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Constructively aligned teaching and learning in higher education in engineering: what do students perceive as contributing to the learning of interdisciplinary thinking?[†]

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Increased attention to the need for constructively aligned teaching and learning in interdisciplinary higher education in engineering is observed. By contrast, little research has been conducted on the implementation of the outcome-based pedagogical approach to interdisciplinary higher education in engineering. Therefore, the present design-based research was undertaken to develop, implement, and evaluate a constructively aligned learning environment in the interdisciplinary field of food quality management. The practical aims were to reduce the perception held by the students of choppiness and to prevent them floundering in the disciplines; the theoretical aim was to accumulate theory on learning environment aspects that would help students to learn interdisciplinary thinking. The design-focused evaluation among 26 students showed that the practical aims were met, and concerning the theoretical aim, eight learning environment aspects were identified such as learning within an interdisciplinary framework. Further research should validate these aspects to continue with tackling teacher challenges on teaching interdisciplinary thinking.

Keywords: interdisciplinary thinking; outcome-based pedagogical approach; constructively aligned teaching and learning; design-based research; design-focused evaluation

1. Introduction

Various pedagogical approaches to interdisciplinary higher education have been implemented worldwide (Johannes and Kasteren 1996; Van Zonneveld 1996; Ivanitskaya et al. 2002; Ollis 2004; Froyd and Ohland 2005; Franks et al. 2007; Lok 2008; Tong 2010; He, Chen, and Wu 2011; Vale et al. 2012; Liebert 2013; Pharo et al. 2013). These approaches differ from one another with respect to their intended learning outcomes and their *designs*. Among the various intended learning outcomes employed by these approaches are the following: the ability to work in multidisciplinary teams (Hersam, Luna, and Light 2004; Boni, Weingart, and Evenson 2009; Chanan, Vigneswaran, and Kandasamy 2012); the ability to integrate disciplinary knowledge (Guo and

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Liu 2011; Fortuin, Van Koppen, and Kroeze 2013); and the ability to solve complex problems (Ng, Yap, and Hoh 2011; Mascarelli 2013; Mobley et al. 2014). The various designs used in interdisciplinary higher education are, by way of example, short-term training sessions (Hackett and Rhoten 2009; Schmidt et al. 2012), mid-term courses (Rhee, Cordero, and Quill 2010; Nardone and Lee 2011; Wagner et al. 2012), and long-term curricula (Mc Fadden et al. 2011; Gero 2013; Knight et al. 2013). Other aspects of the designs that differ from approach to approach are, for instance, the instructional strategies used by teachers and the roles of the disciplines (Newell 1992; Klein 2005; Davies, Devlin, and Tight 2010; Augsburg et al. 2013).

The defining characteristic of interdisciplinary or interdisciplinarity is the ability to integrate disciplinary knowledge (Klein 1990). When this complex cognitive skill is not taught, it is likely that the teaching and learning will remain multidisciplinary, which is an additive process and does not involve the integration of disciplinary knowledge. The skill of disciplinary knowledge integration can be performed by individuals (Nikitina 2005; Augsburg 2006) or by interdisciplinary collaborations (Thompson 2009; O'Rourke et al. 2013). In interdisciplinary higher education, the name given to the ability to integrate or synthesise knowledge of disciplines is 'interdisciplinary thinking', or 'interdisciplinary understanding' (Eisen et al. 2009; Spelt et al. 2009). In interdisciplinary thinking, the blending of knowledge enables the integration of disciplinary knowledge and allows an advance in understanding (Klein 2010). This integration ability is an important intellectual cognitive activity of our minds that needs to be taught as an intended learning outcome across interdisciplinary higher education (Eckstein 1976; Gardner 2008; Harrison, Macpherson, and Williams 2007; Newell 2010). Interdisciplinary thinking has been defined by Boix Mansilla, Miller, and Gardner (2000, 17) as follows:

> The capacity to integrate knowledge and modes of thinking in two or more disciplines or established areas of expertise to produce a cognitive advancement – such as explaining a phenomenon, solving a problem, or creating a product – in ways that would have been impossible or unlikely through single disciplinary means.

In interdisciplinary classrooms, the intended learning outcome of interdisciplinary thinking can be, for instance, a conceptual model that demonstrates the application of factors derived from different disciplines (Boix Mansilla and Duraising 2007; Repko 2012). The definition of interdisciplinary thinking provides scope for various specific intended learning outcomes of interdisciplinary thinking. For each of these specific learning outcomes of interdisciplinary thinking, the disciplinary perspectives are blended by students to bring about an advance in understanding.

While the need for empirical research into the successfulness of pedagogical approaches to teaching and learning interdisciplinary thinking in higher education is recognised (Lattuca, Voigt, and Fath 2004; Nikitina 2006; Woods 2007; Gouvea et al. 2013), such empirical research with regard to engineering students is still limited. Previous empirical research for engineering students indicated that the lack of coherence between course elements (Eisen et al. 2009) and the lack of clarity as to the learning outcomes (Borrego and Cutler 2010) may result in perceptions by students that the course is 'choppy', that is, just bits and pieces, and that they themselves are floundering in the disciplines. Eisen et al. (2009, 103) reported that the most common complaint about the designed interdisciplinary courses was still their tendency towards choppiness and lack of clear connection or organisation, despite their efforts. A pedagogical approach that has been identified as having the potential to prevent these perceptions is the outcome-based pedagogical approach (Gharaibeh et al. 2013; Lattuca, Knight, and Bergom 2013). It is argued that the constructive alignment principle of the outcome-based pedagogical approach may help teachers in designing consistent interdisciplinary learning environments and may help students in understanding what is expected from them in those learning environments (Yang 2009; Borrego and Cutler 2010). The implementation of the constructive alignment principle likely leads to the required supportive environments to achieve the interdisciplinary learning outcomes (Smith and Carey 2007; Stefani 2009).

It is the interplay between the concepts outcome-based education, constructive alignment, and interdisciplinarity that likely amplify the fostering aid of interdisciplinary learning environments in supporting students to achieve the intended learning outcome of interdisciplinary thinking. The concept outcome-based education considers a precise clarification of intended learning outcomes; these outcomes represent students' desired performances of particular abilities or competencies (Spady 1994). The emphasis on students' performances led to a student-centred way of teaching. Additionally, the concept constructive alignment considers a precise formulation of teaching, learning, and assessment that perfectly matches with the intended outcomes (Harden, Crosby, and Davis 1999). The focus on a perfect match leads to the design of consistent learning environments. The concept interdisciplinarity considers a precise explanation of the connections between relevant disciplinary insights (Newell 2007). The scrutiny of those connections results in a comprehensive understanding which is required for interdisciplinary thinking. The joint use of outcome-based education, constructive alignment, and interdisciplinarity by designers of interdisciplinary higher education would contribute to the design of consistent and supportive learning environments with clear connections between the disciplinary course elements, aiming at the intended learning outcomes of students demonstrating the connections of relevant disciplinary insights and their gained comprehensive understandings.

The present research implemented the outcome-based pedagogical approach to interdisciplinary higher education within the context of a food quality management course. This course on food quality management encountered problems with perceived choppiness and poor alignment. The practical aims of the implementations were to reduce the perception held by the students of choppiness and to prevent them floundering in the disciplines; the theoretical aim was to accumulate theory on key learning environment aspects that would help students to learn interdisciplinary thinking. These research aims were formulated in agreement with the methodology of design-based research in education that features the simultaneous pursuit of theory building and practical improvement by analysis of students' reasoning and of the learning environment (Cobb et al. 2003; Plomp and Nieveen 2013).

The present research focus was on theory building in the field of key aspects of interdisciplinary learning environments (Gilkey and Earp 2006; Misra et al. 2009), instead of theory building in the field of interdisciplinary collaborations among faculties in higher education (Wolman 1977; Kockelmans 1979; Pharo et al. 2012), or theory building on designing interdisciplinary curricula in higher education (Haynes 2002; Chandramohan and Fallows 2009; Chen, Hsu, and Wu 2009; Holley 2009). The conviction that student enquiry can help in assessing the quality of the designed prototypes (Sandoval and Bell 2004; Graybill et al. 2006; Biggs and Tang 2011; Aziz, Yusof, and Yatim 2012; Fernandez et al. 2012) has led to several investigations in interdisciplinary higher education in engineering using student enquiry (Rhee, Cordero, and Quill 2010; Ng, Yap, and Hoh 2011; Wagner et al. 2012). The needed advance in scientific understanding into key design aspects for interdisciplinary higher education in engineering (Vedeld and Krogh 2005; Hmelo-Silver and Azevedo 2006; Richter and Paretti 2009; Rives-East and Lima 2013) via design-based research and student enquiry motivated the present research.

2. Roots of the actual design of the interdisciplinary learning environment

The actual design of the constructively aligned interdisciplinary learning environment (see Section 3) was based chiefly on outcome-based education theory (Section 2.1), a literature review of the teaching and learning of interdisciplinary thinking (Sections 2.2 and 2.3), and the course content for food quality management (Section 2.4).

2.1. *Outcome-based pedagogical approach*

The pivotal characteristic of the outcome-based pedagogical approach is the emphasis placed on the learning outcomes that are intended to be achieved in the learning environment. Therefore, the outcome-based pedagogical approach requires the precise clarification of what students need to enact (Biggs 1999; Biggs 2012). This requirement stems from the conviction that student achievement is enhanced when the learning outcomes are clarified by teachers and designers. The intended learning outcomes need to be clarified in terms of verbs that suggest abilities such as memorise, classify, analyse, and build. The outcome-based pedagogical approach of Biggs and Tang (2007) also features the constructive alignment principle, which prescribes the alignment of the individual instructional elements with the intended learning outcomes. The outcome-based design model for higher education of Biggs and Tang (2011, 105) comprises three parts: the intended learning outcomes, the teaching and learning activities, and the assessment tasks. These parts need to be constructively aligned in designing education. The outcome-based pedagogical approach can be used in aligning curricula, aligning courses, or aligning the actual teaching in classrooms.

2.2. *Sub-skills of interdisciplinary thinking*

The mastery of five sub-skills likely leads to the achievement of the intended learning outcomes of interdisciplinary thinking (Spelt et al. 2009). These five sub-skills are (a) having knowledge of disciplines; (b) having knowledge of disciplinary paradigms; (c) having knowledge of interdisciplinarity; (d) higher order cognitive skills; and (e) communication skills. The sub-skills d and e concern the mastery of functioning knowledge which is explained as knowing how to apply knowledge. For example, knowing how to communicate the cognitive advancements, sub-skill e, resulting from blending the knowledge of the disciplinary perspectives is a necessary ability of being an interdisciplinarian (Woods 2007). The five sub-skills of interdisciplinary thinking can be considered as intermediate learning outcomes helping teachers and designers in identifying essential teaching, learning, and assessing activities to achieve the intended learning outcomes of interdisciplinary thinking.

2.3. *Enabling conditions to develop interdisciplinary thinking*

Particular enabling conditions embedded in the learning environment likely foster the development of interdisciplinary thinking (Spelt et al. 2009). The categories of enabling conditions are (a) personal characteristics, (b) prior experiences, (c) teacher, (d) pedagogy, (e) learning process pattern, (f) learning activities, and (g) assessment. These categories are grounded in the concepts of outcome-based education and constructive alignment (Spelt et al. 2009). More specifically, each category provides enabling conditions that are aligned with student achievements in learning outcomes of interdisciplinary thinking. The enabling conditions in categories (a) and (b) are student attributes, whereas those in categories (c)–(g) are attributes of the learning environment itself. This distinction has consequences for the manner in which these conditions can be embedded in the learning environment. For example, embedding of enabling conditions of categories (c)–(g) is expressed as follows: The greater the presence of the enabling conditions of categories (c)–(g) in the learning environment, the more that will facilitate student achievement of the intended learning outcomes of interdisciplinary thinking. These enabling conditions can be considered as design propositions necessary to be embedded in the actual design of an interdisciplinary learning environment.

2.4. *Interdisciplinary and problem-based learning in food quality management*

The interdisciplinary course on food quality management teaches the 'Techno-Managerial' (T-M) approach which involves the integration of disciplinary knowledge from the technological disciplines and the managerial disciplines (Luning and Marcelis 2006). The T-M approach is to deal with the complexity involved in managing the quality of food products. The complexity lies in the fact that the causes of food quality problems may lie within one or more disciplines. The course teaches students complex problem-solving which involves four sequential phases of an interdisciplinary research process (Luning and Marcelis 2009). In each of these phases, students are required to apply the T-M approach. The first research phase considers the appreciation of the complex food quality management problem followed by an in-depth analysis of the problem in the second research phase. The third research phase deals with diagnosing the actual problem situation to bring about the best solution in the fourth research phase (Luning and Marcelis 2009). The new learning environment included these four phases with the aim of achieving in each phase the intended learning outcome of interdisciplinary thinking. This problem-based learning as a teaching strategy is one of the three commonly used pedagogical strategies for interdisciplinary teaching (Nikitina 2006).

3. Actual design of the constructively aligned interdisciplinary learning environment

Table 1 shows the actual design of the learning environment in a format analogous to that of the outcome-based design model of Biggs and Tang (2011).

The four specific intended learning outcomes are a sequential line of outcomes (outcomes I–IV) in agreement with the four phases of the interdisciplinary research process taught in this

Table 1. The actual design of the constructively aligned interdisciplinary learning environment.

Teaching and learning elements	Specific intended learning outcomes	Assessment elements
(1) *Lecture*	(I) *Apply*	(5) *Plenary*
Content, skills, and methodology lectures with the aim of teaching the sub-skills of interdisciplinary thinking	Disciplinary knowledge integration which is achieved by applying the T-M approach to the complex problem	Feedback by teachers with the aim of assessing the intended learning outcomes of interdisciplinary thinking
(2) *Individual task*	(II) *Construct*	(6) *Peer*
Interdisciplinary problem-solving task with the aim of learning the five sub-skills of interdisciplinary thinking	Disciplinary knowledge integration which is achieved by constructing the T-M research instrument	Feedback by students with the aim of assessing the intended learning outcomes of interdisciplinary thinking
(3) *Individual presentation*	(III) *Identify*	(7) *Individual*
Progress and final presentations by students with the aim of learning from each other's individual outcomes concerning interdisciplinary thinking	Disciplinary knowledge integration which is achieved by identifying the technological and managerial causes for the complex problem	Feedback by teachers with the aim of assessing the five sub-skills and the intended learning outcomes of interdisciplinary thinking
(4) *Group task*	(IV) *Create*	(8) *Self*
Group interdisciplinary problem-solving with the aim of collaboratively learning the five sub-skills of interdisciplinary thinking	Disciplinary knowledge integration which is achieved by creating the interdisciplinary argument in support of the best solution for the complex problem	Reflection by students with the aim of assessing the five sub-skills and the intended learning outcomes of interdisciplinary thinking

course. The learning periods of these four learning outcomes were of similar duration, thereby providing the students with repeated opportunities to learn interdisciplinary thinking. The teaching and learning, and the assessment elements (elements 1–8) were constructively aligned with each of the four intended learning outcomes. The teaching element (1) lecture was to teach the five sub-skills of interdisciplinary thinking (Table 1), whereas the learning elements of (2) individual task, (3) individual presentation, and (4) group task were to engage students in the learning activities concerning the five sub-skills of interdisciplinary thinking. The assessment elements of (5) plenary feedback, (6) peer feedback, (7) individual feedback, and (8) self-reflection were to formatively assess student performances. The present research investigated the following research question: *What do students perceive in the learning environment as contributing to the achievement of the intended learning outcomes of interdisciplinary thinking?* The answer to this question would lead to refinement of the actual design, which can, in turn, be the input for new iterative cycles of design and implementation to proceed with theory building and improving educational practices (Edelson 2002; Barab and Squire 2004).

4. Method

4.1. *Present design-based research*

The present design-based research provided insights from three different angles: (a) the adequacy of the implementation of the pedagogical approach of Biggs and Tang to the teaching and learning of interdisciplinary thinking; (b) the usefulness of the constructed actual design in teaching and learning of interdisciplinary thinking in the field of food quality management; and (c) the particular aspects of the learning environment that enable engineering students in learning interdisciplinary thinking. The present research dealt with the developmental stage of 'what is happening in the interdisciplinary learning environment' prior to the developmental stage of 'is there a systematic effect between the instructional design and the learning outcomes' (Shavelson et al. 2003; Collins, Joseph, and Bielaczyc 2004). The developmental stage of what is happening requires formative evaluations of gathering information on the actual practicality and actual effectiveness, instead of summative evaluations, proving the systematic effectiveness of newly created designs (Nieveen 2007). Following the generic model for conducting design-based research in education (McKenney and Reeves 2012, 77), an interdisciplinary team of teachers and researchers co-created the interdisciplinary learning environment in a systematic manner. The formative evaluation was conducted by asking the students whether they considered that the new learning environment had contributed to their achievement of the intended learning outcomes.

4.2. *Course context*

The context of the redesigned course was a European university dealing with the delivery of education in the domain of healthy food and living environment. This domain is rarely related to a single discipline; often there are multiple disciplines involved. Therefore, the connections between disciplinary knowledge of the natural sciences and social sciences, in both education and research, are fostered. At this university the philosophy of outcome-based education has been implemented and continuous improvement takes place. The redesigned course is part of an interdisciplinary graduate programme on food quality management consisting of three interrelated interdisciplinary courses and different clusters of disciplinary courses. The redesigned course is the second course in the row of these interdisciplinary courses.

4.3. *Course redesign*

The steps of the course redesign included alpha trials in academic year 2009–2010 and beta-testing in academic year 2010–2011 (McKenney and Reeves 2012). Each of these steps was followed by an in-depth reflection phase including comparisons with other interdisciplinary courses, the purpose of which was to enable a comprehensive understanding (Postholm and Moen 2011). A team of four researchers conducted the course redesign, its implementation, and evaluation. The role of the first two authors was to take care of the development, implementation, and evaluation of the course redesign. This was done in close collaboration with the second two authors, other researchers, and teachers in the departments of food sciences and educational sciences who all reflected upon the research and design activities. The redesigned course took 12 weeks, in which the students were required to participate every weekday (full-time) during the first four weeks and to spend a minimum of 20 hours of the study week (part-time) during the remaining eight weeks (in total 12 European credits). At the start of the course, students received instruction about the student-driven pedagogy in this course and their accompanying responsibilities of the learning processes.

4.4. *Course evaluation*

The course evaluation included 20 statements and questions intended to ascertain the perceived contribution of the total learning environment and its individual elements (see Table 1) to the achievement of the intended learning outcomes. This design-focused approach to evaluation questions the link between the educational design and the outcomes (Smith 2008). From Table 1, four statements were derived from the specific intended learning outcomes (middle column), 12 questions were derived from the individual teaching and learning elements (left column), and four questions were derived from the individual assessment elements (right column). Responses to the four items covering the perceived contribution of the total learning environment ranged on a scale from one (1 = *strongly disagree*) to five (5 = *fully agree*). Responses to the 16 items covering the perceived contribution of the individual teaching, learning, and assessing elements ranged from one (1 = *very low extent*) to five (5 = *very high extent*). The evaluation form also included an open question by means of which the student was invited to elaborate on the given response. At the end of the course, the 30 students received an email asking them to complete the evaluation form, and 26 students completed this form. The 26 students ranged in age from 23 to 41 years; the majority of them (20 out of the 26) had a background in food sciences. The group comprised 18 women and eight men from 12 nationalities.

4.5. *Data analysis*

A mixed methods data analysis (Johnson and Onwuegbuzie 2004) determined the perceived contribution of the actual design (Table 1) to the achievement of the learning outcomes of interdisciplinary thinking. The quantitative part of the mixed methods data analysis included the construct of frequency distributions of the answers given to the 20 items. Having an ordinal measurement level of items, the *mode* (most frequently given answer) is the adequate descriptive statistic to show the central tendencies in the perceived contributions (Reid 2014). The qualitative part of the mixed methods analysis included comparing and contrasting of the answers given (Boeije 2010) to the open questions using MAXQDA 10. The comparing and contrasting showed that similar responses were made by students on particular aspects of the learning environment. A label to these particular aspects of the learning environment was given, following the method of pattern coding (Saldaña 2009). The grouping of the similar responses was labelled when at least five students addressed that particular aspect in their response.

5. Results and discussion

The quantitative results, presented in Tables 2–5, showed the contribution of the constructively aligned learning environment to the achievement of the intended learning outcomes as perceived by the students.

In Table 2, for all inquiry items, with respect to the total learning environment, the most common categories (*mode*) are categories 4 and 5.

In Table 3, for all inquiry items with respect to the teaching element, the most common categories (*mode*) are categories 3 and 4. The perceived contribution was not consistent for the three lecture types; the lecture type of skills lectures earned a lower rating. Accordingly, a refinement to the actual design (see Table 1) is the better alignment of the skills lectures to the achievement of the learning outcomes of interdisciplinary thinking.

In Table 4, for all inquiry items with respect to the learning elements, the most common category (*mode*) is category four, with the exception of one instructional part of the individual task which relates to the food problem description. The relatively lower score for this instructional part tallied with our expectations. Since the individual task was an ill-defined problem task, the food problem description did not include all the necessary information. This was deliberate because the lack of information is consistent with the daily practice of complex problem-solving that students will encounter in their future careers.

The data presented in Table 4 on the student perception on the contribution was, however,

Table 2. The perceived degrees of contribution of the total learning environment to the achievement of the intended learning outcomes measured per specific intended learning outcome ($N = 26$ students).

Total learning environment	The perceived degrees of contribution				
Specific intended learning outcomes:	(1) Strongly disagree	(2) Partly disagree	(3) Neutral	(4) Partly agree	(5) Fully agree
Apply: The learning environment enhanced my ability to < apply > the T-M approach in situations involving a food quality management problem	0	1	1	8	**16**
Construct: The learning environment enhanced my ability to < construct > a T-M research instrument for use in situations involving a food quality management problem.	0	0	0	**13**	**13**
Identify: The learning environment enhanced my ability to < identify > technological and managerial causes of situations involving a food quality management problem	0	0	1	**13**	12
Create: The learning environment enhanced my ability to < create > an interdisciplinary argument for the best solution in a situation involving a food quality management problem	0	0	3	**13**	10

Note: The *modes* (most frequently given answer) are printed in bold.

Table 3. The perceived degrees of contribution of the teaching element to the achievement of the intended learning outcomes measured per type of lecture ($N = 26$ students).

	The perceived degrees of contribution				
Teaching element:	(1) Very low extent	(2) Rather low extent	(3) Neutral	(4) Rather high extent	(5) Very high extent
Lecture: To what extent did the < content > lectures facilitate you in achieving the intended learning outcomes?	0	1	7	**11**	7
Lecture: To what extent did the < skills > lectures facilitate you in achieving the intended learning outcomes?	1	0	**11**	8	6
Lecture: To what extent did the < methodology > lectures facilitate you in achieving the intended learning outcomes?	1	0	6	**12**	7

Note: The *modes* (most frequently given answer) are printed in bold.

broad relative to Tables 2 and 3. This broad range in perceptions may be attributable to several factors: the range of student prior social and educational experiences; the range of student preferences for a particular type of pedagogical approach; the delivery of the course by the teaching staff; or the extent of alignment between the intended learning outcomes and those elements involved; or a combination of factors. Extension of the design-focused evaluation with semi-structured questions related to these factors is recommended.

In Table 5, for all inquiry items, with respect to the assessment elements the most common categories (*mode*) are categories 3 and 5. Table 5 indicates that students perceived plenary and individual feedback as being more valuable than peer feedback and self-reflection. This discrepancy in attributed value seems to be due to the fact that these engineering students were more familiar with plenary and individual feedback than with peer feedback and self-reflection. It might even be the case that these engineering students were engaging in peer feedback and self-reflection for the first time. Extra time was spent on introducing peer feedback and self-reflection to the students and should be continued.

With respect to the qualitative results, 25 of the 26 students perceived the new learning environment as constructively contributing to the achievement of the intended learning outcomes; one student perceived the new learning environment as still not being interdisciplinary and argued what disciplinary knowledge integration actually is. Table 6 shows the identified key aspects of the learning environment to the achievement of the intended learning outcomes of interdisciplinary thinking.

The perceived contribution of the key aspect 'learning within an interdisciplinary framework' (Table 6) reflects the interdisciplinary levels model of Gouvea et al. (2013) which shows an interdisciplinary framework between the disciplines physics and biology comparable to the interdisciplinary framework in this research between the technological and managerial disciplines. Additionally, the perceived contribution of key aspects related to the learning and the assessment instructional elements (Table 6) mirrors the active learner-centred model of Nardone and Lee (2011) that included particular learning activities for interdisciplinary courses such as reflecting. The successfulness of reflecting in interdisciplinary learning has also been addressed by Gilkey et al. (2006), Boix Mansilla and Duraising (2007), Woods (2007), and Lyall and Meagher (2012). The successfulness of each of these key aspects needs further investigation.

Table 4. The perceived degrees of contribution of the learning elements to the achievement of the intended learning outcomes measured per part of the learning elements ($N = 26$ students).

	The perceived degrees of contribution				
Learning elements:	(1) Very low extent	(2) Rather low extent	(3) Neutral	(4) Rather high extent	(5) Very high extent
Individual task: To what extent did the < assignment introductions > facilitate you in achieving the intended learning outcomes?	0	3	5	**14**	4
Individual task: To what extent did the < assignment descriptions > facilitate you in achieving the intended learning outcomes?	0	1	3	**17**	5
Individual task: To what extent did the < food problem description > facilitate you in achieving the intended learning outcomes?	1	6	**8**	**8**	3
Individual task: To what extent did the < assignments report writing > facilitate you in achieving the intended learning outcomes? *	0	0	1	**14**	10
Individual presentation: To what extent did the < students' presentations > facilitate you in achieving the intended learning outcomes?	0	4	5	**10**	7
Individual presentation: To what extent did the < your own student presentation > facilitate you in achieving the intended learning outcomes?	1	0	4	**14**	7
Group task: To what extent did the < food problem group assignment > facilitate you in achieving the intended learning outcomes?	1	4	4	**13**	4
Group task: To what extent did the < food quality management topic group > facilitate you in achieving the intended learning outcomes?	2	3	5	**11**	5
Group task: To what extent did the < interdisciplinary research learning community > facilitate you in achieving the intended learning outcomes?	2	4	6	**11**	3

*one response is missing
Note: The *modes* (most frequently given answer) are printed in bold.

In retrospect, the development of the new learning environment facilitated in this particular context a common understanding of how to teach interdisciplinary thinking and how to critically evaluate new interdisciplinary learning environments. From the development viewpoint, a major limitation was the considerable investment in time that was required to enable the team members to adopt the interdisciplinary mode of thinking, coming as they did from various disciplines. In contrast, from the research viewpoint, the major limitation was the lack of empirical research into the contribution of constructively aligned course designs to the learning of interdisciplinary thinking, which forced us to adopt a fully structured approach in the innovation process (Van

Table 5. The perceived degrees of contribution of the assessment elements to the achievement of the intended learning outcomes measured per assessment element ($N = 26$ students).

	The perceived degrees of contribution				
Assessment elements:	(1) Very low extent	(2) Rather low extent	(3) Neutral	(4) Rather high extent	(5) Very high extent
Plenary: To what extent did the < plenary feedback > facilitate you in achieving the intended learning outcomes?	1	2	7	7	**9**
Peer: To what extent did the < peer feedback > facilitate you in achieving the intended learning outcomes?	1	3	**13**	9	0
Individual: To what extent did the < individual feedback > facilitate you in achieving the intended learning outcomes?	0	0	3	6	**17**
Self: To what extent did the < self-reflection > facilitate you in achieving the intended learning outcomes?	3	5	**11**	5	2

Note: The *modes* (most frequently given answer) are printed in bold.

Table 6. The perceived contribution of key aspects of the total learning environment and its individual elements, which was expressed by *n* students ($N = 26$ students).

Part of the learning environment:	The perceived contribution of key aspects	*n*
Total learning environment	Learning within an interdisciplinary framework	12
	Learning via a step-by-step roadmap	8
Teaching element	Receiving cognitive guidance	8
	Receiving examples to familiarise oneself	5
Learning elements	Engaging in a range of disciplinary perspectives	10
	Conducting disciplinary knowledge integration a number of times	12
Assessment elements	Determining concrete improvements	9
	Tackling difficult issues during learning activities	8

Boekel 2009) and the decision to strictly follow the principles of scientific research in education (Shavelson et al. 2003).

Additionally, the design-focused evaluation proposed by Smith (2008), being used as a formative evaluation in the educational design process, matched well with the research aims. However, the need for elaboration with semi-structured questions and the validation of this kind of evaluation is recognised, to allow investigations of a large number of educational innovations and to validate the design-based research methodology (Joseph 2004). Therefore, an appropriate balance needs to be found between the internal validity of the evaluation, that is, the 'truth' of the findings by means of methodological alignment between theory, educational innovation, data gathering, and interpretation (Hoadley 2004), and the external validity, that is, the 'generalisability' of the findings (Kelly 2004). At this point, it is also worth noting that the open manner of enquiry remains necessary in order to take account of the confirmation bias inevitable in design-based research (Stam 2011; Kelly 2004).

The major recommendation for further research is the repetition of the outcome-based pedagogical approach to fields other than food quality management in order to ascertain whether it has indeed potential in fostering the learning of interdisciplinary thinking. The repetition is also

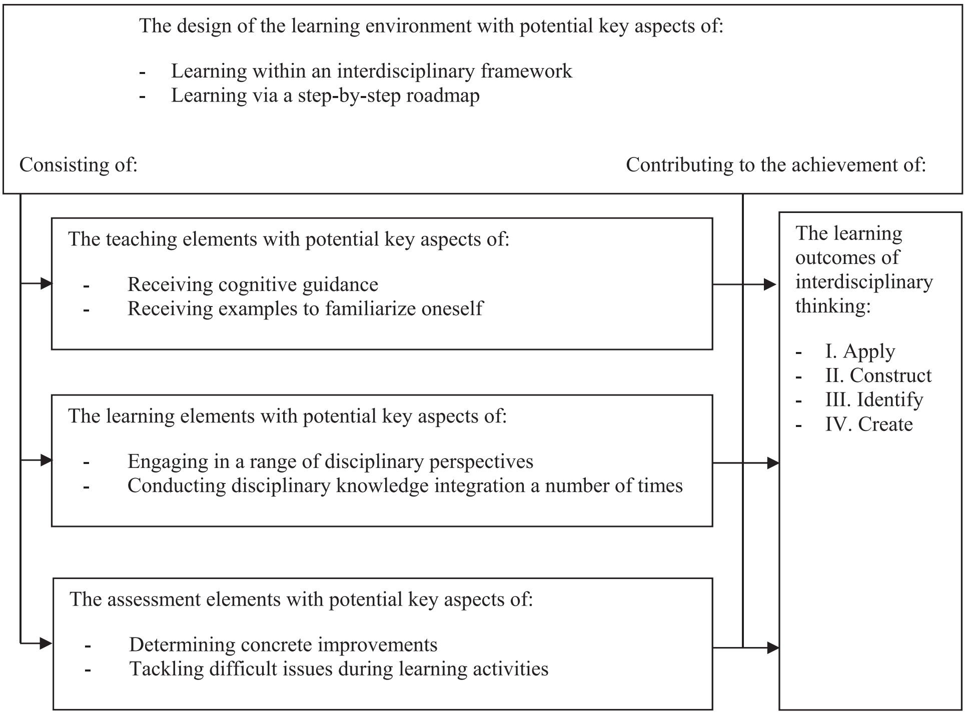

Figure 1. The initial design framework with hypothesised relationships between potential key aspects of the learning environment, the individual elements of the learning environment, and the learning outcomes, based on Briggs (2007).

recommended to determine whether the Hawthorne effect, which is the effect of enhanced attention of the interdisciplinary team received by the students, occurred (Brown 1992). Additionally, the repetition is recommended to validate the identified key aspects of the learning environment which may lead to design frameworks (Kelly 2004; Edelson 2002) or design principles (Mulder and Kintu 2013). Figure 1 presents the initial design framework on teaching and learning interdisciplinary thinking in higher education in engineering, based upon present empirical research. It is also recommended to take the lessons of Goodman and Huckfeldt (2013) into account in extending empirical research with larger groups of students in interdisciplinary higher education in engineering.

In conclusion, the implementation of the pedagogical approach of Biggs and Tang seems to be adequate for the redesigned course to enhance the teaching and learning for interdisciplinary thinking in the field of food quality management (Tables 2–5). The adequacy lies, in our opinion, in the student-centred approach to teaching and learning that likely leads to autonomous students. In turn, these relatively more autonomous students are likely better equipped in reaching the necessary adequacy in the disciplines themselves, in adequately synthesising the disciplinary knowledge, and then in revising the obtained disciplinary knowledge integration (Nikitina 2005; Boix Mansilla and Duraising 2007; Repko 2012). This better equipment is important because each engineering student in interdisciplinary higher education develops unique scholarly identities and areas of expertise (Graybill et al. 2006) which is required for working in industry (Martin et al. 2005) and in research (Lach 2014). The identified refinements of the actual design (Table 1) are, for instance, better alignment of the skills lectures (Table 3) and continuation of the in-depth instruction on peer and self-assessment (Table 5). The particular eight aspects of the new learning environment (Table 6) that would help engineering students in learning interdisciplinary thinking need further validation in future research as schematically represented in Figure 1. In sum, the teacher challenge of implementing the outcome-based pedagogical approach to the food quality management course seemed to be tackled via this educational innovation. However, new challenges to optimise this innovation simultaneously emerged.

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