Multidimensional Analysis of Knowledge-Linking within the Concept of Energy in Student Essays

Abstract
In Germany there is a very conservative tradition to teach science in separated subjects during the secondary level of education. Considering the importance of knowledge-linking in all relevant learning theories of the 20th century, cross-curricular core concepts, like the concept of energy, found their way into German educational standards for biology, chemistry, and physics in 2005 (KMK, 2005a-c). The aim was to foster both more vertical (i.e. intra-subject) and more horizontal (i.e. inter-subject) linkage in subject-differentiated science education. Existing structural models or approaches to analysing and describing knowledge-linking focus exclusively either on the aspect of vertical or horizontal linkage. Based on existing models and approaches, we developed a theory-based model (MAverBE) that allows a general analysis of the linking performance in essays. In this study, we investigate to what extent we can identify vertical and horizontal linkage structures in student essays on the cross-curricular core concept of energy in grade 9. Our results presented here give an empirical insight into students’ knowledge-linking in the sense of a normative survey. This survey should permit future comparative studies both on a national and international level to prove the popular assumption of the superiority of integrated-science teaching concerning knowledge-linking.

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1. INTRODUCTION

Germany's disappointing results in the past TIMSS (Baumert et al., 1997) and PISA studies (Baumert et al., 2001; Prenzel et al., 2004) have been explained by a lack of linking processes in science teaching. To enable more linkage by focusing on central linkable terms in teaching, core concepts found their way into the German educational standards for biology, chemistry, and physics (KMK, 2005a-c). The integration of cross-curricular core concepts, such as the concept of energy, served the intended purpose to establish stronger intra-subject as well as inter-subject linkage, although science is traditionally taught in a subject-differentiated way in the German educational system (Demuth et al., 2005). Fischer, Glemnitz, Kauertz and Sumfleth (2007, p. 662) refer to intra-subject as vertical linkage and inter-subject as horizontal linkage. However, there are serious doubts whether there is sufficient horizontal linkage within the concept of energy at all. For example, Eisenkraft et al. (2014, p. 2) state that students rarely link the concept of energy from the individual subjects of biology, chemistry, and physics. The authors see the reason for this gap in the fact that the term energy is used very differently in the individual science subjects (Eisenkraft et al., 2014, p. 1-2). Therefore, we want to investigate the vertical and horizontal linkage of students’ knowledge in the field of energy before the end of compulsory schooling.

2. THEORETICAL FRAMEWORK

2.1 Hierarchical and non-hierarchical linking of terms in human knowledge

Since the introduction of national educational standards and competence modelling, numerous German research groups have been dealing with the issue of knowledge-linking in the course of learning processes (e.g. Neumann et al., 2008; Wadouh et al., 2009; Lau, 2011; Knobloch et al., 2013; Wadouh et al., 2014; Podschuweit et al., 2016; Kubsch et al., 2019; Podschuweit & Bernholt, 2020). From the perspective of educational psychology, learning equals the acquisition of knowledge in which “[knowledge structures] are constructed and modified” (Steiner, 2006, p. 164, translated by the authors). In the process of knowledge construction, new knowledge elements are combined with already existing knowledge elements. The accumulation of isolated knowledge elements, which for instance stem from the memorisation of definitions, leads to “inert knowledge” that cannot be retrieved in application (Renkl, 1996). In order to enable active access to certain knowledge, “it should be linked to numerous knowledge elements if possible” (Renkl, 2021, p. 9, translated by the authors). The process of linking new knowledge elements to already existing ones is also called “linkage” (Renkl, 2021, p. 9, translated by the authors). The importance of linking processes is fundamental to several learning theories, such as constructivist learning theories (e.g. Jonassen, 1999) and also the theory of cumulative learning (Gagné, 1970). Gagné (1970, p. 52) describes “rule learning”, in which terms are linked together to form chains as one of eight different types of learning. Nowadays, the idea of chains of terms is extended to the idea of structural networks of terms. Structuralists, such as Aebli (1980; 1981) and Schnozt (1994) suggest to treat the construction of terminological knowledge systems as a propositional network. Each term consists of numerous term elements that are linked to each other in different ways (Aebli, 2003).

Humans form terms to be able to cognitively deal with their environment (Schnozt, 1994). In this context Aebli (2003, p. 245, translated by the authors) states that the formation of a term means having “a phenomenon under control”. In addition to forming terms, another ability of our cognitive system is to link terms to create higher units. Aebli (1981, p. 103f.) refers to this process as objectification. As a result of objectification processes, hierarchies of complexion and abstraction are formed within the terminological knowledge (Schnozt, 1994, p. 30 in accordance with Dörner, 1976). In complexion hierarchies, nouns are linked in “has as part” contexts, verbs describe processes and causal relationships are also represented (Dörner, 1976). Complexity hierarchies can emerge at different levels of abstraction (Dörner, 1976). The varying level of abstraction of a term can be recognised by how many different terms can be subsumed under this term (Achtenhagen et al., 1992, p. 97f.). The more abstract a term is, the more terms – or as Aebli (2003) would say term elements – can be subsumed...
under it. Aebli (1981, p. 206) extends Dörner’s (1976) remarks on the hierarchical structure of terminological knowledge to the effect that hierarchical structures only exist temporarily. When a person reconstructs a term, for example when trying to define it, the hierarchical structure of the term is formed during this process and is removed again afterwards. Aebli (1981, p. 206f.) calls this process perspective formation and notes that this perspective formation can take place from different points of the terminological network even if it describes the same subject matter.

In the literature there are different models and approaches which describe either vertical or horizontal linkage within terminological knowledge. In the following two chapters we provide a selection of important contributions relevant to our research.

### 2.2 Models for the description of vertical linkage

The model of vertical linkage of Fischer, Glemnitz, Kauertz and Sumfleth (2007) distinguishes between the linking activities remembering, structuring and elaborating and six different levels of linkage. These linkage levels are labelled, with hierarchically increasing complexity, as *single fact*, *several facts*, *single relation*, *several unconnected relations*, *several interconnected relations*, and *generic concept*. The model of vertical linkage is pervasively used in German science education research. For instance, Wadouh, Sandmann and Neuhaus (2009) utilized it for the analysis of students’ linkage performance in videotaped biology lessons. Neumann, Fischer and Sumfleth (2008) examine, among other things, teachers’ vertical linkage in videotaped chemistry and physics lessons and found significant differences between individual teachers. Kauertz (2008) and Ropohl (2010) used the vertical linkage model to construct tasks of varying difficulty for competence assessments. In detail, Kauertz (2008, p. 111) investigated the relationship between task difficulty and linkage level within a task and found that task difficulty increases in the order of *single fact*, *single relation*, *several facts*, *several interconnected relations*, *generic concept* and *several unconnected relations*. Even though Kauertz (2008) could not statistically validate this order regarding all possible options, he proved the relationship between task difficulty and the number of elements to be linked. Ropohl (2010, p. 117) emphasises the usefulness of distinguishing between the *fact*, *relation* and *generic concept levels* as a feature that determines the difficulty in tasks for formal assessments. Based on the findings of Kauertz (2008) and Ropohl (2010), the vertical linkage model was used in a modified form. In this modified form, only the following five levels are distinguished: *1 fact*, *2 facts*, *1 relation*, *2 relations* and *generic concept* (e.g. in Kauertz et al., 2010, pp. 142-143). In that way, the model of vertical linkage takes qualitative as well as quantitative aspects of linkage into account. The ESNaS competence models [ESNaS is the German acronym for: Evaluation der Standards für die Naturwissenschaften in der Sekundarstufe I, in English: Evaluation of the standards for science in the lower secondary level] use these levels of linkage to describe the complexity dimension (Kauertz et al., 2010; Hostenbach et al., 2011; Wellnitz et al., 2012; Ziepprecht et al., 2017).

If only the quality of the linkage is to be considered and not also the number of elements to be linked, there are two alternatives. On the one hand, one can only refer to the distinction between *fact, relation* and *generic concept levels* from the model of vertical linkage. This is what Knobloch, Sumfleth and Walpuski (2013) recommend, for example, in the process of analysing the quality of student statements in experimental small-group work phases. On the other hand, one can use the model developed by Bernholt and Parchmann (2011) which, in contrast to the model of vertical linkage, focuses exclusively on the quality of the linkage. Bernholt and Parchmann (2011) used the content-independent model of hierarchical complexity of Commons, Trudeau, Stein, Richards and Krause (1998) as a theoretical basis and adapted it to analyse chemistry lessons. This model differentiates between the five linkage levels *everyday experiences, facts, processes, linear causality, and multivariate interdependencies* (Bernholt & Parchmann, 2011). This model is also used for the analysis of videotaped lessons (Podschuweit et al., 2016; Nehring et al., 2017) and serves as a basis in different competence models (Woitkowski et al., 2011; Arx & Bernholt, 2015; Woitkowski & Riese, 2017; Woitkowski, 2020).
Woitkowski, Riese and Reinhold (2011) identified many overlaps but also differences comparing the category definitions of the model of vertical linkage (Fischer et al., 2007) and the model of hierarchical complexity (Bernholt & Parchmann, 2011). Nehring, Päßler and Tiemann (2017) compared both models in practice. In this investigation they analysed teacher questions in chemistry lessons using the model of vertical linkage and the model of hierarchical complexity. The results of the analysis with both models were only comparable up to 70% (Nehring et al., 2017). It is particularly notable that the authors could not even relate a single generic concept to a multivariate interdependency (Nehring et al., 2017). Therefore, depending on the question addressed in the study, the authors recommend using either the model of vertical linkage by Fischer et al. (2007) or the model of hierarchical complexity adapted for chemistry teaching by Bernholt et al. (2011). For formal analysis of the complexity level, they suggest the model of vertical linkage and for a more content-related analysis of the linkage, they favor the adapted model of hierarchical complexity (Nehring et al., 2017, p. 248). In contrast to these recommendations, we argue that in our opinion, it is necessary to combine both models to achieve an accurate description of the analysis dimension vertical linkage level.

2.3 An approach to the investigation of horizontal linkage

Lewing and Schneider (2019) proposed co-occurrence analysis as an approach to the investigation of horizontal linkage. Using a computer-based procedure they looked for co-occurrences of terms in science textbooks. For the authors, two terms are defined as co-occurrent if they appear in two consecutive sentences (Lewing & Schneider, 2019, p. 724). To assign single terms to a specific subject (biology, chemistry or physics) or a combination of subjects, they checked the indices of subject-specific science textbooks. In one of their studies, Lewing and Schneider (2019) compared, among other issues, the linkage of the term energy with terms used in the subjects biology, chemistry and physics in the corresponding textbooks. They found that the term energy is linked more than twice as often with physical terms than with biological or chemical terms (Lewing & Schneider, 2019).

Because all models and approaches we presented in chapter 2.2 and chapter 2.3 focus on the description of either vertical or horizontal linkage, in chapter 3 we will present a model developed by ourselves which allows a general investigation of linking performance and which seems to be appropriate to answer our central research question (see chap. 2.4).

2.4 Research question

Within the German standards for science education, the concept of energy is the only core concept that is relevant in all three separate subjects: biology, chemistry, and physics (KMK, 2005a-c). An analysis of students’ knowledge-linking in this concept seems to be the most functional approach to investigate the following research question:

In what way and to what extent do student statements concerning the concept of energy show both vertical and horizontal linkage structures?

3. METHODS

To answer our research question, we designed an analysis procedure in which students write an essay about the concept of energy first. We chose the essay method because it has many advantages regarding our main research focus (see chapter 6). The students do not need any training which is why we could survey a respectable number of students (in our case all 9th grade students from one school).

For the analysis of students’ cognitive structures, van Kirk (1979) assigned his students sentence generation tasks. A list of terms on topics like ecology stimulated the students’ writing process. Following van Kirk’s idea, we provide our students with a list of 26 terms often mentioned in the context of energy (Figure 1).
Please imagine the following situation:

Paul asks Mia for help.

Hello Mia. I’m glad you’re here! I have to write a text about the topic of energy to save my grade. Unfortunately, I have no idea what to write about energy in this text....

But energy is a big topic. Did your teacher give you any advice on how to prepare the text?

Yes, he gave me a list of important terms related to energy. To prepare the text, the first thing I should do is mark the terms I want to use. Look, this is the list of important terms:

<table>
<thead>
<tr>
<th>endothermic</th>
<th>kinetic energy</th>
<th>metabolism</th>
<th>energy forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>system</td>
<td>photosynthesis</td>
<td>reaction energy</td>
<td>work</td>
</tr>
<tr>
<td>energy flow</td>
<td>chemical energy</td>
<td>electric energy</td>
<td>nutrition</td>
</tr>
<tr>
<td>chemical reaction</td>
<td>energy transformation</td>
<td>particles</td>
<td>potential energy</td>
</tr>
<tr>
<td>cell respiration</td>
<td>activation energy</td>
<td>heat</td>
<td>light</td>
</tr>
<tr>
<td>energy conservation</td>
<td>mitochondrion</td>
<td>exothermic</td>
<td>motion</td>
</tr>
<tr>
<td></td>
<td>energy content</td>
<td>temperature</td>
<td></td>
</tr>
</tbody>
</table>

Now it’s your turn. Put yourself in Paul’s shoes and write a text about energy.

1. First, mark the terms in the box (above) that you want to use for your text on energy.

2. If you think of other terms that you would like to use in your text about energy, write them in the empty box.

3. Write a detailed text on the topic of energy using the marked terms.

Figure 1. Survey instrument for the analysis of the linkage of terms of the concept of energy (Dietz & Bolte, 2021, translated into English by the authors)

To select these 26 terms of the concept of energy, we first looked into the Berlin and Brandenburg curricula of the school subjects biology, chemistry and physics and extracted 108 terms related to the concept of energy (SenBJF Berlin, 2017a-c). In a second step, we presented this list of terms to 107 science teachers and asked them to evaluate which of these terms are most significant to their lesson planning and teaching (Dietz et al., 2021). The resulting list of terms for the students contains the
teachers’ top 5 terms for each subject: biology, chemistry, and physics. Furthermore, we have complemented this list of terms with all terms that appear in at least two or even in all the three different subject specific science curricula of Berlin and Brandenburg (Dietz et al., 2021). To avoid subject-related chains of association, we decided to collect the data (the students’ written essays on the concept of energy) not in one of their biology, chemistry, or physics lessons but during a German lesson. For the analysis of the essays, we utilize Mayring’s qualitative content analysis (2015). In detail, we apply the content-structuring procedure using content and scaling categories. By this way, we developed our own model, which is based on the literature and models introduced in chapter 2.2 and 2.3, and which allows us to analyse the students’ linking performance in both dimensions, namely the students’ vertical and horizontal linking performance. At the end of this process we termed our model “MAVerBE” which is the German acronym for: “Modell zur Analyse der Vernetzung von Begriffselementen” [in English: Model for the Analysis of the Linkage of Terms]. The MAVerBE consists of a three-dimensional category system that allows the examination of students’ statements in terms of vertical linkage level, horizontal linkage, and scientific correctness (Figure 2).

<table>
<thead>
<tr>
<th>MAVerBE – Model for the Analysis of Linkage of Terms</th>
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<tbody>
<tr>
<td><strong>1st dimension: vertical linkage level</strong></td>
</tr>
<tr>
<td>multi-perspective generalisations</td>
</tr>
<tr>
<td>grounded relations</td>
</tr>
<tr>
<td>interconnected relations</td>
</tr>
<tr>
<td>ungrounded relations</td>
</tr>
<tr>
<td>everyday experiences</td>
</tr>
<tr>
<td>scientific facts</td>
</tr>
</tbody>
</table>

The vertical linkage level defines units of analysis.

Note: The dimension “vertical linkage level” combines the Model of vertical linkage (Fischer et al., 2007, elements shown in bold) and the Model of hierarchical complexity (Bernholt & Parchmann, 2011, elements shown in italics). Additionally, we optimized the category definitions of both models and developed an own definition for the highest category.

<table>
<thead>
<tr>
<th>2nd dimension: horizontal linkage</th>
</tr>
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<tbody>
<tr>
<td>biology (B)</td>
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<tr>
<td>chemistry (C)</td>
</tr>
<tr>
<td>physics (P)</td>
</tr>
<tr>
<td>biology/chemistry (BC)</td>
</tr>
<tr>
<td>biology/physics (BP)</td>
</tr>
<tr>
<td>chemistry/physics (CP)</td>
</tr>
<tr>
<td>biology/chemistry/physics (BCP)</td>
</tr>
<tr>
<td>energy (E)</td>
</tr>
<tr>
<td>scientific-technical (NT)</td>
</tr>
</tbody>
</table>

Identification of terms within a unit of analysis and assignment to a category on the basis of curricula

<table>
<thead>
<tr>
<th>3rd dimension: scientific correctness</th>
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</thead>
<tbody>
<tr>
<td>explicitly correct</td>
</tr>
<tr>
<td>implicitly correct</td>
</tr>
<tr>
<td>incorrect</td>
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</tbody>
</table>

Analysis of scientific correctness within a unit of analysis

Figure 2. Structure of our theory-based model for the general analysis of knowledge-linking in essays

For the first analysis dimension, the vertical linkage level, we combine the model of vertical linkage (MVL) by Fischer, Glemnitz, Kauertz and Sumfleth (2007) with the model of hierarchical complexity adapted for chemistry lessons (MHC-C) by Bernholt, Parchmann and Commons (2009, see chapter 2.2).
At the 1st vertical linkage level, we consider simple links between two terms using verbs such as “to be” and “to have”. This includes describing properties, naming objects or concepts, and stating classifications. Depending on the (supposed) origin of the students’ statements we distinguish, like the MHC-C, between the categories of everyday experiences and scientific facts. In contrast to the MHC-C, we do not differentiate hierarchically between scientific terms and terms from everyday life because for us only the simple way of linking is the decisive criterion for our first vertical linkage level.

At the 2nd vertical linkage level, the students formulate more complex relations. In this category we include student statements with at least two terms in the form of causalities, dependencies and conditions which are part of the category relations in the MVL. We also consider descriptions of processes which belong to the category processes in the MHC-C. Considering students’ linguistic competences, in our opinion it is not functional to differentiate between these categories. For example, students could either state that heat is produced during or because of a chemical reaction. The first statement belongs to the category processes in the MHC-C, the second one belongs to the category relations in the MVL because it is a causal connection. In both cases students link the terms chemical reaction and heat in a more complex way than on the scientific fact or everyday experience level. Following the suggestion of Woitkowski & Riese (2017, p. 41) we name this category ungrounded relations.

For the next higher vertical linkage level, in contrast to the MVL we do not take into consideration the number of linked elements. In the MVL it is possible to gain a higher complexity level only by listing facts (category several facts) or relations (category several unconnected relations). Here we follow Common’s et al. argumentation (1998, p. 240) that a higher complexity order cannot be accomplished by arbitrarily organising lower order actions. In our opinion, stating several facts, like naming different energy forms, whether as a list or disseminated throughout an essay, should not be regarded as higher complexity. Commons et al. (1998, p. 252) noticed that an increasing number of linking operations lead to a higher complexity level. Following Common’s et al. idea (1998) a higher complexity level can be achieved through the interconnection of relations. An example for such an interconnection is that students describe processes, which are coupled with each other. For these statements we established the category interconnected relations as the 3rd vertical linkage level. This category is also part of the MVL (Fischer et al., 2007, see chapter 2.2).

Another more complex linking operation is the justification of a relation. The importance of justifying a relation is visible in the MHC-C. The category linear causality is the second highest category in this model (Bernholt & Parchmann, 2011). In this case, we follow the idea of Woitkowski & Riese (2017, p. 41) and call the 4th vertical linkage level grounded relations.

Due to the problems Nehring et al. (2017) reported (see chapter 2.2), we developed our own category for the 5th vertical linkage level. In this category students combine at least two central aspects of the concept of energy and explain this combination using at least one example. Central aspects of the energy concept are defined in various learning progressions and to some extent represent learning objectives in dealing with the energy concept (e.g. Neumann et al., 2013). These central aspects are energy forms and sources, energy transformation, energy transfer, energy degradation, energy conservation, and entropy (Duit 1986; 2014; Neumann et al., 2013; Poggi et al., 2017). According to Aebli’s perspective theory (1981, p. 206, see chapter 2.1), by using the individual terms that represent these central aspects of the energy concept, their hierarchical structure is temporarily formed within the terminological network. Since these are particularly abstract terms, a particularly extensive hierarchical structure is correspondingly to be expected. For us, the combination of two central aspects and their explanation therefore represents a particularly high linking performance since the student forms several pronounced hierarchies within his terminological network and relates them to each other at the same time. As Aebli (1981) speaks of perspectives in the formation of these hierarchies, we call clusters of statements in this category “multi-perspective generalisations”. We present an example of each vertical linkage level from the essays in the results section (see chapter 4.2).
To examine the second analysis dimension *horizontal linkage*, we conduct co-occurrence analyses. In a first step, we code the *vertical linkage level* within the essays using the MAXQDA software (VERBI software, 2019). Thereby we obtain units of analysis, for example *scientific facts*. In a second step, we identify relevant terms within these units of analysis. To assign a single term to a subject (biology, chemistry, or physics) or a combination of subjects (biology/chemistry, etc.), we check the science curricula of the federal states Berlin and Brandenburg (SenBJF, 2017a-c) for these terms. Terms that are not mentioned in any of the curricula, but which we deem relevant for the analyses nevertheless, we consider in a separate category, which we call "scientific-technical terms". The term energy is considered in a separate category. Although the term energy also occurs in all three science curricula (and could therefore be assigned to the corresponding category "BCP"), we want to be able to draw more detailed conclusions about the students’ linking performance through this procedure. In a last step, we generate networks to illustrate the results of our co-occurrence analysis with the UCINET software (Borgatti et al., 2013).

The third analysis dimension *scientific correctness* examines the degree to which the students’ statements are correct. We distinguish between the categories *explicitly correct*, *implicitly correct* and *incorrect*. In the category *implicitly correct* we consider statements in which the students do not express themselves scientific incorrectly but inaccurately. An example of this is when students talk about energy being released in an exothermic reaction. From a scientific perspective, this statement is only partially correct since an exothermic reaction explicitly releases heat energy. A reaction in which energy is released is correctly described as an exergonic reaction (Atkins, 2001, p. 258). With the category *implicitly correct* we take into account the reality of written language in essays where statements are rarely formulated in such a way that they neither would be printed in textbooks nor can be defined as completely incorrect.

Before starting our main investigation, we reviewed the category system in terms of intercoder reliabilities. To do this, two coders coded a priori defined units of analysis from 39 essays about the concept of energy from another study in terms of the analysis dimensions *vertical linkage level* and *scientific correctness*. We determined the randomly corrected Cohens Kappa values following Brennan and Prediger (1981). According to Altman’s interpretation (1999), we obtained very good intercoder reliability values for both dimensions: the *vertical linkage level* (κ = 0.84) and *scientific correctness* (κ = 0.81).

**4. RESULTS**

**4.1 Sample**

At the beginning of the 2019/20 school year, we surveyed 134 9th grade students from a secondary school during a German lesson. Following the analysis procedure, we identified a total of 1,894 units of analysis (and thus an average of 14.3 units per essay) in 132 essays. Two essays had to be discarded because the students did not write anything. On average the students were 13.9 ± 0.4 years old and wrote 126 ± 75 words per essay.

**4.2 Vertical knowledge-linking and scientific correctness**

For the analysis of the first dimension of our MAVerBE, we considered 1,797 of the students’ 1,894 statements. The other 97 statements were assessed as repetitive or unclear in meaning and therefore excluded from further analyses Table 1 shows exemplary statements from the essays for each vertical linkage level.
Figure 3 shows the distribution of the units of analysis across the six categories of the first analysis dimension vertical linkage level. 56.3% of the student statements are on a low vertical linkage level. At this level, students name scientific facts like different characteristics of energy. For instance, they describe energy as existing in different forms. In many cases they also name these forms. The second most common category used, identified in 31% of the students’ statements, is the category ungrounded relations. Student statements clustered in this category are mainly: a) conditions that describe what energy (or a special form of energy) is needed for or b) process descriptions in which energy transformations between different forms of energy occur. Just 12.4% of the student statements are on a higher vertical linkage level. Within the category interconnected relations – detected in 11.2% of the statements – students describe energy transformation processes which are coupled with each other. Only a very small number of students’ statements could be assigned to the highest categories grounded relations (0.9%) and multi-perspective generalisations (0.3%).

<table>
<thead>
<tr>
<th>Vertical linkage level</th>
<th>Example taken from the students’ essays (translated into English by the authors)</th>
</tr>
</thead>
<tbody>
<tr>
<td>everyday experiences</td>
<td>“Energy plays a big role in our everyday life.”</td>
</tr>
<tr>
<td>scientific facts</td>
<td>“There are different forms of energy.”</td>
</tr>
<tr>
<td>ungrounded relations</td>
<td>“Activation energy is the energy needed to start a chemical reaction.”</td>
</tr>
<tr>
<td>interconnected relations</td>
<td>“In biology, every organism needs energy to move [...] You can get this energy through nutrition.”</td>
</tr>
<tr>
<td>grounded relations</td>
<td>“Here, a ball on a hill has more potential energy than one in the village, because although both are attracted to the earth by about the same amount, the ball on the hill can theoretically travel more distance because it still has to roll down the hill.”</td>
</tr>
<tr>
<td>multi-perspective generalisations</td>
<td>“Energy cannot be generated or lost. Energy only transforms itself. But it all ends up with energy being converted into heat energy, for example, when a train runs, it uses electrical energy, or what most people call electricity, but I’ll get to that. Anyway, that electrical energy is converted into kinetic energy, which makes the train move. Now the question is how is kinetic energy converted into heat energy? This is due to the friction between the train and the rails. Many people consider the heat energy to be useless, because it is difficult to convert it again. Especially when it has escaped into the universe.”</td>
</tr>
</tbody>
</table>

Figure 3. Results from the analysis of the essays based on MAVerBE – here concerning the analysis dimensions vertical linkage level and scientific correctness of the students’ statements
In all categories of the vertical linkage level, we considered the majority of statements explicitly correct (Figure 3). However, in total, about a quarter (26.1%) of all student statements are incorrect. In the highest category, *multi-perspective generalisations*, we declared all students’ explanations to be explicitly correct, even if there were minor subject-specific deficiencies in the complex explanations. As a reminder, to reach this category, students have to combine different central aspects of the concept of energy and explain them with at least one example (see chapter 3). The key criterion for our decision at this point was that the overall context of students’ explanations must be correct.

### 4.3 Horizontal knowledge-linking

For these analyses, we only consider explicitly correct student statements (1,022 of a total of 1,797 statements) in order to be able to describe the students’ horizontal linking performances on the individual vertical linkage levels with the appropriate accuracy. The horizontal linking performances on the vertical linkage levels *scientific facts*, *ungrounded relations* and *interconnected relations* are described below, as these categories were most frequently occupied and are therefore of particular importance to our analyses (see Figure 3).

Within the category *scientific facts*, we were able to identify 387 co-occurrences of terms related to the concept of energy in 484 explicitly correct student statements. The number of co-occurrences between terms is smaller than the number of student statements in this category because for some scientific facts the students only use one term related to the concept of energy. The assignment of the terms to individual subjects or combinations of subjects with the help of the Berlin and Brandenburg curricula (see Chapter 3) results in the network representation shown in Figure 4a. The most frequent co-occurrences by far (P↔BCP, 32.0%) was identified between terms from the physics curriculum (P) and terms found in all of the three, the biology, chemistry, and physics curricula (BCP). The high number of these co-occurrences result from the observation that students particularly frequently refer to the terms *potential*, *kinetic* and *electrical energy* (all of these terms belong to the physics (P) curriculum) as a form of energy (which is a term mentioned in all of the three subject specific curricula (BCP)). The second most frequent co-occurrences emerge in relation to the categories terms from the biology and physics curriculum (BP) and terms that occur in all three curricula (BCP) (BP↔BCP, 9.8%). In these cases, students declare chemical energy (BP) as a form of energy (BCP).

Within the category *ungrounded relations*, we could identify 509 co-occurrences between terms in 244 explicitly correct student statements. The significantly higher number of co-occurrences in relation to the number of student statements compared to the category *scientific facts* arises from the fact that students usually formulated relations between at least two terms and often even three terms of the concept of energy. In the generated network we recognize two dominant connections (Figure 4b). First, the connection between the term energy and biology terms (E↔B, 11.1%). In these cases, students explain procedures to gain or to convert energy using the terms *photosynthesis* or *nutrition*. The second dominant line represents *ungrounded relations* between physics terms and terms which appear in both the chemistry as well as the physics curricula (P↔CP, 10.2%). In these cases, students often describe energy transformation processes between electrical energy (P) and *light or heat* (both CP).
horizontal linkage: percentage of co-occurrences

Figure 4. Results from the analysis of the essays based on MAVerBE – here concerning the analysis dimensions horizontal linkage in a) explicitly correct scientific facts and b) explicitly correct ungrounded relations (see Figure 3). The numbers on the lines indicate the percentages of co-occurrences between the categories connected by the line.

(Note: Although we identified more scientific facts than ungrounded relations in absolute numbers in the essays, students combine more terms of the concept of energy in the course of formulating ungrounded relations, which is why the number of co-occurrences in this category is higher than in the category of science facts.)

Finally, we also want to look at a higher vertical linkage level. 5.8% of all student statements were explicitly correct interconnected relations. Within this category, we found 228 co-occurrences between terms in 105 student statements. The percentage distribution of co-occurrences among the different subject categories shows great similarities to the analysis in the category ungrounded relations. Co-occurrences between the term energy and biological terms (E→B, 9.6%) as well as between the physical and physical-chemical curriculum terms (P→CP, 8.3%) also occur most frequently here (Figure not shown). In contrast to the previous category, ungrounded relations, the students describe the same relations with particular frequency but link them to further relations in order to present the issues in more detail.

5. DISCUSSION
On the basis of well-proven models and procedures in research literature, which only allow the analysis of individual facets of knowledge-linking and which deliver different results depending on the choice of model, we have succeeded in developing a comprehensive model (MAVerBE), which allows a three-dimensional analysis of students’ linking performance. With the help of MAVerBE and the analysis procedure presented in this article, we have achieved a profound analysis of students’ linking performance in relation to the linkage of terms of the concept of energy. The analysis procedure we introduced covers both subject-inherent and cross-curricular linking performance and considers the scientific correctness of the conceptual linkages.
Due to the large number of statements on the concept of energy which the students provided in their essays, we can state that the German students we examined have already built-up notable knowledge structures on the concept of energy at the beginning of 9th grade. We can even classify the students’ knowledge structures to a large extent as scientifically explicitly or at least implicitly correct. Nevertheless, we must note that the knowledge structures on the concept of energy expressed by the students are only poorly linked. In more than half of the students’ statements, the students only link two single elements of the concept of energy in a less complex way. Of course, the students might be able to produce more complex connections between the terms of the concept of energy if we interviewed them after writing their essays. We are aware that spontaneously confronting students with the task to write an essay only allows us to investigate the students’ performance and therefore we refrain from generalizing our findings and drawing conclusions about the students’ competence in relation to the concept of energy. It is obvious, that further research is needed at this point to deepen our knowledge-linking analyses and to receive in-depth insights into the students’ actual knowledge structures concerning the energy concept. Nevertheless, we successfully circumvented an inherent problem of the essay method. By introducing the additional category implicitly correct statements to assess scientific correctness, we can still examine statements without being able to ask further questions afterwards.

In addition, we also succeeded in the development of our analysis procedure by identifying dominant horizontal (cross-curricular) linking structures in the students’ knowledge regarding the concept of energy. For this purpose, we assigned terms to biology, chemistry, physics, or a combination based on their occurrence in subject-specific curricula (SenBJF, 2017a-c). Although this form of assignment may not be the best choice or solution, but as these curricula are negotiated by science education experts and highly experienced curriculum developers, they represent a kind of social and professional consensus. We hereby propose at least a functional and above all an approximately objective approach to this kind of analysis. Our analyses reveal that at the 2nd and 3rd vertical linkage level, links between the term energy and biological terms as well as between physical and physical/chemical terms dominate (see Figure 4b). The students produce ungrounded and interconnected relations here particularly frequently with the terms nutrition (a term of the biology curriculum) and electrical energy (a term of the physics curriculum). These results are not surprising insofar as the students are asked to write down their associations that are strongly influenced by the students’ environment, in which food and electricity play important roles. Crossley, Hirn and Starauschek (2009, Appendix Table A) also observed the frequent reference to electrical energy when students of the same age group were asked about energy.

The analysis of horizontal linkage structures may also be of interest to future research. Representatives of the traditional German view of teaching science in a subject-differentiated manner often express the concern that the content of their subject might be underrepresented in integrated science teaching (Labudde, 2014). With the help of the method presented in this study, this hypothesis can be systematically investigated in the future.

In summary, we can state that our work presented here provides a solid basis for further research. For instance, our results can serve as a baseline for investigating different teaching approaches, such as integrated science teaching, with regard to their effectiveness on students’ linking performance in the concept of energy.

6. OUTLOOK
Concerning the next steps of our research, we are particularly interested in investigating the extent to which an integrated science teaching approach (as it is the educational tradition in several European countries, the US, and Australia) yields qualitatively better knowledge-linking of students compared to the common German practice of the subject-differentiated science teaching approach. To investigate this, we have already collected essays from grade 9 students at the same school in the 2020/21 and 2021/22 school years, who received integrated science lessons in grades 7 and 8 respectively as
part of a school innovation project. The data from this sample, collected in September 2020 and 2021, is currently being analysed. Of course, we will compare the findings from these sets of data with the results of the sample we have presented here, in the context of the NFSUN 2021 and its special section in an issue of NorDiNa.

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8. REFERENCES


