they promoted their study track themselves. And the fact that we have now 47 [students in iSTEM].... And in my opinion, that is largely due to the fact that those [students] showed... at [that] moment... what they are doing. (Wilfred)
> ... There was a racecar. ... Some made an icecream car with a cone with a pingpong ball that changed color. ... There was one with ... a construction of straws ... that could unfold. (Will) (58)

> I have worked on that during the holidays, on building my own hovercraft! So, I went to buy a tire and all of those things: "How am I going to keep it in the air?" ... The first years, I think I have done more engineering than my students! Because I tried to build everything and thought: "Now I still have to build that, how am I going to tackle *that*?" ... But when I really thought about it, in fact... it's *not me* who has to engage in [i]STEM, right, it's *my students* who have to engage in [i]STEM. (Will) (59)

> [Y]ou have [students] who wanted a sun-boiler *dome* on top of that... of [their] hexagonal passive house. And I said: ... "Yeah, that has to be in your [CAD program]!" ... And on a certain day, they had [even drawn] a spiral [sun boiler] on top of it: "There you go!" ... But I mean: you have... [they are] triggered by something! And they held onto it, to the end! That's learning, [those boys] will do that for other courses too. (Isaac) (60)

> We were going to build a ball launcher like on the drawings we got [from STEM@school]. But I taught those [students] how to read drawings, eh... with the list of parts, how you deal with that, and so on. [I included] 'design thinking'. Ehm... and *those* are, of course, accents we added because we enjoy them *ourselves*. (Rita) (61)

Narratives of the design and non-design teams who were unsuccessful in implementation suggest that these teams focused primarily on prototype design, in and outside the classroom: the type of electronic components they used, the troubles of getting the components ordered (in time), the technical drawing and material gathering.

Although it was obvious from the interviews that the successful TDTs also put a lot of emphasis on prototype design in the iSTEM course, they did not make as many reflections on prototype design as the aforementioned teams, and they also reflected about inquiry-based teaching, for example:

> That OPER cycle [Orienting, Preparing, Executing, and Reflecting] is annoying, but I actually secretly believe that it can be useful, because then, you try to make the steps, which we consider to be evident, more explicit. (Dawson) (62)

Damian and Dawson narrated how they changed or intended to change their way of teaching towards more inquiry-based (inductive) teaching in their other courses since had started with iSTEM education. Dawson articulated that he was planning to grant students more liberty in their research question in his Chemistry course, while Damian started introducing Physics theory by means of an application to trigger students' attention:

> What I for example do differently now: ... I'm building up the learning content differently [in my other courses as well]. [I] also [teach] electricity [to non-iSTEM students]. Before, I started with Coulomb and I ended with an electric circuit. Now, I first start with building a circuit with light bulbs, and I say: "Behold: this is an electric circuit!" But as long as your... students are interested, if they see such an electric circuit... that link between the circuit and Coulomb.... Before, they had to wait for it for *months*. Now I start (63)

> by building a light-bulb circuit, and then I proceed with the idea of energy that is been transmitted. . . . And if your circuit is built correctly, only then, I proceed with Coulomb. So, I really do this differently than when I wouldn't have taught [i]STEM. So, that's good, right? (Damian)
>
> In the usual courses there's not much [room for] flexibility, [but] in [my] Chemistry [course] I think I will set [students] more free. I feel they need that. . . . I've never been a fan of lab experiments, because you... if I look at myself: I never really knew what I was doing. I see that among lots of students as well, and then I think: "Yeah, what are we wasting our time on?" . . . And now, I find it maybe something to think about: granting [students] more liberty in their research question. (Dawson) (64)

With respect to inquiry- and design-based teaching, the content of the reflections mostly discerned the unsuccessful teams from the successful ones. One of the discerning topics is student evaluation. The reflections of successful teachers reveal forms of process and self-evaluation of students' design-based learning, albeit in a subtle way:

> We ask the student [teams] every week to write down what needs to be done the next week. That's also why they work so hard [in iSTEM], because they consider it *their* task. . . . You also have to remind them of the time [planning] and ask what they want to do and whether they think that's realistic, and which materials they think they need. (Damian) (65)
>
> And if you now [ask] the students: . . . "How would you do it next time?" [they say:] "Ah, smaller screws... Rounded corners, they were too sharp." well, that's good! And we evaluated it as a qualified [prototype]. There's still a lot to do, but they *themselves* [know] how to adjust it. (Isaac) (66)

Reflections of unsuccessful teachers, on the other hand, rather give evidence of mere product evaluation:

> The problem is: last year, for example, we had a student who wasn't good at programming, but he had [made] a beautiful car. But his father had programmed it. And he came with a program of which I said: "Wow, what's *that*?" So I knew it wasn't his [own] work. But yeah, I couldn't let the boy... I said: "Yes, I have to let you pass. Based on what you performed here, I cannot say that it isn't good. But I know it's not your work." (Will)
> . . . That's why we said: "We will evaluate the car... differently. Look, if the car *drives*, then [you get] a 12, because then... it suffices. But, if it can do that and that *more* [you get extra points]." (Wilfred) (67)

Motivation towards/through inquiry- and/or design-based teaching

Teachers of the successful teams articulated how they felt a higher motivation because of the design-based teaching:

> Now, on a personal level: at home, nothing gets done anymore since [I]'m teaching [i]STEM [*laughs*]. But my wife also likes it, and that's [because] you come home and you have something to tell, so, you are reloaded as well, you are enthused again! . . . "Do you know what they invented today [*claps his hands*]?" And you're already looking forward to [what] you're going to do in 2 weeks. And that motivates you! And that is... yeah, I found that important, [it's] contagious in both directions. (Isaac)
> You get a lot of energy from it, right! You get a lot in return! (Ida)
>
> (68)

Conversely, except for Walter, teachers of the unsuccessful teams seemed to struggle a lot with prototype design themselves. It even seemed as if they projected their own struggle onto their students' difficulties:

> I used to go to my class and I could rely on experience. . . . Now you are challenged, your are challenged over and over again. Cause now [the students] have made an error in... in motor type. And now they came up with another motor, . . . two motors actually, and now it has to be programmed again, that's again a new challenge [*sighs*]. (Will)
> That motor is larger [than] the previous one, so, I had to adapt the base plate... (Wilfred)
>
> (69)

> [The] difficulty level of [the learning units for] grade 9 was much easier than the one of [the learning units for] grade 10, I found, yes. Because there's of course much more engineering involved, which I actually... was not so familiar with. (Rita)
>
> (70)

Despite of this struggle, and despite of her self-reported complete desperation last year, Rita claimed to now be in a state where she actually enjoys the problem solving and inquiry inherent to prototype design:

> Last year I was thinking: "I have to stop!" There has been a time where I thought: "I *cannot* keep up with this." True story. . . . [But now,] I *enjoy* myself, when I can teach that! Yes! And... and that searching, I also find that enjoyable, of course. . . . But, Wednesday for example: six of my cars did not work. So I stayed after class. . . . I totally didn't mind to search for [the problem]. When the students are there, then that's more complicated. So I... I mean it, I really *enjoy* it. (Rita)
>
> (71)

The teachers' statements suggest that prototype design in the unsuccessful teams was largely controlled by the teachers instead of by their students. As demonstrated in the following subsection, the teachers of the successful teams showed quite the opposite behavior.

4.4.5 Teacher knowledge and attitude towards student activation

Conceptualization of student activation and effect on students

The teachers of the successful teams made multiple reflections on how to activate and coach students, and on the effect of such student activation. This was the case for successful TDTs as well as for the other teams who successfully implemented the iSTEM learning materials:

> [T]he more you steer students, the more they will adopt the attitude of being steered. (Damian) (72)

> [In iSTEM,] students learn also leadership skills, and in general: self-regulation. ... And when I see all of [our students] here, actually already from the beginning, they can specialize in one thing. And that's all going well. So I find it... actually quite successful. (Dawson) (73)

> Having students *really* go their own path. Like: now there was a rehabilitation machine with part of a bycicle. And we are no welders, and metal... But we looked at each other: "Let's do it!" And it worked. ... We're not frightened by it. Because some [teachers would] immediately put a stop to [the students'] enthusiasm and say: "It's not possible." ... If you're standing in front of your class in an authentic way, you can afford anything. ... And some students are also smarter than us, in [some] areas. (Ida)
> Yes! With incredibly good ideas! Of which you say: "Ah? Ah yes! Right!" ... For them it's nice too ... that we ask: "What would *you* do?" So that they experience that we also say: "Ah! I hadn't thought of that!" (Isaac) (74)

> But the students have changed in the classes. ... They have adopted another attitude, I found. ... [Y]ou could see them grow in two years. Then you have also achieved something, right. (Ida)
> Most of them have developed an attitude [of self-regulation]. ... [Some] begin to [behave]: "Ah, it's a project, so: what will we do? ... What do we have to consider? ... Which steps are we going to take?" ... And for the students, I rest my case, it is the beginning of a whole story, which they do not consider as something disconnected, like "I have a book here, there are formulas and exercises in it. By (75)

> the end of the trimester I have to know that well!" [And] now they say: "Ah, I have a problem, let's solve it!" or "We will be able to *explain* it to someone." (Isaac)

In Daphne's opinion, a good student coach must possess a high level of CK in his/her own discipline, and have just enough insight in other STEM disciplines to know which questions to ask to colleagues and which freedom to give to students. Although her reflection upon student coaching resembles the one of Ida (quote 74), she emphasized the effect on student learning:

> [I] think that students... definitely in grade 9, but I think younger students as well, appreciate if you... say you don't know things. Because then they know, that what you *do* know, you really do know. And that is... that is important, I think. And *that* is the right role of a coach, to investigate: where can we find it? And *then*, they can ask *any* question. Then they can also advance further than your own knowledge. (Daphne) (76)

Dawson stated that participation in iSTEM design had helped him to be a better student coach as he now better understood students' struggle with problem solving, a statement which was agreed upon by Damian and David.

> Actually we went through a search process last year, which our students go through now. I think that helps to be a better coach. Personally I had the feeling last year: "how will we ever... see this through?" If I see that among our students, I can... well, . . . I better understand the despair, the lack of overview among the students. (Dawson) (77)
> . . . To coach is something you have to learn, right. (Damian)

> Things we experienced ourselves, where we have made mistakes ourselves, towards students you can - without saying: "you have to do it like *this*" - you will give students direction. Or enter into dialogue with them, like: "look, if you encounter this and that..." or: "*that* is also an option, maybe try it out". But we will never steer too much, we will never say to students: "you *have* to do it like that!" It is about: pointing out risks. Very little steering. Because of the fact that we also have been in that search process, it is easier to guide them in it. (Damian) (78)

The teachers of the unsuccessful teams barely referred to activation or coaching of students. This might suggest that their classroom practices did not involve much independent student work or room for students' creativity. Will, for example, even seemed surprised about how students come up with ideas themselves, and he made it seem like that happened by accident:

> But be aware: they come up with that *themselves*! Because I... I do not go that far, but they indeed come up with a Bluetooth module, and then that car starts to drive autonomously. . . . And they can control it with their mobile. . . . [B]ut those are things I have never explained them! . . . But, those [students] of grade 10, they come here in my class... eh... on Tuesday afternoon. But they look *up* those things, you know! "Where are we going to buy that material?" And then... they are looking that up... but they discuss with each other. (Will) (79)

Motivation towards student activation

David showed that he had been trying to enact the constructivist idea of encouraging student self-regulation, but was counteracted by his own beliefs about students' expectations of how a teacher is supposed to behave, i.e. imparting knowledge on passively receiving students, making sure a design would function in the end:

> [Designing and implementing] has brought me many doubts about what is actually *good* practice as a teacher. Or what is good to strive for. . . . For me that also means . . . having students wanting to do things they did not expect, or of which they expect that you . . . as a teacher will . . . teach in a certain way. But when you deviate from that, they cannot cope. They think you're not a good teacher. . . . They just like having to sit down and shut up. . . . They are too young to take up their responsibility in something. . . . Yeah, I find it difficult to work like that. . . . [T]he more I think about it, like: "what am I going to change?" the more I will take out of their hands, it seems. And so, that's what I fear: that in the end we arrive where we started . . . "Ah, maybe we should give them that [information] already, so they can start from that." And in the end, . . . students will get the feeling of a false challenge, of which the solution is already predetermined. In the challenge[s] we have now, the solution is not predetermined, but then they don't manage to [solve] them, you see? (David) (80)

Damian on the other hand, seemed to get much satisfaction from his role as a student coach:

> What I actually like the most, is that you are standing . . . in between the students, and that you, consequently, get sucked into the project with them while still being a sort of coach. (Damian) (81)

4.4.6 Overall influence of participation in iSTEM TDTs

In short, a few differences could be distinguished between the successful designers (TDT = +) and the other teams. Although no causal inferences can be made because of the lack of pre-TDT interviews (i.e., it is possible that teachers possessed knowledge and attitude that favored successful iSTEM design instead of the other way around), and although no conclusions can be made that are generalizable for a broad population, this study gives an in-depth view on features that can likely be attributed to successful participation in iSTEM TDTs. Then again, some other features were found that might rather be correlated with successful implementation (IMPL = +). Table 4.9 lists the major findings.

Whereas teachers who successfully designed learning materials pondered about *instructional strategies*, the conversational topic of the other teacher teams very often came down to the endeavors of *prototype design*, and in case of the unsuccessful teams: their *own* prototype design.

The reflections of the successful iSTEM designers show evidence of a high *pedagogical knowlegde* (PK) and *pedagogical content knowledge* (PCK), whereas no statements of the other teams revealed such deep insights into the endeavors of addressing learning content or coaching students. According to Damian, this is a consequence of participation in iSTEM design:

> Because of the fact that you think to this extent about your own... about education, about teaching, and about addressing content to students, I think you learn a lot! Because of the fact that you discuss a lot about it, also afterwards, that you can harvest that as a teacher. (Damian) (82)

Overall, the successful TDTs made many references to the *philosophy* behind iSTEM education: making learning whole, playing the whole game but in a junior version, operationalizing math and science to use as modeling tools. The values that were propagated by the STEM@school coordination seemed to be adopted and even embodied by the successfully designing teachers:

> I have to say, honestly: it has almost become a part of us, like 'playing the whole game', that's what I *did* just now. (Damian) (83)

Teachers who had only implemented the learning materials, felt they had not missed out on participating in the design. They argued that they merely missed knowing the reasons behind decisions that were made in the learning materials. Mostly, they were glad they did not have to start from zero. Teachers who had participated in the TDTs asserted that the design process had taken a lot of time and effort and was not always successful, but that this was inherent to the fact that designing is a growth process.

Table 4.9: Correlations between any (1) / successful (+) participation in iSTEM TDTs or implementation (IMPL) and teacher knowledge and attitude

Finding in terms of teacher knowledge and attitude	versus	Correlated with
view on iSTEM design	view on iSTEM design	
pronounced conceptualization congruent with philosophy**	no coherent conceptualization	TDT = +
personal challenge	–	TDT = +
perception of ownership & engagement**	relief not having to start from zero	TDT = 1
future iSTEM design	future iSTEM design	
ideas for whole new learning units	ideas for small adaptations of existing units	TDT = +
gain in CK	gain in CK	
in disciplines other than own	in own disciplines	TDT = +
through learning from colleagues**	through self-study	TDT = +
instructional strategies	instructional strategies	
deep reflections	superficial reflections	TDT = +
on student problem solving & inquiry- & design-based learning**	on (own or) students' prototype design	TDT = +
controlled by students*	controlled by teachers	IMPL = +
teacher collaboration in implementation	teacher collaboration in implementation	
already familiar**	completely new	TDT = +
evaluation of own success	evaluation of own success	
based on student learning*	based on prototype designs	IMPL = +

*** probably causal effect of TDT on teacher knowledge and attitude*

** probably causal effect of teacher knowledge and attitude on IMPL*

All teachers of iSTEM TDTs were convinced of the fact that it had significantly improved the implementation of the learning units, since it was coordinated by academic researchers, which ensured the establishment of a common vision (key principles). Participation in successful TDTs had facilitated collaboration

among STEM colleagues, generated new ideas, and broadened the teachers' content knowledge. The teachers testified that these aspects had increased their motivation for teaching and for their own disciplines.

These findings provide conclusive arguments to authorize participation in iSTEM TDTs as an adequate form of teacher training for iSTEM education.

4.5 Prerequisites for iSTEM education

Via the interviews, the teachers were asked which aspects they considered to be important or necessary ingredients in the design and/or implementation of iSTEM learning materials. The indicated aspects concerning teacher knowledge and attitude (Section 4.5.1), and those concerning teaching context (Section 4.5.2), are considered to be prerequisites for participation in iSTEM teacher-training programs. The main interest of this section are the aspects indicated by the teachers as important *features of teacher training for iSTEM education* (Section 4.5.3), since these must be taken into account in the development of such programs. These features are supplemented by findings from the research literature on teacher training in Section 4.5.4.

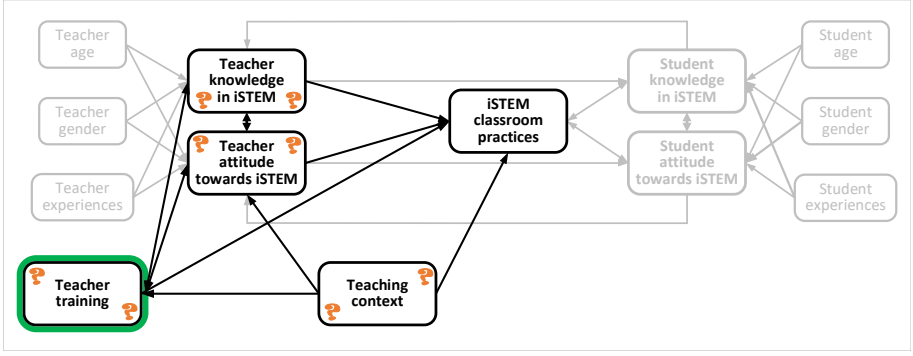


Figure 4.10: Prerequisites in teacher knowledge and attitude, teaching context, and teacher training examined in Section 4.5

In another study, a similar question was asked in interviews of 22 elementary and secondary school teachers in iSTEM education by Shernoff et al. (2017). The teachers mentioned the need for support of the kinds shown in Figure 4.11. The needs reported by the teachers in the study presented in this chapter, were expected to be in accordance with Shernoff et al. (2017).

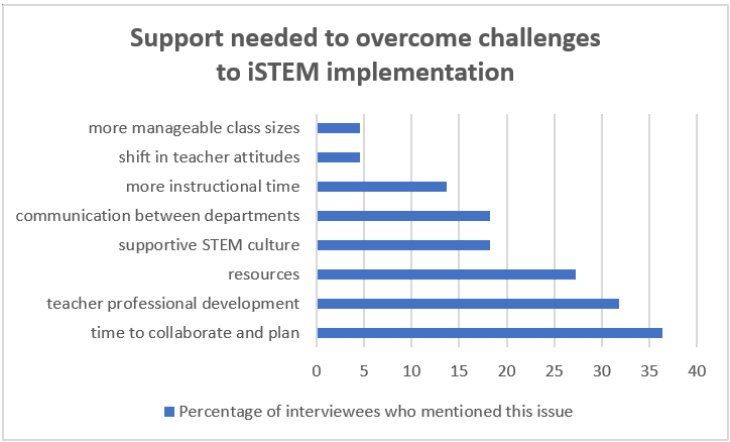


Figure 4.11: Support required by elementary- and secondary-school teachers for implementing iSTEM education (retrieved from Shernoff et al. (2017))

4.5.1 Teacher knowledge and attitude

Adrian, David, Damian, and Dawson indicated that *willingness to learn* new knowledge in less-familiar disciplines is of utmost importance. Sometimes self-study was considered necessary.

The previous section showed Daphne's reflections on what constitutes a good iSTEM designer (quote 3). According to her, a good designer should have a *thorough discipline-specific content knowledge*, a *willingness to collaborate*, and a *strong pedagogical knowledge*.

Willingness to invest time was unequivocally pronounced as an important asset of a teacher designer: as Daphne and Will testified, design often goes on during vacation. Adrian stated that a designer should also be able to protect himself from sacrificing too much personal time. Additionally, the need for a *strong motivation* was mentioned or implied by all interviewed TDTs.

Adrian, David, and Dawson argued that successful participation in TDTs is a matter of *perseverance*, since it is a problem-solving process, often with inevitable pitfalls and uncertainties (see quote 77) (Ríordáin et al., 2016).

This need for willingness to learn and to collaborate, and the perseverance inherent to iSTEM education, was corroborated by Shernoff et al. (2017):

> [T]he ideal STEM teacher would not be intimidated by mathematics and science, but rather would have a passion for and a solid content expertise in both – along with proficiency in related disciplines. [A good candidate would also] have a comfort level with exploring uncharted territory, trying new things, adapting, and the inevitable failure that comes with experimentation. . . . [A]n essential ingredient is the skill of the teacher to facilitate conversations embracing this complexity, highlighting crosscutting concepts and aspects of science and engineering practices that unify the many 'parts'. (Shernoff et al., 2017, p. 10-13)

4.5.2 Teaching context

Team organization

All interviewed teams suggested that an iSTEM team requires a *multidisciplinary expertise*, and should thus contain teachers from different STEM disciplines.

> A team [is needed] that is composed in a multidisciplinary way, . . . of all courses, with expertise, *and* definitely a technical crew. (Adrian) (84)

> I think you... need a good team . . . as varied as possible; [with] teachers who have been teaching for years, and who have an overview of what students can do at what level. . . . But [there] has to be [expertise] in different disciplines. And then you also... need an engineer, or someone who can support you technically. (Daphne) (85)

> What I find important, is . . . the different backgrounds of the... designers. Eh... so that the projects are looked at from different angles and... and that, from each angle, [there is] a decent accent. (Donna) (86)

Daphne meticulously formulated the reason for transdisciplinary collaboration:

> A teacher who embarks on [i]STEM alone [cannot] engage in real [i]STEM, I think. Because then you have way too little cross-fertilization. Because you always look at things from your *own* education. . . . If you are only an expert in one [discipline], you can downgrade in your *own* discipline, but you cannot do so in another discipline, because you . . . don't know where it leads to. You cannot play enough with the *level* of that discipline. . . . [With a team of experts,] you loose much less time with having to look up things, because the expert knows... some things, just like that, or else: knows very quickly *where* he can find it, and *which question* he has to pose. And as non-expert you sometimes don't know which question you actually have to pose. (Daphne) (87)

As shown in the previous section, team 'ASO-F' used common meeting time to align learning content and to exchange instructional strategies (see quote 29). The teachers of the unsuccessful TDT 'TSO-D' also mentioned the fact that they had used common meeting time, to discuss planning and align curricula.

Donna, Ida, and Rita mentioned the importance of *matching teacher profiles* (i.e. a good mutual relationship among the teachers) within an iSTEM team (see quotes 55, 57). Donna even claimed that iSTEM design would otherwise be impossible. Furthermore, Donna and David stressed the importance of *common goals* and being on the same page among the designers in one TDT:

> [Y]ou also... have to have a similar view on [what you develop]. So you know: "That's where we want to go." (Donna) (88)

> [You have to] know well what the goals are, *why* you want to [develop]! (David) (89)

Adrian, Daphne, and Will mentioned the necessity of having an engineer in the team (see quote 85), or at least someone with *technical background and expertise* (see quote 84). Dorothy claimed that her lack of skills in programming had hampered her participation in iSTEM design, while Donna argued that this lack was compensated by the technically-educated colleague in their team.

Team coordination

The STEM@school team provided a framework and vision that appeared to be much appreciated by the TDTs:

> We really were... yeah, a bit *visionless* when we started... until we... got [the] advise [from STEM@school]. ... Also the drive we have gotten from [STEM@school]. Yeah, also... the feedback and... yeah, the enthusiasm to proceed... and that you know: "Yes, okay, you're in a team with a vision you can start from." ... And it's also because the design that we got acquainted with [the professor of Gent who specializes in robots]. I was able to make use of the [STEM@school] network in this way. (Adrian) (90)

> I also think it's great that STEM@school has given us the chance to do new things, and has created a framework for that. (Damian) (91)

A *common vision* among the designers can thus be established through supportive *coordination* by academic or government staff. Therefore, both are important ingredients for participation in iSTEM TDTs. This vision should be provided through a bottom-up approach:

> So, I find: the freedom, the space to [design] [is important]. ... Now we can teach students [the things that are] necessary for them and in which they have interest. (Damian) (92)

Gathering of teachers across different schools was also considered to be part of the coordination, and was valued by several designers. Adrian, Donna and Wilfred claimed that the ability to network with other schools had accelerated the design process, because it resulted in new ideas (see quotes 24, 28).

As mentioned in the previous section, Dorothy expressed the wish for a centrally sustained, long-term framework for teacher collaboration in design (see quote 8), much like the TDTs, long established in the Netherlands (Binkhorst, 2017). In her opinion, such a structure should be managed by the government, and could streamline the many efforts currently undertaken by teachers trying to reorganize their STEM education.

Management support

The school management should know who to engage for iSTEM design, because, in the opinion of Dorothy, teachers who are obliged to participate, will not do a proper job. To make collaboration happen, the school board should also provide commonly scheduled *meeting time*, preferably in paid hours:

> Th[ose] [freed up] Tuesday afternoon[s] have been of utmost importance. For iSTEM design, that's really a must, if you want to do it well. (Damian) (93)

> To do that in a decent way, to [develop] in a decent way, yes. And free, not only freed up in terms of schedule, but also actually having to teach less hours. Otherwise, it's impossible. (Donna) (94)

Several teachers stated that the school management should also enable *easy access to equipment*, to try out some experiments or prototype design, such as computer platforms, sensors, but also a lasercutter and 3D printer are welcome. Daphne argued that this should also be provided by the government, while Adrian and Walter were not waiting for that to happen and narrated that they themselves had started looking for funding elsewhere.

Furthermore, some teachers' reflections indicated that they would appreciate some form of *appraisal for their efforts*. According to Dawson, this can be arranged by administering paid hours which the teacher can use for preparation and meeting. Adrian, Daphne, and Wilfred however explained that a school unfortunately does not always have extra paid hours at its disposal. Another way for the school management and educational advisors to show appreciation

of teachers' efforts was expressed by David: occasional visits, in which a teacher can ventilate his/her concerns, and can receive feedback on his practices:

> Does someone... does someone care that you are renovating education as a teacher? ... [N]o one ... *ever* comes to ask you: "Are you doing okay?" ... If you want to engage in educational innovation, it's all on the teacher's account. ... So here at our school, I regularly try to mention that to the school management. I also say that to all student-teacher trainees as well, that they should organize that at their school: that teachers get the opportunity to visit each others' classrooms. And *then* you get conversation on what you're working towards, what you find important. (David) (95)

4.5.3 Teacher training

Via the teacher interviews, also the desired training was queried, so it could be taken into account for the design of pre- and in-service training for iSTEM education that involves iSTEM TDTs.

As Daphne and Adrian indicated, the pre-service teacher training should foremost equip teachers with a *thorough CK* in their own discipline(s). Without elaborating on what these trainings should look like, some teachers reported the need for a minimal in-service training in technical CK and skills:

> To be a *real* STEM teacher, I think [participants] should... gain some practical experience... [e.g., via] a real internship in a company. (Wilfred) (96)

> I think [there should be training in] programming and electronics. Actually you have to... you have to [know] the basics to... eh... apply it in the STEM learning units. ... I find it a disadvantage that... that programming ... I'm not skilled in that, not at all. ... And we would have ... gone further in that. (Dorothy) (97)

Daphne explained why technological or practical training is important:

> I think it's impossible to be an expert in *all* courses. But maybe you can... take away [some teachers'] *fear* for some things by... a minimum of... of programming, a minimum of design, a minimum of the other courses that are not your own. ... There should be just enough [training] so you would have the self-confidence to know: "I can tackle that, and if I can't, I have my other expert to help me with that." (Daphne) (98)

According to some teachers, the best training for iSTEM education is to carry out a small iSTEM project:

> I think that the in-service training should be a STEM project. ... Like [we give our students] who enroll from another study track. ... You should actually give [attendees] a small "whole game", in which you use an Arduino and have to program, solder it yourself. ... For example, ... making a thermometer from semi-conductor material, with a control light [which glows] green if [the temperature] is below 20 degrees Celsius, orange if it's between 20 and 50, and red if it's above 50. And the read-out had to occur on a display. (Dawson) (99)

> A day or half a day doing a project from A to Z, because there are always a lot of technical questions. ... And that those steps are not always evident. And if you have been able to do that *once*, the self-confidence ... would be higher, and it would also take less time than if you have to find everything yourself. Yeah, it's about stupid things ... little things that caused you to get stuck, and that don't work. (Adrian) (100)

> My first thought, if I'd have to organize [a training], ... I would *make* those teachers *do* it. I would just say: "There you go," like *we* did: "you have to build a scale model of a passive house, and that has to be heated and that has to... be controlled. And let's see the result!" And then those teachers can experience and know what it is. (David) (101)

Walter and Daphne indicated the fact that teachers should *learn to collaborate* and learn from each other as an important component of teacher training:

> Crossdisciplinary collaboration: already at that level, crossdisciplinary sharing of expertise. (Daphne) (102)

Isaac illustrated that he also considered collaboration important in teacher training, so that teachers experience the philosophy in which students should be taught. He proposed problem solving sessions of an afternoon, once a month, or two full days per trimester, for example in programming:

> I would almost [organize] an afternoon ... in which you have to solve several small things, small problems. And then you see that you develop that philosophy of [how] to think and discuss together: "how would you tackle that?" That doesn't have to be strictly scientific. ... That you say, for example: we will do this two days the first trimester, two days the second. ... Eh... for example, if it's about coding, you could say: "Look, people, we will just program this structure, this loop and so on." You explain that. "And by the next time you're here, you'll have had one and a half months. ... I would (103)

> like you to try to write 'something' that does... 'that'!" Something not too hard. ... And then you come together, and [you discuss]: "I wrote something and it doesn't work." The one next to me gets the task: "You will now first help your neighbor." ... And try. Do we succeed? No? And that's how you grow, by being taught in the same philosophy. (Isaac)

According to Adrian, this kind of training would mainly provide opportunities to network. He was not an advocate of peer teaching in training sessions, while David saw classroom observation as a powerful opportunity to learn from peers and to get feedback on own practice (see also quote 95).

Dorothy mainly wanted content-related trainings that were immediately employable in the classroom. Donna expressed the need for training that exemplifies instructional strategies:

> [I would propose teacher training on] [how] to construct a learning trajectory.... And project-based teaching. ... Maybe also how a... What a good project is supposed to comprise, and how a... a decent project is constructed. (Donna) (104)

Damian and Daphne had remarkable ideas for training which seemed oriented towards design-based teaching and coaching:

> I know some friends who work at an R&D department [in a company] so I can... learn much from them, things I take into the classroom. But it would be a good in-service training: 'What are the current practices that are applied in companies when they develop something?' Yeah, that helps to say to students: "Try to break that down into smaller pieces and try to tackle those separately, solve those separately, and then solve everything together." (Damian) (105)

> Being trained to coach and to... guide teams [of students] who... are pursuing different trajectories. ... How can you know if you can let them pursue that lead, or have to say: "Guys, this will go too far, step back onto the main track." How do you do that in such a way that you don't discourage them? ... Ehm... [other training could revolve around] learning to listen to the students' interests. (Daphne) (106)

When asked what would be the best training for iSTEM *design*, David answered that the only way to learn this is by doing so: designing a student task which is authentic. As demonstrated in the previous section (see quote 7), David found that difficult but very important at the same time.

4.5.4 Overview of important features of teacher training for iSTEM education

The teacher interviews indicated several aspects that should be incorporated in teacher training for iSTEM education. The research literature on instructional reform and teacher design teams, provides supplementary information which should also be taken into account in the construction of pre- and in-service teacher training. These important general and iSTEM-specific features are combined and summarized in this section. They are ingredients for teacher learning in the context of curriculum innovation towards iSTEM education. The listed features underpin the formats of participation in iSTEM design that are hereafter proposed as teacher training for iSTEM education.

Strong rationale – Teachers' beliefs and classroom practices are often not completely compatible with the rationale of a curricular reform (Van Driel et al., 2001). However, what teachers are about to learn, should be acceptable to them in order to create a buy-in (Desimone, 2009). If the teachers' current conceptions are not congruent with the reform ideas, the teacher training should create a cognitive conflict in the teachers' minds (Sunal et al., 2001), for example by means of evidence of positive effects of the reform approach on student performance (quote 50) (Pintó, 2005; Singer et al., 2011). A strong vision should be provided (Guskey, 1988), as was done in STEM@school (quotes 90, 91), with attractive, feasible principles (Krajcik, Blumenfeld, Marx, & Soloway, 1994; Davis, 2003; Voogt et al., 2011).

Participation in curricular design – To avoid aversion against the new instructional approach inherent to STEM integration, teachers should have a role in the decision-making process. One way to get teachers on board, is by making them co-designers (quotes 15, 92). When teachers participate in the design of curricular materials, their practical knowledge and beliefs are taken as starting point (Van Driel et al., 2001; Krajcik et al., 1994; Coenders & Terlouw, 2015). As they gain ownership over the new approach (quotes 10, 11, 16, 17, 18, 19, 83), teachers become collaborative architects of their own instruction, which is directly tailored to their teaching context (quote 20) (Parke & Coble, 1997). Furthermore, it is an appealing way to comply with all (other) evidence-based features of effective teacher training (Voogt et al., 2011). Teachers should then be coached to reflect upon:

- which contents lead to the highest cognitive gains in student knowledge (Hattie, 2012; Coenders & Terlouw, 2015),
- which learning goals students are expected to attain via the learning unit that will be developed (quote 5, 89) (Hattie, 2012; Thornton & Bell, 2015),
- which authentic methods allow to evaluate student progress and outcomes (quote 29) (Fulton & Britton, 2011).

Content – Teacher training should focus on deep content knowledge and skills (Supovitz & Turner, 2000; Desimone, 2009; Darling-Hammond, 1998; Voogt et al., 2011). Knowledge training for iSTEM education might focus on:

- modeling: prediction, examples, and characteristics of scientific models (Van Driel & Verloop, 1999),
- disciplinary CK and PCK (Shawer, 2017) in instruction of key STEM concepts (Singer et al., 2011; Shernoff et al., 2017; Dare et al., 2018; Ríordáin et al., 2016), and big ideas, concepts, connections, representations, and misconceptions (quote 3) (Stohlmann et al., 2012),
- how to select effective instructional strategies and student activities (quote 9) (Shawer, 2017) that interconnect these concepts and ideas,
- strategies to deal with work-load pressure: goal orientation, effort regulation, interest enhancement (Shawer, 2017)

Examples – Clear and plausible demonstration of good practices on each of the key principles behind iSTEM education must provide teachers with tangible examples of how to translate the abstract vision into concrete classroom practices (quote 104) (Sunal et al., 2001; Ingvarson et al., 2005; Voogt et al., 2011; Singer et al., 2011; Huizinga et al., 2015). Exemplar training materials for classroom implementation can include potential classroom issues, examples of student work, and structured lesson plans (Coenders & Terlouw, 2015; Shernoff et al., 2017). For design of iSTEM learning materials, exemplar materials should show how to incorporate and meaningfully connect different STEM disciplines (Shernoff et al., 2017; Dare et al., 2018). They could also include research literature about key principles (Coenders et al., 2010) and resources from which teachers can elicit suitable student learning contexts (Stolk et al., 2016).

Active learning in an authentic environment – The training program should emulate the student classroom as closely as possible (Singer et al., 2011), and the principles behind the new instructional approach should be reflected in the professional learning of the teachers (Loucks-Horsley, Stiles, Mundry, & Hewson, 2009). Hence, in order to guide their students' learning process with a constructivist attitude, teachers as well need to construct new understandings by relying on their prior knowledge and expertise, and by engaging in and reflecting upon novel practices in a social environment (quote 82) (Krajcik et al., 1994; Davis, 2003). Just like the students, the teachers should be confronted with an authentic (design) challenge (quotes 6, 14, 37, 38) of which the conditions, constraints, and solution paths are ambiguous, and solving it requires the integration of multiple knowledge domains (McFadden & Roehrig, 2017). Teachers should thus be immersed in inquiry, questioning, and investigation themselves (Supovitz & Turner, 2000; Windschitl, 2003; van Aalderen-Smeets & Walma van der Molen, 2015). This will decrease the fear for shortcomings in skills and knowledge (quotes 98, 100), which often curtails teachers' self-efficacy,

and thus sabotages good classroom implementation (van Aalderen-Smeets & Walma van der Molen, 2015). Through collaborative problem-solving sessions, teachers can get familiar with technology (quotes 96, 97, 98) (Sargent & Husic, 2015) and experience creative engineering practices (quotes 103, 99, 100), and get acquainted with relevant real-world applications (quote 36, 101) (Stohlmann et al., 2012; Meirink et al., 2010; Shernoff et al., 2017). Furthermore, teachers should have the opportunity to try out new practices in the classroom (quote 8) and observe the impact of these practices on student learning (quotes 46, 50, 74) (Ingvarson et al., 2005; Desimone, 2009; Blumenfeld et al., 1994; Hattie, 2012). During the training program and after classroom tryouts, considerable time should be provided for teachers to reflect on the efficacy of their practices (quote 9) (Sunal et al., 2001; Hattie, 2012; Stolk et al., 2016; Kelchtermans, 2001). As such, teachers develop metacognitive strategies, such as goal formulation, decision-making, and self-evaluation (Huizinga et al., 2015).

Collaboration – Teachers should have the opportunity to collaborate with peers (cf. all interviewed teachers) (Rocard et al., 2007), possibly sustained through long-term mentoring (quote 8) (Sunal et al., 2001; Supovitz & Turner, 2000; Desimone, 2009; Joyce & Showers, 2002). This should prevent teacher isolation (quotes 16, 28), and lead to a common understanding (quotes 88, 89) (Sunal et al., 2001; Meirink et al., 2010; Fulton & Britton, 2011). Time should be allocated for discourse and articulation of reflections on the new instructional approach (quotes 9) (Parke & Coble, 1997). However, only in a climate of trust will participants share their difficulties (Blumenfeld et al., 1994; Parke & Coble, 1997). Collaboration across age, gender and grade level (Vangrieken et al., 2015; Stolk et al., 2016), and across STEM disciplines (quote 84) fosters ongoing improvement and exchange of expertise (quote 24, 86, 87, 102) (Parke & Coble, 1997; Davis, 2003; Shernoff et al., 2017). Furthermore, it will directly benefit students, since the instructional strategies will be better tailored to the student level and interests (quote 106). Weekly gatherings can serve to align learning content (quotes 29, 52, 53, 54, 93), and discuss implementation difficulties and student work (Sargent & Husic, 2015). Collaborative action research and peer coaching can provide teachers with rich and frequent feedback on their classroom practices (quote 53, 95) (Van Driel et al., 2001; Desimone, 2009). The exchange of constructive feedback will broaden teachers' perspective and repertoire of instructional tools (Meirink et al., 2010; Voogt et al., 2011; Vangrieken et al., 2015; Shernoff et al., 2017).

Curriculum standards and intended outcome – Teacher learning can be directly related to student learning, so what students will have to learn should be the starting point of training programs (Fishman et al., 2003). Moreover, a training program should be grounded in standards for student performance (quotes 1, 2, 7, 5, 22) and show teachers how to connect standards with student work

(Supovitz & Turner, 2000; Ingvarson et al., 2005; Desimone, 2009). This could counter teachers' dilemma on how to conciliate content coverage versus depth of students' understanding (quote 49) (Pintó, 2005).

Student performance – Evidence of student performance is the most important measure of the impact of a training program (Hattie, 2012; Fishman et al., 2003). It can thus also inform efforts to improve the training program.

Coordination – Teacher trainers should be perceptive to teachers' opinions and expectations (Sparks, 1988), trying to connect the reform framework with the teachers' personal goals (quote 83) (Stolk et al., 2016). Trainers are responsible for creating and guarding a safe, scaffolded environment for mutual risk taking and critical and constructive reflection (Krajcik et al., 1994; Singer et al., 2011). They must provide assistance in planning and reflection (Toolin, 2004; Voogt et al., 2011; Satchwell & Loepp, 2002). The given support should be a combination of proactive support, i.e., scaffolding aiming for achievement of predetermined goals, and reactive support, i.e., just-in-time support as answer to sudden articulated needs (Huizinga et al., 2015). Teacher trainers should structure teachers' group discussions (Binkhorst, 2017) by advancing teacher collaboration from independent storytelling over mutual assistance and sharing of experiences, to interdependent joint work (Vangrieken et al., 2015). Finally, good teacher trainers regularly visit the teachers' classroom to observe their practices and provide them with ongoing feedback (quote 95) (O'Neill et al., 2012; Sunal et al., 2001; Ingvarson et al., 2005). If the training unites university researchers and teachers in its program, the university staff could take up the role of teacher trainers, providing teachers with technological and evidence-based expertise, as well as an outsider's perspective (Blumenfeld et al., 1994). Teacher learning can be facilitated by an online platform, which contains templates for planning, or for the design of student challenges, scaffolding techniques, personal journals, video recordings, and case studies (Blumenfeld et al., 1994; Fulton & Britton, 2011). Such an online platform should take into account all the aforementioned features (Surrette & Johnson, 2015).

Time – Effective programs are frequent, and spread over time (quote 103) (Desimone, 2009), so the principles behind the reform can sink in (quote 16), and teachers have the time to experiment (quotes 8, 93, 94).

In short, a teacher-training program for iSTEM education should develop its participants' ability to embody the key principles behind iSTEM education (Singer et al., 2011): adoption of an inquisitive attitude (Rocard et al., 2007), goal orientation, reflection, collaboration, and tryout of ideas of other disciplines to solve a central challenge, such as, e.g., the design of iSTEM learning materials. In tackling this challenge, the participants can count on frequent and long-term guidance, including a framework, examples, and feedback.

Shernoff et al.'s (2017) also examined the training desired by the 22 elementary- and secondary-school teachers involved in their study on iSTEM education. The emerging themes in their study are presented in Figure 4.12 and are in line with the aforementioned features.

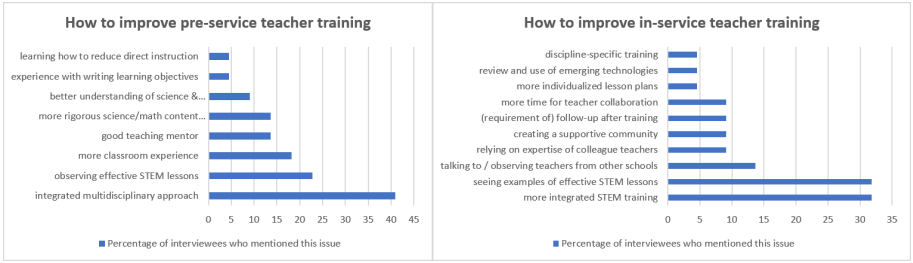


Figure 4.12: Training desired by elementary- and secondary- school teachers for iSTEM education (retrieved from Shernoff et al. (2017))

4.6 Proposed teacher training for iSTEM education: two formats including iSTEM TDTs

Section 4.5 raised the need for pre- and in-service teacher training programs that run for a whole year, take into account the features mentioned in the teacher interviews and in the literature (Section 4.5.4), and focus on the design of iSTEM learning materials, in the form of teacher design teams (TDTs). Based on these requirements, this work proposes two formats of teacher training for iSTEM education, in which participants take part in iSTEM TDTs. These formats are presented in this section. Section 4.6.3 finally shows how the proposed training programs respond to each of the important features of teacher training, determined in Section 4.5. The proposed programs are complementary to a thorough disciplinary CK training and are in no way an alternative to this crucial part of teacher preparation (Supovitz & Turner, 2000).

In the proposed formats, the participants work in teams of five to seven members. The teams should be supported by one or multiple teacher trainers - further referred to as 'coordinators' - with a strong affinity towards secondary education, with some practical (technological) skills, and with access to discipline-specific research literature. These coordinators preferably have a broad, multidisciplinary network of experts to rely on. Assigning university staff to the role of coordinator can warrant that the targeted student goals optimally correspond with the required knowledge and skills students are expected to

master at the beginning of their higher-education studies. Binkhorst (2017) provides guidelines and a nine-step method for an alternate shared and vertical leadership approach for team coordinators to support TDTs. The participating teachers from their part are expected to bring eagerness to learn, audacity, and collegiality into their training.

If the trainings would be administered as outlined in this section, the coordinators should use the recommended classroom observations and teacher discussions as a means to evaluate these training program in the light of their objectives:

Participating (future) teachers can:

- adopt, and in the end also embody the principles behind iSTEM education;
- deepen their content knowledge in the discipline(s) of their expertise;
- broaden their content knowledge in disciplines less familiar to them;
- exhibit confidence in problem solving;
- formulate student learning goals and keep them in mind;
- create learning activities that foster students' conceptual and self-regulatory learning;
- build links between different STEM disciplines and expose them to students in an authentic way;
- identify adequate, research-based instructional strategies;
- rely on colleagues, and take part in constructive argumentation and feedback;
- assume an investigative attitude;
- explore authentic and engaging learning contexts;
- guard the coherence of the developed learning activities;
- get familiar with technology that can facilitate iSTEM instruction (platforms, software);
- grasp student learning opportunities as they emerge through their own problem-solving process.

4.6.1 Training with CODEM for iSTEM

The training format proposed in this subsection makes use of the model constructed in a previous study (see Chapter 3): CODEM for iSTEM (Collaborative Online design of Educational Materials for integrated STEM). This training format was implemented in in-service training as a workshop, and in pre-service teacher training as a year course.

One *workshop* took place at the international conference EAPRIL (De Meester, Langie, et al., 2017). The primary purpose of this workshop was to validate the model (see Section 3.4.2 of Chapter 3 for more information). However,

the participants' activities were observed, and the discussion at the end of the workshop was recorded, allowing to identify some learning gains. Two teams, consisting of a mixture of educational researchers and actual teachers, worked with CODEM for iSTEM during the workshop. One team had written down the learning contents and goals they had collaboratively identified. The learning goals they listed showed deep insights among the team members: the goals were formulated in a clear and observable way and demand students' higher-order thinking and modeling (see Figure 3.26). Also the members of the other team showed through their reflections that they had reasoned deeply about the education they wanted to offer their students. The reflections of these two teams were compared to the reflections of the members of a control team, which did not have CODEM for iSTEM at its disposal. The reflections of the control-team members were more superficial, and were inextricably linked to the challenge they had designed, instead of the other way around.

After implementation of this training format in *a pre-service course*, one team coordinator (teacher educator) was interviewed on the effects she had observed. She stated that this format had helped her students (pre-service teachers) to achieve the targeted learning objectives, such as creating a motivating, authentic learning environment, and using multimedia. She had, however, realized that interest and motivation in technical systems are important prerequisites, which she intended to communicate to prospective student teachers who plan to enroll for this course. Furthermore, in the opinion of the coordinator, working with CODEM for iSTEM had given the student teachers a better image of STEM. She stated that, before, the student teachers were probably not really aware of the integrated character of STEM, and that a clear link exists or can be made among all of these disciplines. She concluded with:

> In terms of integrating disciplines, I do think that this was a revelation to the student teachers: this is also possible. I hope that in their usual courses, they will also apply some of the underlying instructional principles and start from a rich context. I mean, these are things we always tell them, but this time they investigated this to the very core, so I hope this will be reflected in their classroom practices. (Pre-service teacher educator)

Additionally, the team coordinator stated that she had learned a lot about the whole STEM experience herself, and that she had also employed CODEM for iSTEM together with colleagues to create workshops for a promotion event of the university college.

The training format consists of three stages, the third of which was not implemented in the aforementioned workshop.

Introduction to the training

For this digital training, an introductory session is needed in which the coordinator(s) set the framework and objectives for the participants. Since student teachers do not have as many classroom experiences as their in-service colleagues, and need more support and examples, the rationale behind iSTEM design is presented through a rather top-down approach. However, to get some buy-in, the trainees are encouraged to actively take part in the seminar by sharing their opinion and proposing possible approaches. With in-service participants, this introductory session can be replaced by session 1 of the in-service training sessions (see Section 4.6.2). For a workshop, this introduction should be kept rather concise.

Firstly, the objectives of the training are presented to the participants. Then, the key principles behind iSTEM education (see Chapter 2), evidence from research (such as in Section 4.2.1), and an overview of the design process (see Chapter 3) are presented, and the participants examine some designed learning units. The online tool CODEM for iSTEM is introduced, its functioning is demonstrated, and the estimated time that is needed for each phase is shown.

Training via the online tool

The training sessions following the introductory session are determined by the online tool CODEM for iSTEM (see Section 3.4.1 of Chapter 3) and by the approach and pace of each team. Theoretically, no contact hours have to be administered between the team members and their coordinator(s), as important messages and feedback can be communicated via the discussion forum or via comments on the shared documents in the online environment. The online tool alerts the coordinators when some documents need revision. In practice, some contact hours with the coordinator(s) give the teams the opportunity to ask for more information, examples, or equipment. The team members should, however, meet physically on a regular basis. In case of a workshop, the participants discover the first steps of the Brainstorm phase of CODEM for iSTEM.

Tryout in the classroom

Finally, as part of the training, the participants should try out the learning materials, designed with the support of CODEM for iSTEM, in the classroom. While implementing the materials, they should check whether the intended learning goals are being attained, and verify which possible adjustments are needed (see also the follow-up sessions in Section 4.6.2).

4.6.2 In-service training sessions in iSTEM design

The teacher training proposed in this subsection consists of a series of six in-service training sessions and a few follow-up sessions. These training sessions can be adapted to be implemented in pre-service teacher training as well, but should be spread over the course of at least an entire school year. This program was submitted to and published in a journal for teacher educators, see De Meester, Knipprath, et al. (2017).

Many important steps from CODEM for iSTEM (see Section 3.4.1 of Chapter 3) are implemented. Since this section focuses on teacher training, the steps are explicitly supplemented here with the specific skills and knowledge they aim to achieve among the participants.

Session 1 – Need for a vision

The first session attempts to align the participants' attitude and beliefs with the key principles and rationale of iSTEM education. An exchange of classroom experiences, student testimonies, or reports on the decreasing interest in STEM-studies can make the need for iSTEM education more palpable to the participants. The participants discuss the possible problems and try to formulate solutions. As such, the motive for the curriculum design arises bottom-up from within the participating teachers: increasing students' interest in STEM by showing them the relevance of STEM.

When the motive for the design is established, the coordinators present the objectives of the training program (as mentioned before), since participants should know what they will be capable of after the training.

The coordinators now provide the teachers with (at least two) examples of learning units: some well-designed, others badly-designed with respect to the key principles behind iSTEM education. From the examples, they ask the participants to identify the aspects that can be categorized under high-quality iSTEM education, and the aspects that cannot be labeled as such. The participants are also asked to justify this categorization. While doing so, they have to keep in mind the motive for iSTEM education. The coordinators tactfully direct the discussion towards the key principles behind iSTEM education, which will be the guiding principles of the curricular design. Additionally, the key principles could be further explored through small workshops in a rotation system: see Box 4.2. Such workshops immerse participants in the type of instructional strategies they themselves will soon be designing for their own students.

Box 4.2 Small workshops on the key principles of iSTEM education

A. Integration and problem-centered learning

1. The participants are given a certain theme.
2. They sit together in monodisciplinary teams to discuss learning content that could be linked to the given theme.
3. The participants are rearranged into multidisciplinary STEM teams.
4. Then, the participants discuss their discipline-specific learning content in the multidisciplinary teams and try to find links, for example by means of a concept map. Meanwhile they try to formulate a central problem that covers these learning contents in a logical sequence. The coordinators provide each team with feedback on the quality of the problem statement and on the learning opportunities that could possibly be included.
5. In a whole-group discussion, the teachers share the problem statements and learning sequence they designed.

B. Inquiry- and design-based learning

1. The participants are given some materials, such as an Arduino, some sensors, and some Lego or Knex. Furthermore, the participants receive an evaluation rubric with the description of the design and inquiry competences that are expected of them.
2. The participants, who are divided into multidisciplinary STEM teams, are asked to make a design with which the variation of a certain quantity can be examined. The coordinators provide feedback on each team's collaboration and communication. They ask the participants to justify the decisions made in their design.
3. Within their team, the participants are asked to evaluate their team's process by means of the rubric.
4. In a whole-group discussion, the participants finally share which STEM concepts they learned or examined in order to build the design and prepare the inquiry.

C. Student-activating strategies for conceptual learning

1. The participants are divided into several teams for:
   - a discussion around a few concept cartoons on scientific theses
   - the construction of a representation of a given problem, the possible scientific principles underpinning the problem, and a model of the answer
   - the construction of a verifiable hypothesis on a scientific

topic that encompasses many student misconceptions, conduction of an experiment and re-evaluation of the hypothesis

2. In a whole-group discussion, the answers and models of the different teams are compared and discussed.
3. The participants share their ideas on how the activities foster conceptual change, and how they could assess whether conceptual change has occurred among students or not.

Via a mind map these principles can be visualized, as presented in Figure 4.13. Immediately, the translation should be made to the general learning goals of iSTEM education for the students (step 'GDT' of CODEM for iSTEM). This mind map should be exposed centrally in the room for all participants to refer to at any moment during the training.

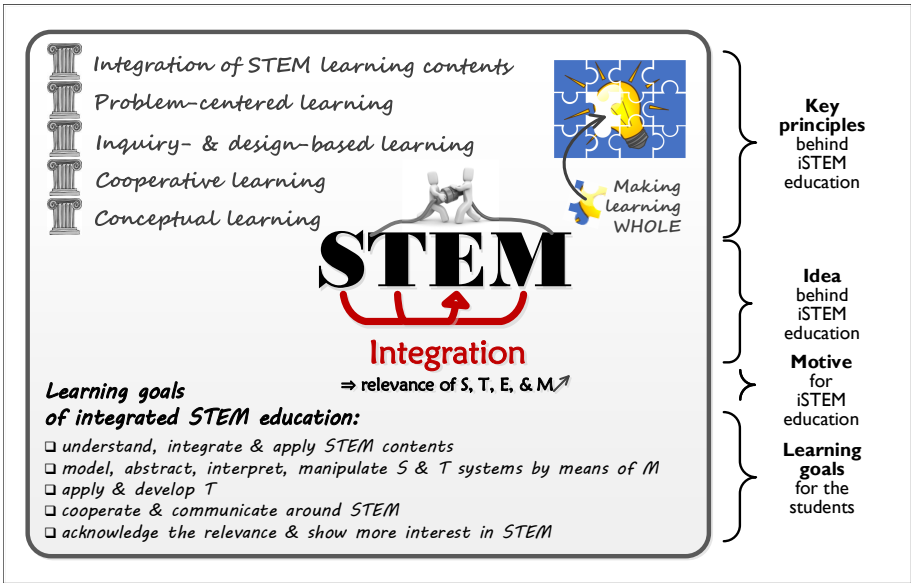


Figure 4.13: Mind map of the vision and goals underpinning the design of iSTEM learning materials according to STEM@school

At the end of the first session, a rubric can be co-constructed together with all participants. Such a rubric shows a continuum of achievement levels for each of the principles behind iSTEM learning and can serve as an instrument to evaluate the designed learning activities later-on.

Session 2 – Brainstorm around a chosen theme

In this session, teams are created, composed of teachers from different STEM disciplines, in such a way that each discipline is represented by at least one participant who has some expertise in it (in accordance with step 'TFD' of CODEM for iSTEM). The composed teams can now choose a theme around which they want to design their instruction, and browse the STEM curricula for related concepts and skills (steps 'BCT' and 'CIL' of CODEM for iSTEM). As described in step 'CF' of CODEM for iSTEM, the teams now have to design a central challenge around this learning content: a problem statement or driving question that must be solved by students that connects the desired STEM learning contents.

The participants now try to establish crossdisciplinary connections and refine the challenge via the collaborative construction of a concept map (as illustrated in Figure 3.21). A concept map is a powerful tool for the team members to detect gaps in their own and each others' knowledge: they might encounter some concepts that are not fully understood by everyone (e.g., concepts from STEM disciplines with which they themselves or their colleagues are less familiar). An opportunity presents itself for peer-to-peer tutoring, in which participants are enlightened by their team members on concepts from STEM disciplines other than their own (broadening their own CK).

In this training session, the participants are asked to take an investigative and creative attitude in which they check their ideas for feasibility, consult experts and other resources for information, and iterate between the learning contents and the formulated challenge.

Session 3 - Draft of integrating learning activities

Within their teams, the participants first try to embed the listed learning contents in discipline-specific and crossdisciplinary learning goals for their students to achieve. The coordinators focus the participants' discussions on the formulation of unambiguous, observable learning goals (step 'GRS' of CODEM for iSTEM).

To prevent classroom activities from becoming the goals instead of the means, the participants must now try to design learning activities that directly contribute to the achievement of the formulated learning goals and that explicitly integrate the targeted concepts, as described in step 'DLA' of CODEM for iSTEM. The coordinators can support the teachers' brainstorm with some concrete examples.

Guided by their coordinators, the participants will inspect their designed learning activities for coherence: the activities should address and connect the desired STEM concepts in a profound but comprehensible way and at the same time obviously contribute in solving the central challenge. The coordinators help the participants to look for ways to model and integrate concepts that are difficult to students.

The participants are sent home with an assignment: a literature study (step 'CLS' of CODEM for iSTEM). The exploration of research on (conceptual) learning can strengthen the participants' disciplinary knowledge, but also extend their repertoire of instructional strategies (deepening their CK and enriching their PCK). The coordinators can provide some articles (a) on beforehand, to guide the participants' search for information (proactively), or (b) on the participants' request (reactively).

Session 4 – Planning of the implementation of a learning activity

In the fourth session, the participants are gathered again in their teams. Informed by the suggestions from research literature, they can supplement the learning activities they already designed in previous session with exercises, experiments, and instructional strategies (step 'AAS' from CODEM for iSTEM). Furthermore, they are asked to check whether the devised learning activities will achieve the intended learning goals, and how they will bridge the STEM disciplines the team wanted to integrate. The coordinators verify if the learning activities incorporate (different forms of) student evaluation.

The next phase of the design concerns planning. Alignment among the annual programs of the different STEM courses is key to integration, and this alignment inextricably causes shifts in the usual order in which learning contents have been addressed. When teachers have to schedule their designed learning activities per week, often an animated discussion is set in motion. With this discussion, the participants develop their collaborative skills, since they learn to consider some issues from different perspectives, bring sound arguments, and make concessions when necessary. In their neutral role, the coordinators will act as mediators. Indeed, a consensus is the necessary ticket to the next step.

The time has come to try out the designed learning activities in practice, to evaluate them on the key principles defined in session 1. Possibly, the designed learning unit cannot be tested as a whole within the time frame of the training. If the learning unit is too large, the teams should choose a learning activity from their design that shows a fine example of STEM integration and that can be meaningfully conducted with students without having to present the full challenge (provided that the learning activity is well contextualized). The

purpose of the tryout is twofold: (1) to test the effectiveness of the designed learning activity, and (2) to verify if the final implementation – what the design and thus the training is aiming at - complies with the established principles behind high-quality iSTEM education. The teams will preferably try out their chosen learning activity in a classroom of students. If it is impossible to schedule this implementation in student classrooms, the activity will be implemented for peer participants from the other teams.

During the preparation of this tryout, which will involve some experimentation and/or prototype design (step 'EPD' of CODEM for iSTEM), certain needs will emerge among the participants. Therefore, the next session is a session-on-request: the participants may indicate which additional training they need to be able to support the student learning activity with more self-confidence in the classroom.

Session 5 – Training-on-request

The training-on-request session can be scheduled in the longer spare period in which the participants prepare and implement the learning activity. In the requested training session, the coordinators give the participants the time, space and means necessary to fulfill their specific needs, as well as tools that are immediately applicable in the design and in practice. Possible concepts for this training-on-request - possibly realized in multiple, parallel sessions - are:

- peer-to-peer tutoring of contents from less-familiar disciplines;
- a session 'inquiry-based learning' around a certain hypothesis;
- a session 'reverse engineering' to explore the assembly and functioning of a product;
- a tutorial or collaborative debugging session in technology around a given setup: programming, electronics ... (e.g., one of the workshops presented by Bergner et al. (2012));
- a company visit related to the chosen theme;
- ....

This training session should, in the first place, enable participants to solve similar problems in other contexts independently, i.e., without the scaffolding training environment. To this end, the participants should continuously be triggered to reflect upon their problem-solving strategies and to constructively search for reasons behind emerging failures or successes. By learning how to deal with practical problems autonomously, the participants will also learn how to better coach their students and grasp learning opportunities as they emerge.

Before the next training session, all teams will try out their designed and prepared learning activity in a classroom (with students) or in an extra training session (with peers). The teams who will implement the activity in classroom context, are asked to videotape their classes. The coordinators encourage co-teaching during the implementation. Co-teaching helps teachers realize that they do not have to be omniscient, and that, by redirecting student questions to their colleagues, they embody the interconnection of STEM disciplines.

Session 6 – Evaluation of a designed learning activity

In this last session, the teams will exchange constructive feedback on each other's learning activities and reflect on their own, based on observations of student behavior in the videotaped lessons or on own experiences. The enacted learning activities should be evaluated on (1) efficacy (achievement of student learning goals), and (2) alignment with the key principles behind iSTEM education. After the exchange of feedback, the participants reflect in their own team on the discrepancies between these findings and their initial intentions. The learning goals for the students, formulated in session 3, and the evaluation rubric, constructed in session 1, can serve as a basis for feedback and reflection. This reflection fosters the participants' metacognitive thinking: they learn to verify whether their beliefs, and their designed activities are compatible with the objectives of iSTEM education. In the end, the mind map of session 1 can be refined based on the participants' practical experiences.

Follow-up sessions and support

In the event that the teacher training is continued in the next year (which is highly recommended), some follow-up sessions should advance the continuous improvement of the designed learning materials and associated teacher competences. For example, one of the follow-up sessions could especially be devoted to the design of methods and instruments to assess students' performance in the different learning activities. When such instruments are designed collaboratively and based on a shared vision on iSTEM education, the evaluation in the classroom becomes less teacher-dependent and more goal-oriented.

In another follow-up session, the participants will be asked to bring along some evidence of their students' performance on those assessments, such as logbooks on student behavior, answers, or test scores, and student-generated artifacts and reports. In this session, the participants discuss their students' results and reflect upon their own behavior, learning materials, and classroom practices.

Again, the efficacy of the designed and enacted learning activities is evaluated against the degree to which the intended learning goals are achieved by the students. The conclusions of this evaluation should inform further adjustments in behavior and materials. The participating teachers must be reminded of the the fact that this type of follow-up session aims for them to 'learn', and that their errors or problems should be considered tools based on which they can enhance their learning through reflection.

For the enactment of the designed learning activities, teachers could use ongoing feedback. To this end, the coordinators and school managements should set up a framework in which teachers get the chance to experiment, and in which regular classroom observations by and reflective discussions with their coordinators or colleagues are organized that will inform them about their progress, possible improvements, and effects on student learning (much like 'lesson study', see e.g., Lewis, Perry, Friedkin, & Roth, 2012).

4.6.3 Overview of proposed teacher training programs for iSTEM education

Previous subsections presented two formats of pre- and in-service teacher training for iSTEM education. Table 4.10 shows how the programs explicitly work on some of the teacher learning goals, while the other targeted goals are addressed throughout the programs. Table 4.11 is a recap of how these training formats respond to the important features of teacher training, as summarized in Section 4.5.4.

Table 4.10: Some of the targeted teacher learning goals and their pursuit by the proposed iSTEM training programs

Teacher learning goal Participating teachers can:	**Training with CODEM for iSTEM**	**In-service sessions**
□ deepen their CK in familiar disciplines	CIL,CLS,RFS	s3-4
□ broaden their CK to less familiar disciplines	GDT,CIL,CLS,DLA	s2,3,4,5
□ exhibit confidence in problem solving	CBS,EPD	s3,5
□ formulate and mind student learning goals	GDT,GRS	s3
□ create activating learning activities	CLS,DLA,AAS	s3,4,f-up
□ build authentic links between STEM disciplines	BCT,CIL,CF	s2,3
□ rely on colleagues, debate constructively	CIL,REF,TPR	s6,f-up
□ get familiar with educational technology	RFS,EPD	s5

Table 4.11: Establishment of the important features of professional development (PD) by the proposed iSTEM training programs

PD feature	**Training with CODEM for iSTEM**	**In-service training sessions**
Strong rationale	Motive, vision, and student learning goals explained in introductory session	Bottom-up established motive (s1) Vision induced via exemplar learning units (s1) Student learning goals deduced from vision (via mind map) (s1)
Participation in curricular design	Identification of STEM learning contents and challenge (CIL,CF) Formulation of student goals (GRS), draft of learning activities (DLA)	Identification of STEM learning contents and challenge (s2) Formulation of learning goals, draft of learning activities (s3)
Content	Peer-to-peer tutoring of non-familiar concepts Research literature study (CLS) Self-study	Peer-to-peer tutoring of non-familiar concepts (s2) Research literature study Extra CK training (s5)
Examples	Small examples in each step Overview of existing research-based instructional strategies (DLA,AAS)	Exemplar learning units to help identify iSTEM features (s1) Peer classroom observations (s6)
Active authentic learning	Challenge formulation (CF) Research literature study (CLS) Experiment & prototype tryout Reflection on action questions in each step	Challenge formulation (s2) Research literature study Classroom tryout Justification of match between goals and activity (s4) Evaluation of classroom-tryout observations (s6)
Collaboration	Concept mapping (CIL) Peer-to-peer tutoring of non-familiar concepts STEM content alignment (CIL,DLA)	Concept mapping (s2) Peer-to-peer tutoring of non-familiar concepts (s2) STEM content alignment (s4) Peer feedback on classroom observations (s6)
Curriculum standards, student performance	Consultation of curricula (SCA,GDT) Focus on student learning goals (GRS) Iterative improvement	Consultation of curricula (s2) Focus on student goals (s2) Classroom observations (s6) Investigation of student results (follow-up)
Coordination	Quality control (phXCx) Team composition (TFD) Research literature (CLS) Equipment (EPD)	Exemplar learning units (s1) Team composition (s2) Research literature (s3) Debate mediation & focus (s3,4) Equipment & CK training (s5)
Time	Weekly gatherings in one semester + iteration after classroom tryout	Six sessions spread over one year + follow-up sessions

4.7 Conclusion

Student learning, the goal of education, is impacted via the teachers' classroom practices (e.g., Fishman et al., 2003; Darling-Hammond, 1998) by the teaching context (e.g., Krajcik et al., 1994), and by teachers' knowledge and attitude (e.g., Pintó, 2005; Roehrig et al., 2007), also in iSTEM education (Thibaut, Knipprath, et al., 2018b; Freeman et al., 2014). In turn, teachers' knowledge and attitude can be improved through teacher training (e.g., Thibaut, Knipprath, et al., 2018c), for example in the form of teacher design teams (TDTs) (Coenders & Terlouw, 2015; Binkhorst, 2017). This chapter focuses on participation in iSTEM TDTs as a form of teacher training for iSTEM education.

First, the influence of participation in iSTEM TDTs on teachers' knowledge and attitude was investigated through semi-structured teacher interviews. Reflections of TDTs who were successful in the design of iSTEM learning materials were compared with those of unsuccessful TDTs, and with those of teams who merely implemented the learning materials. Although bias could have occurred, some interesting findings emerged. First of all, this study corroborates the findings of Coenders et al. (2010) and Voogt et al. (2011) that participation in TDTs fosters teachers' sense of ownership over the vision behind the design (in attitude as well as in conceptualization). Successful iSTEM TDTs furthermore exhibit a climate of 'learning from colleagues of other STEM disciplines', urged by the design process. These teachers show excitement about the way participation in iSTEM TDTs challenges their subject-matter knowledge and skills and the manner in which they used to teach learning contents to students. These findings are in line with those of Bakkenes et al. (2010): collaboration leads to new ideas. Furthermore, teachers of successful TDTs reason a lot more and more deeply about instructional strategies, such as problem-centered teaching, student-activating inquiry and design, and student coaching, thus showing a higher level of PCK than teachers of the other teams. The latter teams mainly (although not exclusively) vent about the endeavors of prototype design and application. Deep reflections on teaching and learning were also noticed by Mooney Simmie (2007) as a result of participation in TDTs. Overall, teachers who successfully participate in iSTEM TDTs seem to be more meaning-directed, focus on teaching strategies to help students actively construct their own knowledge, and are involved in a community of experts, while unsuccessful and non-designers show more features of application-directed, individual learners (Henze, van Driel, & Verloop, 2009). The metacognition demonstrated by successful iSTEM TDTs shows monitoring of their own design and teaching process, which will result in a growth mindset, better self-regulation, improved transfer ability, and, therefore, in an increased problem-solving efficiency (Dominowski, 1998; Kelchtermans, 2001; Dweck et al., 2014).

The interviewed teachers were also asked which features of teacher knowledge, attitude, context, and training they considered to be important or desirable prerequisites for successful design and implementation of iSTEM education. Perseverance in problem solving, and willingness to collaborate and invest time appear to be important teacher assets for iSTEM education. In accordance with Thibaut, Knipprath, et al. (2018b), teachers indicate access to equipment and appraisal of their efforts by the school management as necessary features of their teaching context. For the design of iSTEM learning materials, teachers assert that multidisciplinary teams should be formed, who are granted common meeting time, and are supported with a vision that is established through a bottom-up approach, as was the case in STEM@school. According to the interviewed teachers, pre- and in-service training should include profound content instruction and some technical and engineering experiences to equip teachers with enough self-confidence to tackle the challenge of iSTEM design. Moreover, teacher training should incorporate strategies to coach students in problem solving and design. Other research has shown that teacher training should start from teachers' practical knowledge and beliefs, and should be grounded in curriculum standards (e.g., Van Driel et al., 2001; Desimone, 2009). Training sessions should be frequent and spread over a long period of time (Desimone, 2009). Coordinators should provide teachers with examples of good practice (e.g., Sunal et al., 2001). Furthermore, it should involve teachers in collaborative, authentic learning activities and reflection (e.g., Supovitz & Turner, 2000). Participation in TDTs is a form of teacher training that meets all of these requirements.

Based on these important features of teacher training for iSTEM education, this chapter proposed two training programs that involve participation in iSTEM TDTs, given its positive influence on teachers' knowledge and attitude. The two programs are complementary to a thorough training on disciplinary content knowledge. One program makes use of the online platform CODEM for iSTEM, which is elaborated in Section 3.4.1 of Chapter 3. The other program consists of six sessions and some follow-up sessions for in-service training. The training programs scaffold the participants' design process with evidence-based strategies and foster their reflection about iSTEM education in terms of learning goals and motivating challenges, while they collaborate in multidisciplinary teams throughout an entire school year. Each program immerses the participants in the scientific inquiry and engineering experiences they design for their students. The participants are encouraged to try out the designed activities in the classroom, and to observe and reflect on the effect these activities have on their students' knowledge and attitude. Meanwhile, the participants acquire a profound, common understanding of the rationale, principles, and objectives of iSTEM education, inquiry and problem-solving skills, a broader and deeper CK and PCK, collaboration skills, and metacognitive thinking skills.

Chapter 5

Conclusion

5.1 Problem statement

To tackle the societal and ecological issues of tomorrow, and to establish a competitive position as a knowledge economy that is fostered by technological innovation and scientific research, Europe requires manpower with broad and deep literacy and skills in STEM (Science, Technology, Engineering, and Mathematics) (EU STEM Coalition, 2016). STEM study tracks are a quite popular choice among students in secondary education. However, by the time these students enroll for higher education, many opt out of them (Vlaamse Overheid, 2015b). This dropout aggravates the labor market's growing need for highly-qualified STEM workforce even more. Research on student attitudes towards STEM subjects and careers suggests that students' interest in STEM diminishes along with their years in secondary school (Sadler et al., 2012; Van den Berghe & De Martelaere, 2012; Archer et al., 2013). These findings also reveal that students are not excited about school science and they are not inspired by how it is being taught (Sjøberg & Schreiner, 2010; De Meyer et al., 2016). A possible reason for students' lack of interest is the rather compartmentalized way in which the mathematical, scientific, and technological courses are being taught (Wandersee & Clary, 2006). This consideration calls for an integrative approach to STEM education, in which students get to explore and exploit the many links between discipline-specific concepts in meaningful applications (Sanders, 2000). Previous research studies have established that, where such an approach is applied, students demonstrate a satisfactory ability to apply integrated STEM concepts, enhanced higher-order reasoning skills, improved social skills, a higher self-efficacy in science and motivation for learning,

and an increased interest in and pursuit of STEM studies and careers (e.g., Becker & Park, 2011; Thibaut, Knipprath, et al., 2018a; Gerber et al., 2001; Hänze & Berger, 2007; Apedoe et al., 2008; Kutch, 2011).

Studies on the implementation of iSTEM education are growing in number (e.g., O'Neill et al., 2012; Hanesian et al., 2003; Hernandez et al., 2014; Shernoff et al., 2017; English, King, & Smeed, 2017; Dare et al., 2018). The number of reports on the design of iSTEM education by means of multidisciplinary teacher teams is, however, still limited (James et al., 2000; Satchwell & Loepp, 2002; Berland, 2013; Walshe, Johnston, McClelland, et al., 2014; Guzey, Moore, & Harwell, 2016) and some important questions remain: What should integrated STEM education consist of, and which aspects should be considered by teacher teams during its design? How do teachers enhance their knowledge and attitude through participation in iSTEM design teams? The work presented here aimed at contributing to this underexplored area of research by examining the principles, process, and learning opportunities of designing learning materials for integrated STEM education.

5.2 Contributions of this work

The research presented in this work was conducted in the scope of STEM@school, a program that aimed at designing and implementing an abstract, integrative approach to STEM education to show students the relevance of STEM subject matter and to increase their interest in STEM, while maintaining a high student achievement in terms of knowledge and skills. With the support of STEM@school researchers, several teacher design teams engaged in designing learning materials that were grounded in the curriculum standards of the separate STEM courses and that covered a whole semester of grade 9, 10, or 11 in secondary education.

With respect to the growing lack of technical workforce, the Royal Flemish Academy of Belgium for Science and Arts (KVAB) formulated some recommendations that should specifically empower teachers in STEM education (Veretennicoff et al., 2015). Table 5.1 shows how the chapters of this work contribute to establishing the KVAB's recommendations. This work extracted design principles for iSTEM education through an extensive research review. A tool was developed to support teacher teams in their design of iSTEM learning materials, based on a case study of four teacher design teams. This work furthermore identified how participation in such teams encourages teacher learning for iSTEM education.

Table 5.1: The KVAB's recommendations for assisting teachers in STEM education
and this work's contribution

	KVAB's recommendation	This work's contribution
(1)	STEM education should connect to the values, interests and everyday life of pupils. New content should be addressed from within a tangible context. STEM education has to show the relations to their own lives, challenges the world faces, human values, ethical choices and other domains.	search for authentic themes and real-world student challenges, as demonstrated in Chapter 3
(2)	STEM education should strive for a better integration of the four STEM components (Science, Technology, Engineering and Mathematics), with respect for their own, separate value.	an integrated, problem-centered, inquiry- and design-based approach to STEM education inspired by discipline-specific research on conceptual learning, cocreated by teacher teams, as elaborated in Chapter 2 and illustrated in Chapter 3
(3)	STEM education should allow pupils to experience the creative processes inherent to STEM: reasoning, inquiry, design, problem solving. These processes shed light on the various facets of STEM and can be beneficial to the social image of STEM studies and professions.	
(4)	All actors in the educational landscape should prepare for a reconceptualization of education within the STEM disciplines. Course-specific educational research should be encouraged and expanded.	
(5)	Upgrading the status of teacher should be prioritized, by acknowledgement of the professionalism and adaptation of the career path.	(beyond the scope of this work)
(6)	Schools should be encouraged to establish a STEM department, consisting of a cross-disciplinary team of STEM teachers and external professionals who shape a profound learning trajectory by structural cross-disciplinary debate.	tools to empower STEM teacher teams to design iSTEM education in Chapter 3, and prerequisites for their teaching context in Chapter 4
(7)	Teachers should be invited to lifelong learning. To this end, time, as well as opportunities for professionali- zation should be provided.	approach and program to foster teacher learning for iSTEM education proposed in Chapter 4
(8)	At university level, a master of STEM education should be introduced.	
(9)	A center for STEM education should be established, gathering and developing expertise. It should be easily accessible.	(beyond the scope of this work)

Design principles and requirements for high-quality iSTEM education

This work set the scene for the design of iSTEM learning materials. Chapter 1 shed light on the competences students should have at their disposal to become the versatile, creative, and communicative STEM workers the labor market is counting on. These desired competences inspired the formulation of learning goals students should achieve by engaging in iSTEM education. Students should be able to integrate discipline-specific STEM concepts and apply them in a crossdisciplinary manner in order to solve a real-world problem. Furthermore, they should be able to set up and carry out an inquiry or prototype design in order to provide an answer to a certain problem or question. In doing so, they construct and use abstract models of scientific phenomena or technical systems. iSTEM students learn to take ownership over their own learning process through active project management and cooperative participation in teams. As such, they gradually assume a more positive attitude towards STEM subjects.

These learning goals were envisaged when extracting the key principles behind iSTEM education from the existing literature. These key principles are: (1) integration of STEM learning contents, (2) problem-centered learning, (3) inquiry- and design-based learning, (4) self-regulated and cooperative learning, and (5) conceptual learning. In turn, these key principles were translated into design guidelines. The learning materials should be constructed around an engaging and authentic student challenge that entails a design or inquiry question or task. The challenge ideally consists of several subproblems of an increasing complexity that are to be solved by means of one or more learning activities. In these learning activities, students acquire the solution to a subproblem by setting up and conducting experiments and designs, in which they make crossdisciplinary connections between STEM concepts by means of abstract modeling. The learning activities are accompanied by activating instructional strategies that encompass cooperation in teams, formative evaluation and reflection, and that take into account suggestions from research on student learning in the separate disciplines. All of these principles were merged into a checklist of requirements on learning materials for high-quality iSTEM education.

An evidence-based support tool for teacher teams to design iSTEM learning materials: CODEM for iSTEM

A new approach to STEM education implies that new curricular materials need to be designed, tailored to the teachers' contexts. To examine which activities constitute such design, the design process of four multidisciplinary teams of STEM teachers was examined in depth via case-study research. These teams participated in the exploration and enactment phase of STEM@school and

were supported by STEM@school researchers who took up the role of team coordinators. Five phases were distinguished in the observed design processes: (1) a context analysis phase, (2) a theme selection phase, (3) a brainstorm phase, (4) a reporting phase, and (5) a development phase. In each of these phases, several steps could be distinguished. These steps were analyzed against the compliance of the designed learning materials with the requirements of high-quality iSTEM education. Important steps appeared to be the formulation of a challenge, the breakdown of this challenge into subproblems, the identification and linking of STEM contents, the design of STEM-linking learning activities, and the exchange of feedback. Some pitfalls were identified as well: no learning goals or instructional strategies were defined, and there is a risk of dealing with the challenge merely from a discipline-specific perspective, without making links to the other STEM disciplines.

This work revealed that teachers tend to produce and gather a lot of information, but often refrain from developing purposeful strategies to convey this information, as they forget to think in terms of the goals they want their students to achieve. However, in general, teacher design teams manage to debate and think on a crossdisciplinary level, and actively look for meaningful mutual connections within the context of the formulated challenge. However, in this linking of learning contents and construction of learning activities, there is still room for improvement, and, therefore, a support model seems appropriate.

The model 'CODEM for iSTEM' was created with the aim to support multidisciplinary teams of STEM teachers in their efforts to design iSTEM learning materials. CODEM for iSTEM stands for Collaboratively Organized Design of Educational Materials for integrated STEM. It is conceived as a flowchart which includes the important steps established via the case study, as well as conditions to avert the possible pitfalls. Iteration is built in to ensure that learning contents and challenge are aligned. In each step, a certain output must be produced, which forms the input of subsequent steps. A comprehensive description of important actions in the step, and scaffolding questions guide the teacher teams towards this output. The description contains the actions observed in the case study, supplemented by recommendations from the literature on instructional models. The conditions in between certain steps call for the team members and the team coordinator to check the quality of intermediately produced outputs against the requirements for high-quality iSTEM education. As such, CODEM for iSTEM helps teachers to focus their thinking on what really matters: establishing iSTEM learning goals among their students.

CODEM for iSTEM was also transformed into a digital version: Collaborative Online Design of Educational Materials for iSTEM. The tool allows the team members to consult the information that is relevant to them at their stage of the design process. The team members and coordinator can exchange information

and questions via a discussion forum of the step at hand. The tool only allows the team members to advance in team, as to ensure the crossdisciplinary collaboration. The built-in conditions stimulate the team members to reflect on their work. As such, CODEM for iSTEM provides a tool that is immediately employable in pre-service teacher training and that could be implemented in cross-school and international professional learning communities.

In-depth insights into the opportunities of iSTEM teacher design teams for teacher learning + two formats for teacher training

This work examined the learning gains experienced by teachers who participated in iSTEM teacher design teams. Teacher learning in the scope of curricular reform is expressed in a change in teachers' knowledge, beliefs, and behavior, which in turn becomes obvious in their classroom practices. In teacher training for iSTEM education, the goal is to foster classroom practices that are more congruent with the key principles behind iSTEM education. As a promising trigger for change in teachers' classroom practices, teacher learning for iSTEM education through participation in iSTEM design teams (iSTEM TDTs) was investigated in this work. Via team and individual interviews, teachers were queried on their experiences and perception of own professional growth through their participation in iSTEM TDTs in the scope of designing STEM@school learning materials.

This work found that participation in successful iSTEM TDTs enables teachers to establish a community of experts who learn crossdisciplinary contents via colleagues. Teachers in successful design teams take ownership over the key principles behind iSTEM education. They exhibit deeper reflections on instructional strategies than their peers in other teacher teams, adopt more student-activating approaches, and seem to be less restrained by practical (technical) concerns. Teachers in iSTEM TDTs experience the design of iSTEM education as *the* way to reconcile curriculum coverage with highly motivating student activities. The testimonies of teachers from successful iSTEM TDTs suggest a broadening and deepening of their content knowledge, an expansion of their pedagogical content knowledge, and an improvement of their metacognitive skills and self-efficacy. These learning gains endorse coordinated participation in iSTEM TDTs as an effective form of pre- and in-service teacher training. Therefore, this work proposes two formats that involve this concept: one program involves the use of the online tool CODEM for iSTEM, the other program consists of six sessions plus follow-up sessions spread over at least one school year. The programs stimulate crossdisciplinary dialogue rooted in the iSTEM key principles and STEM curriculum standards. In both programs, teacher learning is supported by team coordinators, who provide the participants

with frequent and ongoing feedback and opportunities to reflect. The proposed training programs immerse teachers in the authentic problem-centered, inquiry- and design-based learning they want their own students to experience. As such, the programs involve the essential features of effective teacher training (Ingvarson et al., 2005; Garet et al., 2001; Desimone, 2009) and are aimed at strengthening the promising learning outcomes found in the teacher interviews.

In short, based on evidence gathered through four years of research on teachers' design of iSTEM learning materials, this work has constructed a scaffolding tool that empowers teacher teams to design learning materials for high-quality iSTEM education: CODEM for iSTEM. This tool provides comprehensive explanations, authentic learning opportunities, real examples, reflective questions, opportunities for exchange of expertise and feedback, and quality checks. As such, CODEM for iSTEM is readily employable for blended learning in pre-service teacher training or professional learning communities, or as a supportive guideline for professional development programs. This work has also established that teachers who participate in iSTEM TDTs cross the boundaries of their disciplinary knowledge while learning from their colleagues, expand their repertoire of instructional strategies, and demonstrate metacognitive reflection that shows ownership over the key principles behind iSTEM education. As such, this work has brought research one step closer towards a better understanding of the opportunities, needs, and constraints of teacher design teams shaping their own, high-quality, integrated STEM education.

5.3 Limitations and future research

The findings produced by this work can also be considered an incentive for further research. They give rise to new questions and possible tracks of inquiry, which are discussed in this final section.

Up until now, CODEM for iSTEM still has the form of a prototype. That is, it exists in a working version that has been tested as such in teacher training programs, but its functions could be exploited more, and it could be upgraded to a more dynamic instrument. The tool can be improved in terms of assessment, in terms of shape, and in terms of support. The layer under the user interface of the online tool allows to gather a lot of information about the team members' activities, such as team composition, time spent on a certain step, consultation of previous steps, messages exchanged on the discussion forum, and redirections to previous steps at quality controls by the team coordinator. In a more advanced version of CODEM for iSTEM, the working documents of a team could be

integrated in the website. As such, the team members' alternation between the information of the tool and the relevant documents could be recorded as well. Analyses of these data could provide valuable information on the amount of time that is required per step, and could indicate which steps raise a lot of questions or are frequently revisited by the users. These analyses can inform teacher teams on success factors and pitfalls. Appendix I shows what such analyses could look like. Furthermore, more modern media could be integrated in the online tool, such as e.g., video tutorials, or interactive polls or exercises that elicit reflective team debates. Each time the team arrives at a condition (quality check) that queries whether or not a requirement for high-quality iSTEM education is met, a rubric should pop up, that prompts the team to evaluate its own work on a descriptive scale for the requirement at hand. Also the team coordinator is asked to evaluate the team on this scale and provide feedback. The comparison of both evaluations can form the basis for a reflective team discussion. Finally, CODEM for iSTEM should be updated with new developments in STEM and in science and technology education. Finally, CODEM for iSTEM must be further validated and refined by implementation in school contexts and among teacher teams who want to design or optimize their assortment of iSTEM learning units.

The teacher interviews in this work produced an in-depth, but small-scale image of the learning gains resulting from participation in iSTEM teacher design teams. Moreover, no pre-design interviews were taken, and the findings are partly based on teachers' self-reported growth in knowledge or attitude. It would therefore be interesting to check and extend the tentative findings from this study and the proposed training programs in a more controlled environment. Future studies could thus expand the line of research of this work by implementing more ways to assess teacher learning as a result of participation in iSTEM teacher design teams. Ideally, the research setup should appoint an experimental team (the iSTEM teacher design team) and a comparison team for the study, both with a very similar composition in terms of STEM expertise, education, age, gender, school, ... Three types of assessment instruments should be designed for data collection: a test on knowledge and (integrated) application of basic STEM concepts (K_T), a questionnaire or survey on attitude towards (i)STEM (A_T), and an interview guideline on self-concept (i.e., own perception of knowledge and attitude) and on own instructional practices in (i)STEM (I_T), much like the one implemented in this work. Once these instruments are developed and validated, they can be implemented at several moments in the research program, as shown in Figure 5.1. It is important to use the same instruments at the different stages and across both teams, in order to be able to compare the results and make statements about the learning gains of the teachers involved in the study. As an important goal of teacher learning for iSTEM education is to improve student understanding in and motivation for STEM subjects, a similar test and survey should be developed at student level (K_S and A_S) to gauge

this improvement. These should be administered among the students of both teacher teams. During the design phase and the implementation phase, the teachers' practices should furthermore be observed to ensure that the intended program is executed with a high fidelity. These observations can also be used to verify teachers' reflections during the post-implementation interviews (I_T). The results of the initial assessments should be controlled for, when comparing the results of the final assessments. The test and survey results would enable quantifying and defining the areas in which teachers of iSTEM design teams and their students outperform those of the comparison team. As such, these results enrich the findings on the teacher reflections about instructional strategies and personal growth. With the research setup of Figure 5.1, also the formats for teacher training, proposed in this work, can easily be tested and revised.

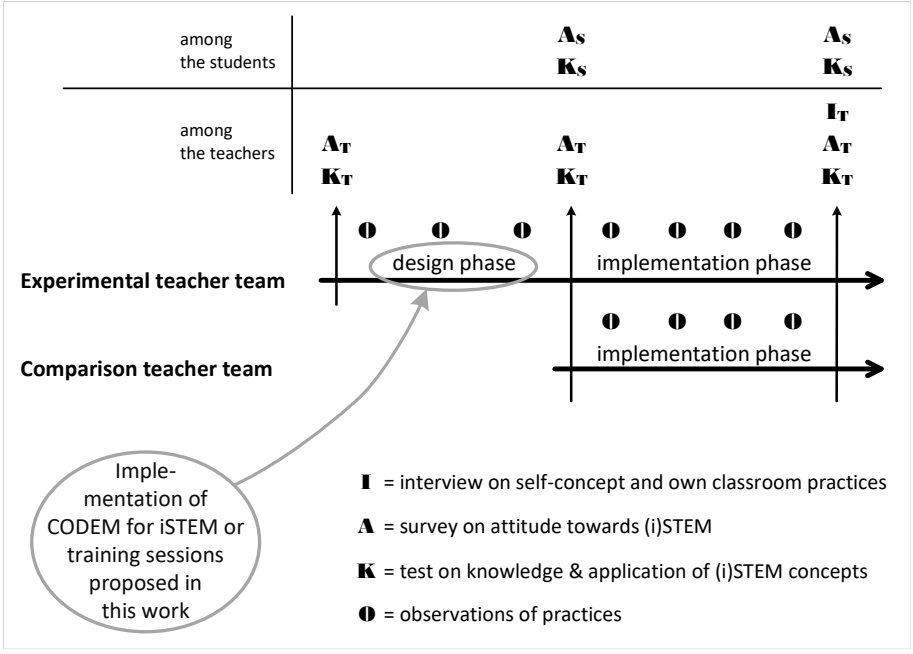


Figure 5.1: Possible future research setup to study teacher and student learning as a result of teachers' participation in iSTEM teacher design teams

The effects of long-term implementation and renovation of the materials designed in STEM@school would also provide interesting matter for inquiry. How do teachers' classroom practices evolve and what are the eventual study and career choices of their students? Which ideas brought upon the teachers and students

by STEM@school are lasting? Does participation in iSTEM teacher design teams equip teachers with durable skills? Are these skills visible in a regular update of the learning-unit assortment? Is an improvement in student understanding and attitude palpable at university level? Are students better prepared for STEM studies, with a higher attrition as result? Does the labor market experience a boost in generic skills among STEM graduates? A sustainable incorporation of the key principles in the design and implementation of iSTEM education is crucial. In this respect, the work presented here emphasizes the importance of teacher coordination and support. The government should take up a leading role in offering that support. To prevent iSTEM education from fading out, the government must provide resources and agencies that leverage current efforts in the pursuit of more and better qualified STEM workers.

Finally, STEM education faces challenges posed by student groups other than the ones targeted with the design of this work. Think tanks should be organized on how to integrate contents from the different STEM disciplines for students of grades 7 and 8, or even younger students. The constraints of such design lie in the small conceptual knowledge base these students can draw upon, and their limited capacity to handle the complexity of real-world problems. Another exercise that should be made, is on how to design iSTEM education for students of study tracks other than 'Sciences' and 'Industrial sciences'. Other study tracks are often more specialized in a certain domain (e.g., sports, social sciences, carpentry, pharmacy). Design teams will have to search for an engaging student challenge that accentuates key concepts and practices of that domain, and that operationalizes the needed concepts of the (other) STEM disciplines in a transdisciplinary and hands-on approach in view of that challenge (Basham, Israel, & Maynard, 2010). The challenge should be particularly relevant to the real-world issues and careers associated with these students' main study domain. The abstraction level and hands-on skills required in the challenge must be tailored to the cognitive and practical demands of their study track. Apart from adjusting these parameters, the steps to design learning materials for these target groups are not expected to differ much from the ones in the model provided by this work. It will be interesting to see how the actions and questions contained within those steps will be given shape by future iSTEM teacher design teams.

Appendix A

iSTEM initiatives and programs

Without the intention of giving an exhaustive overview of all existing initiatives, this appendix sheds light on some of the programs that focus on iSTEM, and to which this work has contributed. These programs offer readily-available learning materials for various teacher needs, going from a science-technology project day to short hands-on, inquiry-based modules for a few hours during a few weeks.

Junior College STEM

Junior College (`https://www.kuleuven.be/onderwijs/juniorcollege`) is an initiative of KU Leuven to bring math and science to a higher level for students of grades 11 and 12. Junior College offers teachers in higher secondary education a variety of learning units on mathematics, physics, life science, but also on computer science, astronomy, and earth science. The learning units are meant to be implemented within the students' regular timetable (not interfering with the usual lesson plan), for example during two class periods of Math or Science per week. The learning units incorporate recent academic-scientific developments within the relevant STEM disciplines. By challenging and inspiring students for STEM, Junior College bridges the gap between secondary education and university and creates an awareness of the cognitive demands and practices involved in higher STEM education.

This work contributed to Junior College STEM by means of the design of the learning unit 'Cochlear Implants'. In this learning unit, students get acquainted with the mathematical equivalent of a sound wave and the Fourier analysis happening in their ears. A malfunctioning cochlea can be the cause of impaired

hearing. A cochlea normally makes Fourier transformations of the incoming sound waves. A cochlear implant (CI) is specifically developed to take over this function. The learning unit decomposes this ingenious technological device into its subsystems, and the students study the different processes going on in these subsystems. They learn to represent the sound signals and processes of the CI subsystems into block diagrams, and as such simulate the functioning of a cochlear implant through software, using their newly acquired mathematical-scientific insights (De Meester et al., 2013), as shown in Figure A.1.

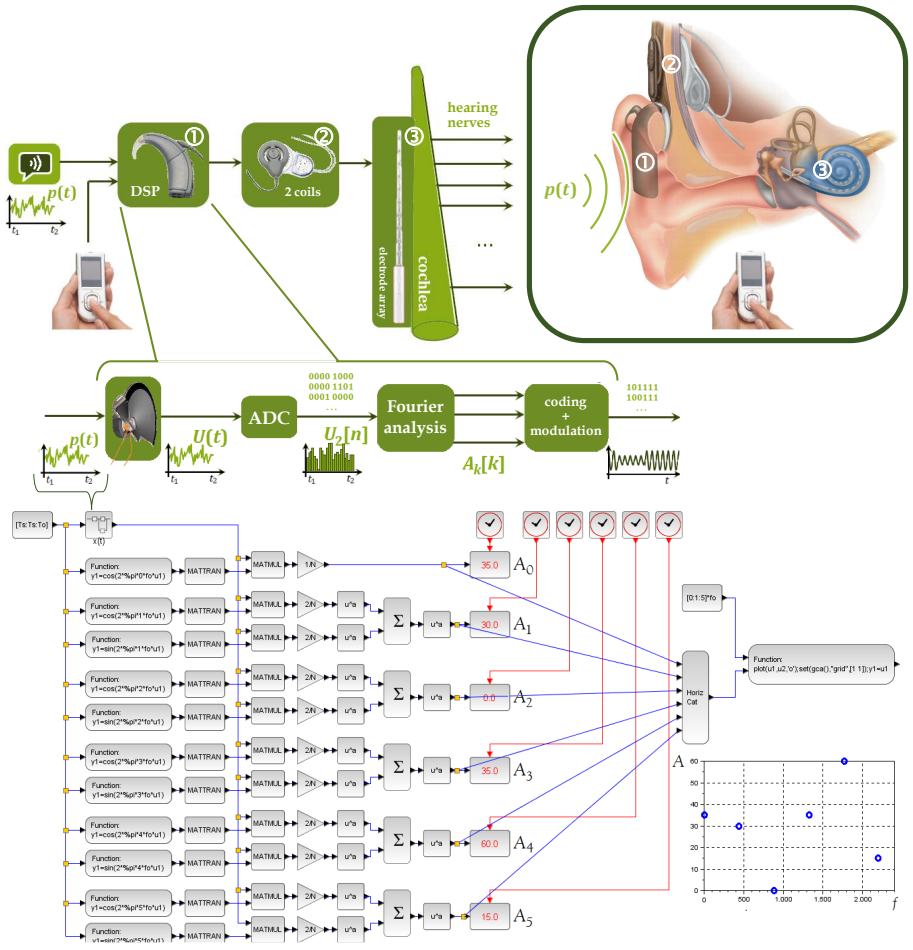


Figure A.1: The block diagram of a cochlear implant and students' simulation of its Fourier analysis in Junior College

RVO society

RVO society (`https://www.rvo-society.be/`) wants to enthuse students in elementary and secondary school for science and technology. RVO society provides completely-developed classroom activities and learning units, material kits, and workshops on the learning units for in-service teachers, but also extracurricular activities for students, such as STEM academies. This initiative bridges the gap between research and education by translating state-of-the art innovations and knowledge into educational activities, as such demonstrating the relevance of the different STEM disciplines. The educational activities aim at increasing students' technical literacy and interest in STEM by emphasizing the contribution of technology to solutions for climate change and applications in health care. The activities are rooted in the personal interests of students and learning is initiated through experience.

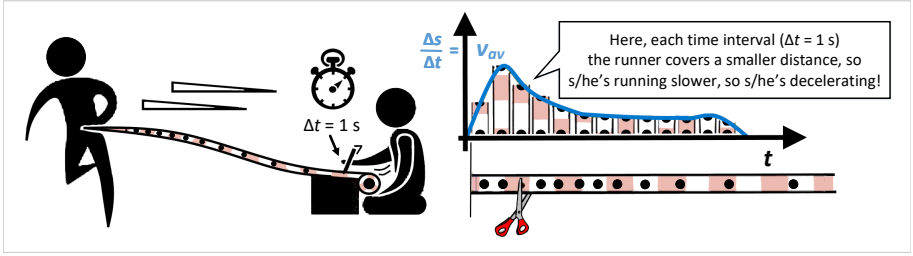


Figure A.2: Learning activity developed by RVO society (Vanden Bosch, 2008): a student runs, unrolling a tape while, every second, another student puts a dot on the unrolling tape (*left*), by cutting the tape on the dots and placing the tape strips next to one another, the graph of average velocity as a function of time is reconstructed (*right*).

For secondary education, RVO society developed learning units in which students learn to program a Lego train (Dehaene, Decuyper, & Goddé, 2013) or a small car through graphical programming, engage in biological inquiry to measure the quality of the air (Planet Watch), build and control a drone (Drone-Age), or measure the effect of trees on microclimates by means of sensors (Bos Online). In another project of RVO society, science and technology students cooperate with students in health care to design a solution to a need from health-care institutions. With these and many other developed units, RVO society offers interesting learning activities that cut across the different STEM disciplines.

Innovation Lab

Innovation Lab (`https://eng.kuleuven.be/innovationlab`) has developed complete learning units for secondary-school teachers who want to implement a STEM project day. This initiative offers workshops on the developed learning units for in-service teachers, and rents out complete material kits. Innovation lab aims at students of grades 9 to 12 with a predisposition for science and/or engineering. During their participation in such a project day, students engage in experiments, inquiries, and hands-on activities using their mathematical and scientific school knowledge.

In the learning units developed by Innovation Lab, students build their own battery and fuel cell, engage in materials science when they build their own composite catapult, program a robot to play poker, or filter pond water in biochemical labs. In one learning unit, students build, program, and simulate an eye-controlled wheel chair. They learn how eye movement can be translated into electric signals that can be measured by means of sensors, as illustrated in Figure A.3. Students also engage in cryptography to secure their program code.

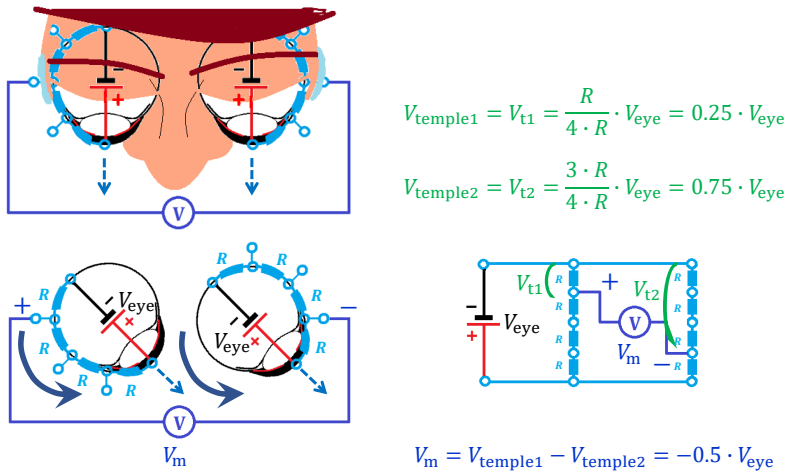


Figure A.3: Representation of the eyes' biopotential: There is a biopotential (voltage difference) between the front and the back of the eye balls. Two electrodes placed at the temples give a readout voltage that is different from zero when the eyes turn. In Innovation Lab, students learn to model this bio-electric phenomenon by means of an electric circuit, in which the eye balls are represented by a constant voltage source.

Appendix B

Qualitative research methods used in this work

Design-based research

Design-based research is an appropriate research methodology to study processes that:

- reflect a real-world practice (Barab & Squire, 2004);
- involve human interactions, and multiple people who bring in different expertise (Barab & Squire, 2004);
- involve multiple, mutually-dependent variables: participants, collaboration and distraction, means, outcome, sustainability (Barab & Squire, 2004);
- involve intensive collaboration between researchers and practitioners towards a product that can immediately be implemented in practice (Reeves et al., 2005);
- involve a revision of a learning environment through iteration and reflection (Reeves et al., 2005);
- integrate known, as well as hypothetical design principles (Reeves et al., 2005);
- might result in developmental principles that can be employed in future work (Reeves et al., 2005).

Case study research

Case study is an appropriate research method for studies in situations to which the following statements apply.

- The process investigated through case-study research typically takes place in a real-world context (Kitchenham et al., 1995) and involves "a contemporary set of events over which a researcher has little or no control" (Yin, 2013). A case study does not try to detect *how often* but rather *why* some events occurred (Balbach, 1999). In this type of research, often *how?* and *why?* questions are posed, for example, about "the specific application of initiatives or innovations to improve or enhance learning and teaching", in order to learn something about such interventions (Case & Light, 2011).
- The aim of the research is to identify important patterns and themes in the process under study (Stake, 1995).
- The boundaries between the process under study and the context cannot be clearly distinguished (Yin, 2013). However, the results of case-study research do not have to be widely generalizable to every environment. Of interest is the usefulness of the outcomes for the particular environment in which this research has been carried out. Hence, the results are context-dependent and should be interpreted as such (Kitchenham et al., 1995; Balbach, 1999; Case & Light, 2011).
- Case-study research does not expect the process under study to run a predictable and measurable course (Balbach, 1999).
- The process under study does not happen under controlled experimental conditions: it is impossible to control all but one independent variable to detect its effect on one or more dependent variables (Kitchenham et al., 1995).
- The effects of the process under study cannot immediately be identified, and they cannot be attributed to one single cause, since they are often the result of multiple small changes throughout the process (Kitchenham et al., 1995). On the other hand, unexpected impacts can occur that would not be picked up by other types of research, but might be worth considering. Case-study research provides a way to observe and interpret what actually happens, in order to get insight in possible links between the process and the outcome (Balbach, 1999).

In case-study research, the sampling of the cases should be purposive and should yield a lot of information (Mortelmans, 2007; Baxter & Jack, 2008). The decision of which and how many cases will be studied, depends on the researcher's ability to generate enough properties of the emerging activities (or steps) to clearly define, and interrelate them. This implies that the selection and number of

cases is not preplanned, and during the study, more cases can be added to the investigation (Mortelmans, 2007; Charmaz, 2008). In the selection, exclusion, and retention of cases, caution should be paid for case contamination. This occurs when variables that might explain a certain phenomenon under study are being eliminated by the case selection (Mortelmans, 2007). Therefore, cases may not be too similar or related to one another. To enable identifying but also exploring the emerging steps in the process under study, the sampling criteria should control for variables that are known or expected to affect the process, but they should also allow variation on these influential variables (Mortelmans, 2007; Kitchenham et al., 1995).

Grounded theory

In Grounded Theory, a theory emerges bottom-up from the data (Case & Light, 2011). Through different stages of coding, categories are developed and refined through constant comparison of the codes and testing the occurring events against the properties of the categories. During the analysis, additional research subjects can be selected, and extra data and sources of evidence can be gathered to explore the (variation in) properties of each category and to interrelate categories until there is theoretical saturation, i.e., until the point where additional data collection and analysis does not substantially change the findings anymore (Mortelmans, 2007; Case & Light, 2011).

Table B.1: Characteristics of case-study and grounded-theory research, based on Creswell et al. (2007)

	Case-study research	**Grounded theory**
Type of problem	a problem that can be informed by events that are context-bound	a problem or issue for which no theory exists or existing theories are inadequate
Subject under study	a program, activity, series of events, one or more individuals	a process, action or interaction involving many individuals
Type of research question	*How is <the problem> being tackled?*	*Which theory/model can explain the effects of <the issue>?* *Which theory/model best represents <the issue>?*

Table B.1 – continued

	Case-study research	**Grounded theory**
Features	detailed descriptions of occurring actions in each case to build an in-depth contextual understanding of the situational conditions (Yin, 2013)	theory construction based on data on people's actions, interactions, and social processes, collected in the field
Data	- documents - meeting reports - direct observations - interviews - participant observations - physical artifacts	- direct observations - interviews
Data analysis strategies	- direct interpretation - categorical aggregation - detailed descriptions of the case-specific or cross-case events (Stake, 1995; Yin, 2013)	- open coding (segment labeling) - focused coding (category development) - axial coding (category interconnection & refinement) - memoing - theoretical sampling - theoretical saturation (Charmaz, 2008; Saldaña, 2009; Hahn, 2008; Case & Light, 2011)
Result	the lessons learned from the case study; applied generalizations of how the initial problem could be solved, to facilitate training for this issue	a theoretical, visual model or diagram that explains the process, indicating causes, strategies, contextual and intervening conditions and consequences, shaped by the researcher's and participants' views, (inter)actions, values and beliefs

Appendix C

Transfer of concepts across contexts

Figure C.1 shows two problems in two different contexts, both of which require a solution that relies on an thorough understanding of the concept 'resistance'.

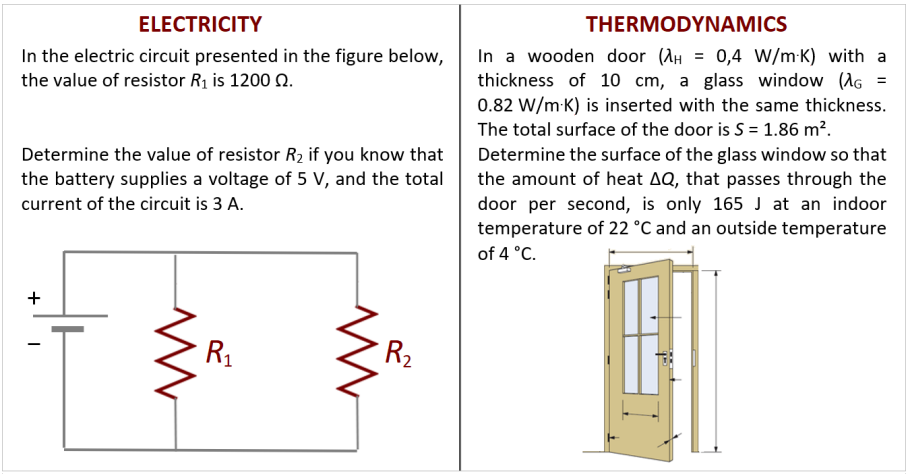


Figure C.1: Example of two analogous problems:
one in the context of electricity, one in the context of thermodynamics.
Transfer triggers the application of context-bound knowledge of parallel resistor configuration, the formula for equivalent resistance, and Ohm's / Fourier's law when solving the problem in the other context (De Meester et al., 2018).

Appendix D

Description of the actions within each observed step

(Process starts with a big group of STEM teachers who are enthusiastic to co-develop)

TGI

- deciding for which target group (of students) to develop

SCA

- analysis of the context of the target group,
- more specifically: analysis of the curricula of the STEM courses (Science (or more specifically Physics, Chemistry, Biology), Technology (or Applied sciences), Engineering, Math):
  - prior knowledge of the target group
  - standards the target group must achieve
- extracting contents the target group must learn, from the curriculum standards
- discussing these learning contents

BCT

- grouping/categorization of learning contents to identify overarching themes

- identifying/choosing overarching themes
- choosing a sequence in which the themes will be scheduled in students' school year based upon logic succession of learning contents

TFD

- splitting up the big group of enthusiasts into "smaller" multidisciplinary teams
- allocating the chosen themes to the formed teams

(Big group of STEM teachers is now split up into teams of about eight teachers from different STEM disciplines)

CIL

- listing the learning contents, relevant to the theme per discipline (S, T, E, M),
- searching crossdisciplinary links between these contents,
- (if iterated) adding learning contents, necessary to solve the challenge, to the list

SFD

- dividing the relevant discipline-specific learning contents
- splitting up the team of teachers into small, monodisciplinary subteams

CF

- searching for a challenge
  - that is fun for the students
  - that includes design or inquiry
  - that is more or less authentic / situated in a real-world context

RFS

- identifying the constraints of the chosen challenge,
- checking these constraints for enough room for student creativity, for open-endedness
- consulting experts in the field of the chosen theme
- checking the practical feasibility of the formulated challenge

CBS

- identifying the different subproblems contained within the challenge

DLA

- borrowing existing / creating new learning activities in view of the challenge;
  - that involve learning contents from different STEM disciplines
  - in which students are actively engaged
- crossdisciplinary collaboration between team members

EPD

- designing a prototype, or
- trying out experiments related to the challenge
- ordering components / equipment
- keeping documentation: codes, drawings, experiment results

REF

- presenting intermediary ideas and design activities to other teams (of the big group)
- listening/being updated about the other teams' ideas and activities
- giving feedback on the other teams' ideas and activities
- documenting feedback from the other teams on own ideas and activities

TPR

- revising the initial scheduling of the themes (i.e. verifying if the learning contents are addressed in a logic sequence in the scheduling of the themes)
- in case of doubts about the sequence: balancing pros and contras for switching
- deciding upon the final scheduling of the themes

SW

- writing the scenario for solving the challenge, based on the identified subproblems
- including scaffolding questions

  - that successively introduce students to a new subproblem,
  - that recapitulate what students (should) have learned when solving that subproblem and reconnecting what students (should) have learned to the challenge
- identifying gaps among the outlined learning activities and communicating them to the team members

SF

- elaborating the outlined learning activities, taking into account the feedback from the other teams
- gathering information based on the notes and information gathered during the experiment tryout and prototype design

MB

- bundling of the script and the syllabi

SRF

- reviewing syllabus by all team members
- refinement based on the feedback of the team members

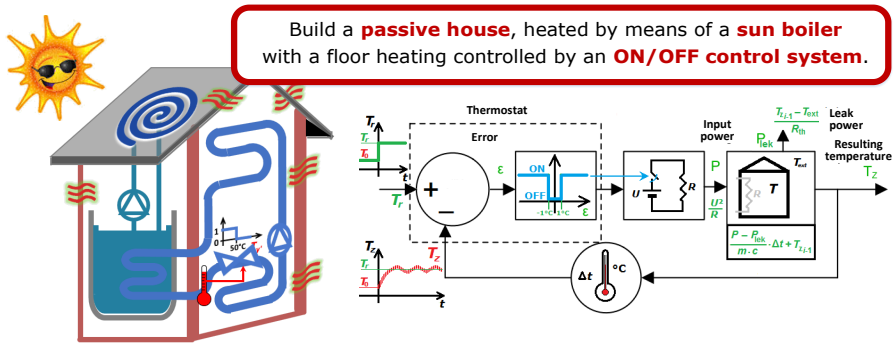


Figure D.1: Challenge formulated in step 'CF' by a STEM@school team within the theme 'thermodynamics' (see Goovaerts, De Cock, et al. (2018))

Appendix E

Standards from S, T, M curricula that could be connected

Collaborative investigation of the separate STEM curricula can yield a list of discipline-specific standards that can be linked via a real-world theme. In a learning unit on water treatment, for example, students could examine the photosynthesis of algae, a phenomenon that requires some chemical as well as biological insights on cell respiration. To investigate the concentration of certain specimens, the students could build a spectrophotometer, which requires some knowledge of atomic energy levels and conductivity, but also of electronic design. The exponential increase of the measured concentration can be studied via mathematical models. The standards from the separate STEM curricula that are associated with these learning contents are shown in Box E.1.

Box E.1 Example of curriculum standards associated with the theme 'water treatment')

Physics (VVKSO, 2014c; GO!, 2014c):
Students can:

- ☐ explain the origin of electric current as a consequence of voltage by means of an atomic model
- ☐ indicate the difference between conductors and insulators
- ☐ describe the energy and impact of a photon
- ☐ relate the phenomena 'emission' and 'absorption' to Bohr's atomic model
- ☐ identify the interaction between science and society in the field of ecology and technology

Chemistry and **Applied chemistry** (VVKSO, 2014b; GO!, 2014b; KathOndVla, 2017; Gemeenschapsonderwijs, 2006b):
Students can:

- ☐ use chemical products responsibly and safely
- ☐ explain how an atom can absorb and dissipate energy by means of the quantitative nature of the energy levels of their electrons
- ☐ describe the concept of a covalent bond between two atoms
- ☐ calculate concentrations and dilutions, and determine the relation between mole, mass, and volume percentage
- ☐ describe the concept of dynamic chemical equilibrium
- ☐ investigate experimentally and explain the influence of factors like division, temperature, catalyst, concentration on chemical equilibrium
- ☐ explain the acidic-basic behavior of salts in water
- ☐ define pH as -log[H_3O^+] and calculate the pH of acids, salts and bases

Biology (VVKSO, 2014a; GO!, 2014a):
Students can:

- ☐ observe, recognize, indicate, and draw cells and their structure by means of microscopic inquiry
- ☐ describe the functions of cell structures, in relation to the cell type
- ☐ recognize and describe the similarities and differences between prokaryotic and eukaryotic cells
- ☐ recognize and represent the chemical structure of saccharides, lipids, proteins, and nucleic acids
- ☐ determine experimentally, describe and explain active and passive transport of substances across biomembranes, and the factors influencing this transport
- ☐ explain substance and energy transformation for autotrophic and heterotrophic organisms
- ☐ represent schematically the substance and energy transformation in the chloroplast in photosynthesis reactions and cell respiration
- ☐ discuss the importance and the course of mitosis and explain its meaning and influencing factors

Electromechanics (GO!, 2016):
Students can:

- ☐ account for the choice of control components such as switches, sensors, and actuators, with regard to the application
- ☐ discuss the technology of active components, such as diodes and LEDs and measure their functioning

Mathematics (VVKSO, 2004; Gemeenschapsonderwijs, 2006a):
Students can:

- ☐ recognize the difference between linear and exponential growth, and explain the concepts initial value, growth factor, decay time
- ☐ determine the table, domain, values, continuity, limits, asymptote, course, and formula of a logarithmic or exponential function by means of its formula or graph
- ☐ explain a logarithmic scale

Appendix F

Students' misconceptions and accommodating strategies

Box F.1 lists literature findings of some common student difficulties and misconceptions in kinematics, together with some instructional strategies that might help overcome them, such as using concept cartoons (Figure F.1).

Box F.1 Student difficulties in kinematics, and strategies to address them, found in literature

- × inability to determine if and when two object have the same velocity (Trowbridge & McDermott, 1980) or the same acceleration (Trowbridge & McDermott, 1981);
- × inability to discriminate between position and velocity (Trowbridge & McDermott, 1980);
- × no qualitative understanding of acceleration as the ratio $\Delta v/\Delta t$ (Trowbridge & McDermott, 1981);
- × inability to choose the corresponding time interval Δt (Trowbridge & McDermott, 1981);
- × inability to discriminate between position and acceleration (Trowbridge & McDermott, 1981) or between velocity and acceleration (Trowbridge & McDermott, 1981);
- ⇒ establish a connection among concepts (Trowbridge & McDermott, 1980, 1981)
- ⇒ exercise via class discussions, lab experiments, real-world applications (Trowbridge & McDermott, 1981)
- ⇒ allocate enough time to the digestion of concepts (Trowbridge & McDermott, 1981)

× inability to discriminate between height and slope of a graph; no interval reasoning (Wemyss & van Kampen, 2013; Planinic, Ivanjek, Susac, & Milin-Sipus, 2013);
× inability to discriminate between graph and image (Planinic et al., 2013);
⇒ use all forms of graphs, among which some not going through the origin (Wemyss & van Kampen, 2013)

× no engagement with the question or with the graphical representation when a numerical value is asked (Wemyss & van Kampen, 2013);
× recognition of constant velocity in a linear position-time graph, but inability to determine the velocity value (Wemyss & van Kampen, 2013);
⇒ generate a physics concept from data, through data analysis and reflection (Woolnough, 2000)

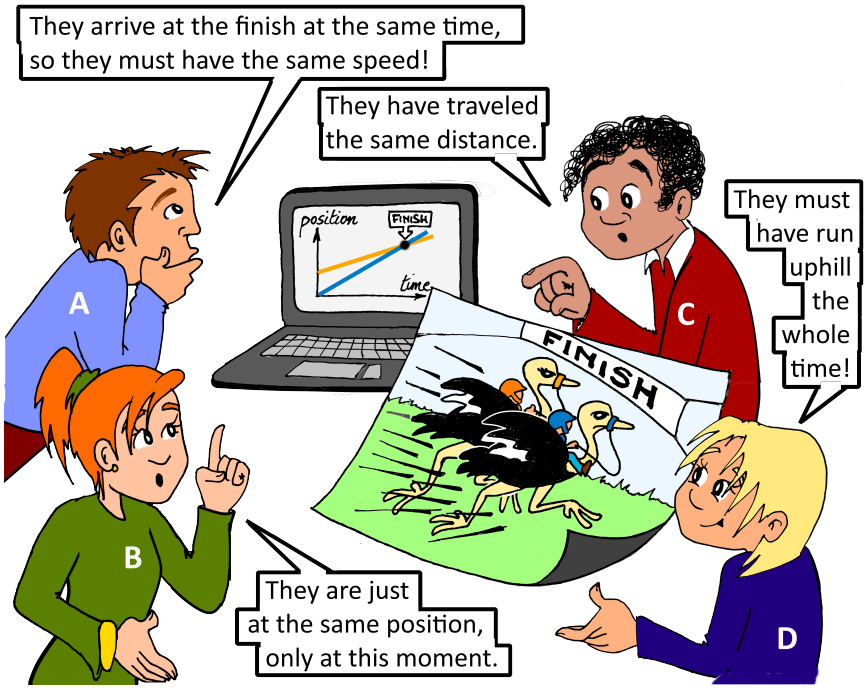


Figure F.1: Example of a kinematics concept cartoon with common student misconceptions as distractors

Appendix G

Survey on CODEM for iSTEM

1. Is the model complete? Which steps do you think are missing?
   Or does the model contain redundant steps? Which ones?
2. Which of the model's steps did you experience during your design process(es)?
   Which of the steps in the model didn't you experience during your design process(es)? Do you think those steps are important?
3. The rhombuses represent conditions, they must be checked by the team coordinator based on the team's intermediary results. Do you think including them was a good idea?
4. Are the steps represented in a logical sequence?
5. Based on your experiences, which steps are really necessary or important according to you, given the target group (i.e. STEM teachers)?
6. Does the model seem suitable to support teachers?
7. The digital model contains per step the following features.
   - references to documents that are produced by the team in an earlier step and are the input needed in the step at hand, and documents that should be delivered by the team as output of the step at hand
   - a description of the actions that should be undertaken in the step at hand (based on research literature and case-study observations), and questions to guide the team in those actions
   - examples from designed learning materials
   - a discussion forum
   - a reference to the requirements on iSTEM learning materials (based on the key principles behind iSTEM education)

   Which features are missing?

Appendix H

Teacher-interview questions

Background

1. How old are you?
2. What is your education?
3. Which courses do you teach?
   Which courses have you taught?
   For how long?
4. Have you taught in other schools?
   For how long?
5. Do you have other work experience outside teaching?
6. (TDT) How long have you been participating in iSTEM development?
   (IMPL) How long have you been involved as enactor of the iSTEM learning materials?
7. Which (i)STEM-related professional development have you attended?
8. How would you describe iSTEM education?

(How) did participation in iSTEM development facilitate iSTEM implementation?

1. What does this educational reform mean for you...
   ... (TDT) in terms of development?
   ... (IMPL) in terms of implementation?
2. Would you say your team made a successful entry in this reform?
   How would you describe a successful entry?

3. (TDT) How do you perceive 'developing' iSTEM learning materials?
4. (TDT) What are the prerequisites for participation in development of iSTEM?
   What are the prerequisites for a successful implementation of iSTEM?
5. (TDT) What are the advantages and disadvantages of participation in development of iSTEM?
   (IMPL) What are the advantages and disadvantages of implementation of iSTEM?
6. (TDT) Would the implementation of iSTEM also have been successful if you had not participated in the development of iSTEM learning materials, do you think?
   (IMPL) Would the implementation of iSTEM have been easier if you had participated in the development of iSTEM learning materials, do you think?
   With the experience you have had in STEM@school, would you (again) enroll in development of iSTEM learning mateirals in the future (in the scope of STEM@school or self-initiated)?

(How) did participation in iSTEM development / iSTEM implementation influence your knowledge and attitude?

1. (TDT) (How) did participation in development of iSTEM learning materials change you on following aspects (Kelchtermans, 2001):
   (IMPL) (How) did iSTEM implementation change you on following aspects (Kelchtermans, 2001):
   - your self-knowledge?
   - your self-efficacy (your estimation of how effective your teaching is)?
   - your motivation for teaching and for your course(s)?
   - your teaching practices (PK & PCK)?
   - your knowledge (CK & PCK)?
   - your ideas about teaching, about students, about your course(s)?
   - your professional future perspective?
2. Could you make a metaphor?
   "Developer of iSTEM education is like ..."
   "Enactor of iSTEM education is like..."

Which training is necessary to develop / implement iSTEM learning materials?

1. (TDT) Can you cite aspects of your teacher training and/or other trainings that contributed to the development process?
   (IMPL) (TDT) Can you cite aspects of your teacher training and/or other trainings that contributed to the implementation?
2. (TDT) If you could propose teacher training, professional development, summer courses for iSTEM development yourself...
   (IMPL) If you could propose teacher training, professional development, summer courses for iSTEM implementation yourself...
   What would they look like?
   What / which topics should be addressed?
   What don't you need?
   One session, or multiple sessions? How long can they last?

Appendix I

Analysis of CODEM for iSTEM-generated data

Four sets of data are registered by the online version of CODEM for iSTEM and can be generated for analysis: (1) the time spent by each team member on a certain step, (2) the history of savings of the output documents on each team's shared cloud folder, (3) the content of these intermediary documents, and (4) the final learning materials designed by each team. The first two sets of data could provide some indications and help to explain what is observed in the latter two.

(1) The logs of the registered time per step can be extracted into a spreadsheet and transformed into a pivot table. Such a pivot table allows to represent the data in a desired way, e.g., per team member.
(2) The history of the output documents in the cloud folder and of each team member's contribution can be retrieved and compared to the times in the aforementioned logs.
(3) The content of the output documents in the cloud folder and of each team member's contribution can be coded.
(4) The evaluation of the designed materials against the requirements for high-quality iSTEM education can be coded.

A combination of steps (1), (3) and (4) might result in an analysis that looks like Table I.1.

Table I.1: Fragment of the analysis of the output documents of some steps made by a pre-service teacher team

step	**#** min.	**Output documents observation**	**Developed syllabi - expert evaluation**	**Other indicators**
GDT	31	list of syllabus titles with a few relevant discipline-specific curricula standards & final requirements, "class goals" (own formulation?) for Math (trigonometry), Physics (optics), Computer science (programming) (disciplines separated for separate syllabi) + some transdisciplinary final requirements	according to the target group's curriculum standards	
CIL	65	Class goals (knowledge, skills, attitudes) of OUT_GDT1 + a letter (S, T, or M) assigned to each class goal per syllabus (separate letter/discipline for separate syllabi, instead of identification of S, T or M concepts within syllabi) no links between S, T, or M concepts + an attempt to concept map?	no links between STEM concepts or disciplines	
CLS	8	Some very general considerations and tips for teaching Technology, Math and Science + two misconceptions about optics with reference to an article (no instr. strategies)		Meeting report: Reason for thorough examination of the national curriculum for Technology
ph3C1		explicit link possible between STEM concepts		no sending back by Co1&2
CF	2	"Build a parking lot where it is possible to park fluently."	requires the learning of STEM concepts not uniting the learning content open-ended	Meeting report: Conclusion: "A motivational phase about how does everyone come to school? And do your parents always find a parking?"

Appendix J

Estimated time for CODEM for iSTEM

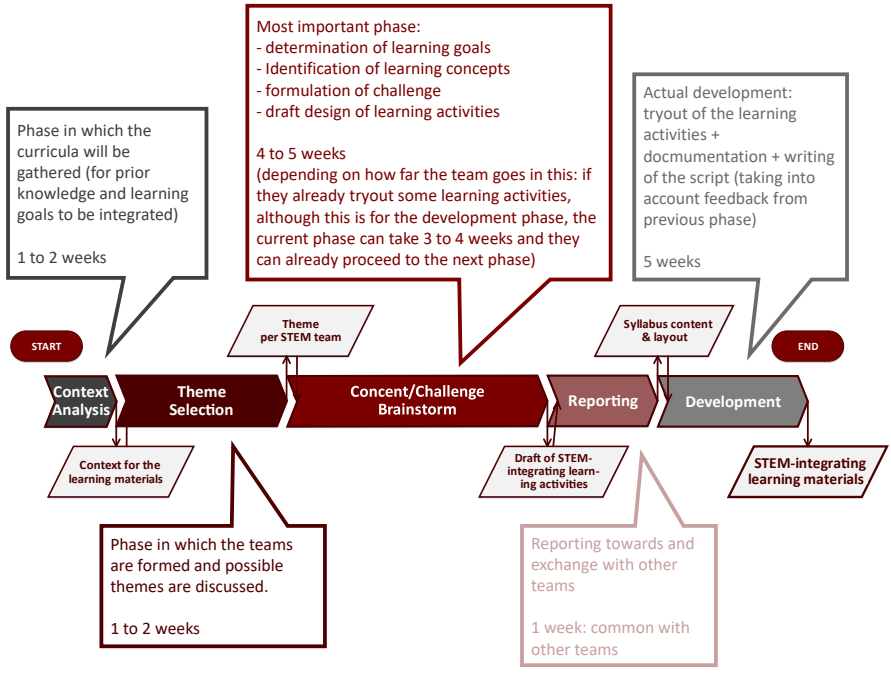


Figure J.1: Estimation of time necessary for each phase of CODEM for iSTEM (at a rate of 4 hours a week)

List of publications

Journal articles

De Meester, J., Goovaerts, L., Buyse, M.P., De Cock, M., Langie, G., Struyven, K., Dehaene, W. (2018). Students' strategies and difficulties when transferring the concept of resistance from electricity to thermodynamics within STEM education. Manuscript submitted for publication.

De Meester, J., Knipprath H., Buyse, M.P., Ceuppens, S., De Loof, H., Goovaerts, L., Hellinckx, L., Struyf, A., Thibaut, L., Van de Velde, D., Boeve-de Pauw, J., De Cock, M., Depaepe, F., Deprez, J., Langie, G., Struyven, K., Van Petegem, P., & Dehaene, W. (2017). Leren ontwerpen van STEM-integrerend leermateriaal, *Tijdschrift voor Lerarenopleiders*, *38*(4), 27-36.

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De Meester, J., Knipprath, H., Thielemans, J., De Cock, M., Langie, G., & Dehaene, W. (2015). Integrated STEM in secondary education: A case study. *Il Nuovo cimento c: colloquia and communications in physics*, *38*(3).

Goovaerts, L., De Meester, J., Buyse, M.P., De Cock, M., Langie, G., Struyven, K., Dehaene, W. (2018). Students' strategies and difficulties when transferring concepts of slope, area under the curve, and programming loop within STEM education. Manuscript submitted for publication.

Knipprath, H., Thibaut, L., Buyse, M.P., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., Boeve-De Pauw, J., Depaepe, F., Deprez, J., De Cock, M., Hellinckx, L., Langie, G., Struyven, K., Van de Velde, D., Van Petegem, P., Dehaene, W. (2018). STEM Education in Flanders: How

STEM@school Aims to Foster STEM Literacy and a Positive Attitude towards STEM. *IEEE Instrumentation & Measurement Magazine*, *21*(3), 36-40.

Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., Boeve-De Pauw, J., De Cock, M., Dehaene, W., Deprez, J., Hellinckx, L., Knipprath, H., Langie, G., Struyven, K., Van de Velde, D., Van Petegem, P., Depaepe, F. (2018). Integrated STEM education: A systematic review of instructional practices in secondary education. *European Journal of STEM Education*, *3*(1).

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Biography

Jolien De Meester was born in Sint-Niklaas, Belgium, in 1986. In 2009, she received the degree of M.S. in Industrial Engineering, Electromechanics from Group T, KU Leuven. The subject of her master's thesis was the design of a mechanical device that simulates a person's imprint on a mattress based on data of his/her personal physique. From 2009 to 2012, she worked as a teaching assistant in Group T, where she was responsible for several exercise sessions and projects at the department of Electromechanics. During this time, she obtained her teacher's degree in the specific teacher education at the KU Leuven faculty of Science. From 2013 to 2018, she worked on her Ph.D. thesis in the MICAS research group at the KU Leuven department of Electrical Engineering, and became part of the research team of STEM@school. Her main focus areas were the design of learning materials for integrated STEM education, and the collaboration in/with multidisciplinary teams of STEM teachers. As of September 2018, she is working in educational development for Odisee, a member of KU Leuven Association, for which she coordinates the integration of the short-cycle tertiary education into the college's technical study programs.



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